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CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

WORKSHOP ON SPS FIXED-TARGET PHYSICS
IN THE YEARS 1984–1989
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6–10 December 1982

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ABSTRACT

This second volume of the Proceedings of the Workshop on SPS Fixed Target Physics in the Years 1984-1989 contains the written version of most of the talks delivered during the plenary sessions held at CERN on December 7 and 8, 1982.

The order of presentation has been slightly changed and some additional material from the preparatory working group meetings has been collected in a few additional papers, which are included for completeness. For the CP violation and rare kaon decays session only the reference is given to the preprint containing the papers presented during a special theory seminar at CERN, which was organized specifically in view of the Workshop.

The programme of the Workshop is reproduced at the beginning of this volume.
# SPS FIXED TARGET WORKSHOP

Monday 6 to Friday 10 December 1982

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Registration on Sunday, 5 December 15.00-20.00 hrs.

### Monday, 6 December

**Plenary session** 9.00–10.15 hrs.

- **9.00–9.15** Opening remarks
- **9.15–10.15** FNAL scientific programme and plans

**Working groups meetings**

- 10.30–13.00 and
- 14.00–18.00

### Tuesday, 7 December

**Working groups meetings**

Plenary session 14.00–18.00

- Structure functions
- Electroweak asymmetry
- Hadronic final states in $\mu$ experiments
- Hadronic final states in $\nu$ experiments
- Theory

9.00–13.00 hrs.

-Muon physics, structure functions, hadronic final states ($\mu$ and $\nu$ experiments)
- **J.J. Aubert**

- F. Eisele
- A. Benvenuti
- H. Montgomery
- A. Tenner
- K. Gaemers
Wednesday, 8 December

Plenary session 9.00–13.00 hrs.

ν, physics
ν oscillations
Neutral currents
νe → e scattering
Theory

Neutrino physics D. Haidt
G. Myatt
F. Vannucci
J. Panman
F. Jacquet and K. Winter
C.H. Llewellyn Smith

Plenary session 14.00–18.00 hrs

Charm physics
Search for beauty
Search for SuSy particles, axion, heavy neutrinos
CP violation
Theory

New particles and decays L. Foà
S. Reucroft
J. Sacton
G. Barbieri
H. Wahl
H. Fritzsch

Thursday, 9 December

Plenary session 9.00–13.00

Hard scattering and jet physics in connection with real γ
Dimuons
Gluonium physics
Spin physics with hadrons and γ: its interest and feasibility
Acceleration of polarized particles in PS and SPS
Theory

Hadron physics D. Treille
K. Pretzl
K. Freudenreich
R. Zitoun
L. Van Rossum
D. Möhl and C. Bovet
R. Petronzio

Plenary session 14.00–18.00

Nuclear beams from PS and SPS
Experimental review and preview
QCD results on quark-gluon plasma and chiral symmetry
Theory

Nuclear beams and targets W. Willis
H. Haseroth
M. Albrow
H. Satz
L. Van Hove

Friday, 10 December

9.30–12.30 hrs.
14.00–17.00 hrs.
17.00–18.00 hrs.

Summary talks by J.J. Aubert, L. Foà, D. Haidt
Summary talks by W. Willis, D. Treille, A. de Rujula
General discussion
NEW PARTICLES
AND DECAYS

Convener: L. Foà

Monday 6 December, morning in ISR Auditorium (bus outside Main Bldg.)

10:30 New results from the hyperon beam: the charmed strange baryon A^0 H.J. Burckhart
11:00 Production of charm and strangeness in a hyperon beam K.P. Streit
11:20 The present experimental status of charm hadroproduction as a guide for future measurements W. Geist
11:40 High precision silicon chambers E. Neugebauer
12:00 High statistics charm study using an active silicon target and silicon strip detectors R. Klanner
12:15 Relevant parameters for bubble chambers as vertex detectors H. Leutz
12:30 The future charm programme at EHS (Bus retour Main Bldg.)

C.M. Fisher

Monday 6 December, afternoon in Bldg. 13, 2-005 (EF)

14:00 Comparison of visual vertex detectors S. Tavernier
14:20 Experimental review of charm particle photoproduction P. Petroff
14:40 Study of charmed particle decay properties and of their production mechanism in a high intensity photon beam P. Roudeau
15:00 Charm photoproduction in the energy range 70 - 200 GeV (WA69 and beyond) E. Paul
15:20 Charm physics with active targets M.A. Giorgi
15:40 Diffractive production of $\Lambda_c$ and a possible measurement of its lifetime F. Fidecaro
16:00 Developments in automatic emulsion scanning G.R. Vanderhaeghe

(BREAK)
16:30  Possible experiments for understanding the $\nu_e/\nu_\mu$ asymmetry, if any, in beam dump experiments  P. Pistilli

16:50  Prompt lepton production in hadron interactions: present status and a possible experiment  C. Fabjan

17:15  Hyperon radiative decays: new results and future possibilities  P. Muhlemann

17:40  Search for a flavour changing neutral current in K decay  A. Grant

Tuesday 7 December, morning in Bldg. 13, 2-005 (EF)

9:00  Spot focusing Cerenkov and avalanche chamber for beauty search in nuclear emulsions  R. Meunier

9:20  Search for beauty in a beam dump exposition looking at multi-muon events  M. de Vincenzi

9:40  Photoproduction of beauty particles and their lifetime measurement  P. Roudeau

10:00  Beauty search in $\Omega'$. An hybrid experiment using CCD area sensor as high resolution vertex detector  G. di Caporiacco

10:20  Possibilities to measure open beauty production in hadronic interaction using a high resolution silicon $\mu$-strip vertex detector  P. Weilhammer

(BREAK)

11:00  Comparison with FNAL charm and beauty programme and general discussion

11:40  Limits on tau-neutrino mass  J. Aspiazu

12:00  Limits on gluino mass from beam dump experiments  V. Kowanski

12:20  Search for R-particles  P. Musset

12:40  Experimental search for light supersymmetric particles in $e^+e^-$ annihilation at SPS  G. Batignani
HADRON PHYSICS

Convener: D. Treille

Monday 6 December, morning in Main Auditorium

10:30 - 11:15  Polarization (L. Van Rossum)
               Theoretical outline
               N.S. Craigie
               M. Fontannaz

11:15 - 12:15  Polarized targets, sources, gas jets...
               T. Niinikoski

12:15 - 13:15  Acceleration of polarized particles
               Ruth, L. Nacach
               E. Grorud

Monday 6 December, afternoon in Main Auditorium

14:00 - 14:30  Feasibility of polarization experiments: a few examples

               Dimuons (K. Freudenreich)
               14:45  Review of the work done by
                      the dimuon group
                      K. Freudenreich

14:55  Influence of the D.I.S. scaling violations on the D.Y. K factor
       J.L. Meunier

15:10  Short-range programme of NA10
       L. Kluberg

15:40  Hot π+ beams and cold p̅ beams
       K. Feudenreich

16:00  Lepton pairs with ossooc hadrons/γ's
       P. Sonderegger

16:05  K factor in the associated
       hadrons to lepton pairs
       M. Krawczyk

These discussions may continue in Bldg. 1, 1-025

16:30 - 17:30  Gluonium
               C. Daum

17:45 - 18:30  Exclusive reactions at large θ
               P. Sonderegger

Tuesday 7 December, morning in Council Chamber

Jets, photoproduction, prompt γ (K. Pretzl)

9:00 - 9:30  Review of the jets workshop
              P. Seyboth

9:30 - 9:50  Gluon radiation
              M. Greco

9:50 - 10:20  Review of the prompt γ workshop
              F. Costantini

11:00 - 11:30  Hard scattering with γ and
               prompt γ: theory
               D. Schiff

11:30 - 11:50  Comparison of photon induced and
               hadron induced processes
               E. Paul

11:50 - 12:20  S. Donnachie
NUCLEAR BEAMS AND TARGETS

Convener: W. Willis

Monday 6 December, morning in Bldg. 21, R-011

10:30 Organization of working group meeting
11:00 Conditions for quark-gluons plasma formation M. Danos
12:00 General discussion on nuclear physics at SPS energies

Monday 6 December, afternoon in Bldg. 21, R-011

14:15 Lepton pairs G. London
14:50 Proposal for diquark search H. Pugh
15:30 Plastic ball H. Gutbrod
16:00 Streamer chamber experiment R. Stock

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F. Eisele,
University of Dortmund, Germany.

INTRODUCTION

In this talk I will try to summarize ideas and plans which have been put forward by members of all collaborations running muon or neutrino experiments at CERN. During our discussions there was general agreement that: i) substantial improvements of structure function measurements in the SPS range are still possible and necessary and ii) it is the responsibility of the present groups and of CERN to provide a "final" set of structure functions in the present energy range.

1. MAIN PHYSICS INTEREST

a) Nucleon structure functions are very important phenomenological input for hard scattering processes involving hadrons like Drell-Yan lepton pair production, single photon production, high $p_T$ scattering in pp and $\bar{p}p$ etc. For these applications we have to know the flavour composition, i.e. the quark and gluon distributions $xu_\nu(x,Q^2)$, $xd_\nu(x,Q^2)$, $x\bar{u}$, $x\bar{d}$, $x\bar{s}$, $xc$, ..., $xG(x,Q^2)$.

b) The study of scaling violations ($Q^2$-dependence) provides a good way to study quark-quark interactions. We expect two contributions, one which falls like $(1/Q^2)^n$ plus a $1/\ln Q^2$ contribution, where the first one represent collective parton effects (higher twists), whereas the second one is due to single parton scattering for which we have a solid QCD-prediction.

c) A new subject is the question of parton distributions in nuclear matter (A-dependence) where substantial interest has been triggered by the new EMC-result\(^1\). If their result is confirmed then it would reinforce the interest in structure function measurements on $H_2$ and $D_2$ targets.

d) We have to cure some experimental defects: We need a decent measurement of $R = \sigma_L/\sigma_T$, we want to fill in some blank kinematic regions (i.e. low $x$ for $H_2$, large $x$ and low $W$) and we have to solve normalization problems both for neutrino and muon experiments.

2. PRESENT STATUS

2.1 Reminder

Most of our knowledge at present is coming from heavy targets. Both muon and neutrino experiments measure the structure function $F_2^N = x(u + d + s + c + \bar{u} + \bar{d} + \bar{s} + \bar{c})$ on complex nuclei. Neutrino experiments have the additional virtue to separate sea and valence contributions. They measure $xF_3(x,Q^2) = x(u_\nu + d_\nu)$ and $q_\bar{\nu}(x,Q^2) = x(\bar{u} + \bar{d} + 2\bar{s})$. Finally the observation of opposite sign dilepton events in $\nu$-physics gives a handle on $xS(x,Q^2)$.

The separation of $u_\nu$ and $d_\nu$ and of $\bar{u}$ and $\bar{d}$ requires additional measurements on elementary targets. The ratios $u_\nu/d_\nu$ and $\bar{u}/\bar{d}$ can be determined by neutrino (and antineutrino) experiments on hydrogen. With some additional uncertainties due to nuclear effects this information can also be obtained from deuterium. Muon experiments measure $F_2^{1P}$ and possibly $F_2^{1N}$. The main
emphasis here is the $Q^2$-dependence. Any analysis of muon data requires however external information about the sea contributions.

2.2 A-dependence

Let me start by this subject because it may influence substantially the future program. Effective quark distributions in nuclear matter are expected to be different from free nucleons, i.e. due to Fermi motion. The real surprise is that the EMC Collaboration sees a rather brutal effect at a level which jeopardizes the evaluation of nucleon structure functions from heavy targets and reinforces the interest in $H_2$ and $D_2$. The EMC observation is shown in Fig. 1: The $F_2$ structure function differs substantially if measured on iron compared to $D_2$ in a kinematic range ($<\nu> = 60$ GeV) where we all believe that scattering off single partons should be the dominant process. Figure 2 gives the difference of structure functions $F_2^N(\text{Fe}) - F_2^N(D_2)$ ignoring the large normalization uncertainty. It suggests that the difference might be mainly due to the sea quark contributions, i.e. the sea contribution in iron might be larger by $\approx 40\%$ compared to free nucleons$^7\)$. This effect needs confirmation by a dedicated experiment.

Actually our present understanding of the Fermi motion effect is also pretty disappointing. The Fermi motion corrections for iron versus $x$ as proposed by various authors differs substantially, mainly at large $x$. As a result the shape of quark distributions at large $x$ ($x \gtrsim 0.5$) cannot be reliably determined from experiments on heavy targets.

The study of the $A$-dependence is an interesting subject by its own. For particle physicists we might say that we can study the "long range confining phenomena" in QCD. For nuclear physicists we might say that these experiments could help to clarify the role of quarks and gluons in the nuclei. A detailed discussion of the physics aspects can be found in the talk of Ch. Llewellyn Smith in this volume$^8\)$. Depending on the verification of the EMC result there may evolve interest in a long term program.

2.3 Flavour composition of the nucleon

The present situation is well documented. See for instance, Ref. 3. Shortly, for isoscalar heavy targets we have a complete set of structure functions $F_2$, $x F_3$, $\bar{q}^0$ and $xS(x)$. They are reasonably well measured including their $Q^2$-dependence. Main defects are: i) the poor knowledge of $R = q_L / q_T$ which affects the determination of $F_2$ and $\bar{q}^0$ mainly at small $x$, ii) normalization uncertainties of up to 20\%, iii) a rather poor knowledge of $x F_3$ at small $x$.

For $H_2$ and $D_2$ targets, the experimental situation is less satisfactory. The structure function $F_2^{HP}$ is quite well measured at large $x$ including the $Q^2$-dependence, the small $x$ region ($x \leq 0.1$) is however missing. A combination with measurements on $D_2$ allows to measure $\alpha_n / \alpha_p$ which, outside of the sea region is related to $d(x)/u(x)$. The present experimental knowledge is given in Fig. 3 combining low energy SLAC data and high energy muon data from EMC. These measurements require separation of neutron and proton interactions in $D_2$ and therefore suffer from uncertainties due to Fermi-motion especially at large $x$. Hydrogen experiments with neutrinos and antineutrinos can do better in principle since they are able to separate valence and sea contributions in the whole $x$-range using $H_2$ data only. Present knowledge is summarized in Fig. 4. The knowledge on $d(x)/u(x)$ at present is rather modest. It is limited by statistics at small and medium $x$, whereas the large $x$ region is inaccessible due to large smearing corrections which are due to poor total hadron energy measurement. The flavour composition
of the sea, especially the measurement of \( \hat{u}/\hat{d} \) is only accessible to neutrino experiments and is poorly known at present.

The longitudinal structure function \( F_L \) (related to \( R = c_L/c_T = F_L/F_2 \)) is by far the hardest to determine and has been a pain in the neck of the experimentalists for a long time. The present experimental situation is summarized in Fig. 5a and b. \( R \) is still very poorly known at small \( x \) leading to substantial uncertainties for \( F_2 \) and \( Q^0 \). We have however, tight bounds at large \( x \) due to a new measurement of the CDHS Collaboration which is only possible for neutrino experiments.

2.4 \( Q^2 \)-dependence of structure functions

The knowledge of the \( Q^2 \)-dependence is important for two reasons:

i) the fractional momentum carried by constituents changes with \( Q^2 \) substantially and has therefore to be known for hard scattering processes. (This assumes that we will make theoretical improvements which allow us to use this knowledge, i.e. what is the mass scale for hard-scattering processes, etc.);

ii) the study of scaling violations gives a good handle to study q-q interactions. We may be able to separate \( (1/Q^2)^n \) effects from \( 1/\ln Q^2 \) effects, i.e. to separate collective parton phenomena (+ kinematic effects) from perturbative QCD effects.

The main interest up to now has been to test QCD predictions. All experiments agree that there are significant scaling violations which extend to high \( Q^2 \) and they are well described by QCD (for large enough hadron masses \( W \geq 3.3 \) GeV). Figure 6 shows \( d \ln F_2/d \ln Q^2 \) for the three high statistics experiments at the CERN SPS to illustrate this point. Though there are differences in detail outside statistical errors, the agreement as a whole is encouraging. These experiments have achieved a determination of \( \Lambda \) corresponding to a measurement of \( \alpha_s \) to about \( \pm 10\% \) and a determination of the gluon distribution. We also have first indications that non-perturbative contributions are important at low \( W \).

Most people are aware by now, that the study of scaling violations cannot prove QCD. It should be pointed out however, that QCD might be disproven. So I think further improvements are important, especially since deep inelastic scattering is one of the few fields where perturbative QCD predictions are based on solid grounds.

A last note: whatever we have learned about QCD from DIS is not affected by the possible \( A \)-dependence of structure functions. Effective parton distributions in iron will follow the same evolution equations as the distributions in free nucleons. The results may depend however on the way how the analysis is done because the data have to be extrapolated to large \( x \) outside the measured region (\( x \geq 0.7 \)). Most groups nowadays use the Altarelli-Parisi equations directly to follow the \( (x,Q^2) \) dependence. This technique is fairly independent of the detailed behaviour at large \( x \) in contrast to, e.g. a moment analysis. Further discussion of this point may be found in Ref. 4.

2.5 Missing kinematic regions

Some kinematic regions are poorly covered at present. The low \( x \) region is not accessible to present muon experiments due to acceptance. It is covered by neutrino experiments but suffers both from statistics and the large uncertainty due to \( R = c_L/c_T \). This is very bad since the low \( x \)-region contains most of the information about QCD. Discriminative tests of
QCD\textsuperscript{1)}, the check of the QCD prediction on $R$ and the determination of the gluon structure function via scaling violations all require precise data, at low $x$. The large $x$ region ($x \geq 0.7$) is unaccessible due to large smearing in the variable $v$. This leaves a large unexplored region $0.7 < x < 56$ in the case of iron which might contain quite interesting physics. Finally, the region at large $x$ and low $Q^2$, i.e. low invariant hadron mass $W$ is not covered by present high energy experiments. This kinematic region is important to separate higher twist contributions $\sim (1/Q^2)^n$ from perturbative $1/\ln Q^2$ contributions.

3. EXPERIMENTAL PROGRAM AND NECESSARY IMPROVEMENTS

i) A verification of the EMC result on $A$-dependence is urgent since it has impact on the long term future.

ii) A precise measurement of the longitudinal structure function $F_L(x, Q^2)$ would be highly desirable since the present uncertainty seriously affects the determination of all structure functions except $xF_3$. Also, the analysis of scaling violations at small $x$ and hence the determination of the gluon distribution suffers. Moreover there is a QCD prediction for $F_L$ to test.

iii) Concerning the flavour composition we would like to improve our knowledge on $xF_3(x, Q^2)$ mainly at small $x$ and to improve our knowledge of $d_\nu(x)/u_\nu(x)$ and $\bar{u}(x)/\bar{d}(x)$. If it turns out that the parton distributions in nuclear matter are really substantially different from free nuclei, then there is a real job to be done. In this case we have to restart the determination of $xu_\nu$, $xd_\nu$, $x\bar{u}$, $x\bar{d}$, $xs$ and of the gluon distribution for free nucleons. Remember that according to the measured effect of the EMC Collaboration, the sea might differ by a very large amount. Such a goal would certainly need an extensive neutrino program on $H_2$ and possibly $D_2$. The measurement of $F_2^{pp}(x, Q^2)$ and $F_2^{\mu}(x, Q^2)$ by muon experiments would be also needed especially for the $Q^2$-dependence.

iv) We should improve our QCD tests and the determination of the gluon distribution. The analysis of $xF_3(x, Q^2)$ measured by neutrino experiments on heavy targets is our best handle to measure $\Lambda$. A substantial improvement is possible there, both in statistics and systematics. A good singlet analysis needs precise data at small $x$ and a good knowledge of $R = \sigma_L/\sigma_T$. Muon experiments should improve their acceptance at small $x$ to cover this region with good statistics.

4. FUTURE PROGRAM AT THE SPS

4.1 Neutrino experiments on heavy targets (iron, marble, etc.)

These experiments aim at a substantial improvement in the measurement of $F_L$, $q_\nu^\leftrightarrow$, $xF_3$ and the gluon distribution and this can only be achieved by them.

The CDHS Collaboration has installed new calorimeter modules with improved resolution and systematics. They also have learned how to use high statistics from wide band beams. This collaboration foresees an extended structure function run corresponding to a total of $\sim 3 \times 10^{18}$ protons in WBB leading to about $10^5\nu$ and $10^6\bar{\nu}$ events above $E_{\nu} = 20$ GeV. This will happen in 1983/84. CHARM has improved their detector. A specific merit of this detector is that the useful hadron energy range can be extended down to about 2 GeV ($\sim 5$ GeV for CDHS). They have presented a new analysis based on $50'000\nu$ and $110'000\bar{\nu}$ charged current events from wide band beam\textsuperscript{6}) at this meeting. Based on this experience they foresee an extended
program in wide band and possibly high band beams. In 1983/84 they expect about $5 \times 10^{18}$ protons on WBB targets (450 GeV) leading to $10^6$ neutrino and ~$500'000$ antineutrino events with average energies $<E_{\nu}> \approx 25$ GeV and $<E_{\bar{\nu}}> \approx 35$ GeV. After 1984 they think of extending towards higher energy by working in a quadrupole focused beam which is expected to yield for $5 \times 10^{18}$ protons on target $300'000$ $\nu$ and $100'000$ $\bar{\nu}$ events with average energies $<E_{\nu}> = 100$ GeV and $<E_{\bar{\nu}}> = 70$ GeV. Both experiments will certainly provide a precise consistent set of structure functions on heavy targets and a substantial improvement of our QCD tests.

4.2 Experiments on $H_2$ and $D_2$

Muon experiments

These experiments have made substantial progress in the control and understanding of systematic errors, which is their major worry. The BCDMS (NA4) Collaboration has an approved program for the years 1982-84 to do high statistics runs on $H_2$ at 100, 200 and 250 GeV beam energy. They expect altogether more than $3 \times 10^8$ events in an increased kinematic range $x > 0.1$ and $Q^2 > 7$ GeV$^2$/c$^2$. They may also do some $D_2$ running though there are no definite plans yet. The main emphasis is on the $Q^2$-dependence and QCD-comparisons.

The upgraded EMC detector after 1984 will allow to measure down to very low $x$-values by adding a small angle system. The kinematic range $Q^2 \geq 1.5$ GeV$^2$/c$^2$ for $0.003 < x < 0.1$ would be accessible. Using this detector, a precise measurement of $H_2$ and $D_2$ structure functions in the whole $x$-range would be possible after 1984. However, no definite plans have yet evolved.

Neutrino experiments on $H_2$ and $D_2$

These experiments are indispensable to separate valence and sea components and to determine the flavour composition separately for up, down and strange quarks. The interest in $H_2$ and $D_2$ experiments is substantially increased if quark distributions in nuclei differ from free nucleons as suggested by the EMC result. In this case, there is a substantial job to be done which might take a long time. Could BEBC be a suitable detector for this work? It has already seen a lot of neutrinos. At present, the WA21 experiment has reconstructed 3400 neutrino and 2900 antineutrino charged current events and twice as many are on film. For $D_2$ a large exposure is underway for experiment WA25, where about 20'000 neutrino and 20'000 antineutrino events are expected for $3 \times 10^{18}$ protons on target.

Clearly, a large amount of effort and money is required to do structure function work with bubble chambers. We should however, keep in mind, that structure function determinations are just one facet of a large bubble chamber exposure.

The most interesting question is: Could large BEBC exposures provide good measurements of $x\bar{\nu}$, $x\bar{\nu}$, $x\nu$, $x\nu$ as a function of $x$ and possibly also $Q^2$?

Present $H_2$ and $D_2$ data in BEBC have a major defect: the total hadron energy cannot be measured but has to be inferred from the charged energy using an empirical correction based on the missing transverse momentum. Figure 7 shows the resulting resolution function due to this procedure as obtained from a Monte Carlo simulation. For bare BEBC filled with hydrogen the resolution function looks just awful to me, especially since it has large asymmetric tails which can only be obtained by model-dependent Monte Carlo.
The effect on the measurement of x-distributions due to this smearing has been estimated by Myatt. The smearing corrections are around -10% for small x and rise very rapidly above x = 0.6 such that a measurement above x = 0.7 is not possible. The systematic uncertainties of these smearing corrections are estimated to exceed 10% for x > 0.4. The situation could be substantially improved if the neutral component of the showers would also be measured by an electromagnetic calorimeter inside BEBC. A solid argon calorimeter has been proposed and would indeed help a lot as shown in Fig. 7.

As a result, for bare BEBC, about four times more statistics could be useful for anti-neutrinos which would correspond to $5 \times 10^{18}$ protons on target. Further increase of statistics would not really help since the systematic uncertainties exceed the statistical errors. Therefore, substantial improvements would require additional gadgets like, i.e., an electromagnetic calorimeter. In this case an exposure which yields about 30'000 charged-current events is expected to yield statistical errors similar to the systematic uncertainties.

It should be clear that the main motivation to use neutrino experiments is the separation of valence and sea distribution in the small x region. Up to now I have not seen a clear strategy how this can be achieved for $H_2$ and $D_2$. Also the relative merits of $H_2$ and $D_2$ exposures have to be reevaluated.

Therefore, I can say that there is a clear need to get precise neutrino structure functions from free protons and neutrons, especially if the A-dependence of structure functions is confirmed. It has however still to be demonstrated if and how the present systematic problems can be overcome. High statistics alone are not sufficient.

4.3 A-dependence measurements
i) Verification of effect

A first check could be made using the $D_2$ exposure in BEBC. The analysis is in progress. It could be checked if the ratio of sea to valence distribution is larger in iron than in $D_2$. The EMC effect suggests a 40% difference which should be easy to check. A direct check can be performed by the BCDSM exposure in 1983 in a parasitic run at 280 GeV. They will be able to run with $D_2$ and Fe targets simultaneously which will reduce systematic uncertainties substantially. They expect a statistics comparable to the present EMC data.

ii) Future program if confirmed

Both muon collaborations have shown interest in a series of exposures to study the A-dependence after 1984. Neutrino experiments will also be needed to separate the effect on valence and sea contributions.

4.4 Polarization measurements

Muon experiments using a polarized target are approved for the EMC collaboration for the year 1984. After 1984 BCDSM might be willing to collaborate using the polarized target in front of the NA4 detector. Unfortunately the polarization effect is strongly diluted by the small fraction of free protons in the target and the small degree of polarization.

4.5 Beams and runs for structure function experiments

Shown below is a tentative program of the SPS for structure function measurements. The solid lines show runs which have been requested and are partially approved. Dashed lines
indicate experiments where serious thoughts are underway in the collaborations. Finally
the dotted lines give some vague ideas of how the program could continue in the far future.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Beam</th>
<th>83</th>
<th>84</th>
<th>85</th>
<th>86</th>
<th>&gt; 86</th>
</tr>
</thead>
</table>
| BEBC       | $\nu + \bar{\nu}$ WBB | $
u, \bar{\nu}$ | $\nu, \bar{\nu}$ | $\nu, \bar{\nu}$ | $\nu, \bar{\nu}$ | $\nu, \bar{\nu}$ |
| CDMHS      | 450 GeV | $\nu, \bar{\nu}$ | $\nu, \bar{\nu}$ | $\nu, \bar{\nu}$ | $\nu, \bar{\nu}$ | $\nu, \bar{\nu}$ |
| CHARM      | quadrupole beam | $\nu, \bar{\nu}$ | $\nu, \bar{\nu}$ | $\nu, \bar{\nu}$ | $\nu, \bar{\nu}$ | $\nu, \bar{\nu}$ |
| BCIMS      | $H_2, D_2$ polarization | $\nu, \bar{\nu}$ | $\nu, \bar{\nu}$ | $\nu, \bar{\nu}$ | $\nu, \bar{\nu}$ | $\nu, \bar{\nu}$ |
| EMC        | shadowing polarization $H_2, D_2$ | $\nu, \bar{\nu}$ | $\nu, \bar{\nu}$ | $\nu, \bar{\nu}$ | $\nu, \bar{\nu}$ | $\nu, \bar{\nu}$ |

5. **COMPARISON WITH THE DOUBLER (Fermilab)**

Both muon and neutrino experiments will be operational starting in 1984. The $Q^2$ and
$W^2$-range are doubled such that this machine offers a unique chance to find thresholds, to
establish the propagator effect and hopefully something unexpected which happens to be
in this new energy domain.

The main emphasis in my presentation has been on the conservative issues like flavour
composition, $\ln Q^2$-dependence, $A$-dependence, which do not profit necessarily from higher
energy. There high statistics, well understood detectors etc., are much more important.

The main limitation of the Doubler is flux (or event rate). There will be about
$2 \times 10^{18}$ protons on target/year (100 days running) and this lack of protons is not com-
penated by the higher flux and cross-section. Moreover, it will take quite some time to
understand and control the partially new detectors in the new energy range. It is surely
more interesting to work at the Doubler, but I think structure functions will not be the
main issue at the Doubler. SPS experiments are in good shape to lead in all fields, where
the increase in energy is not essential.

6. **SUMMARY**

i) We need a reliable set of structure functions for the nucleons: $x_{u, d, s}, x_{u, d, s}, xG(x)$. The CERN neutrino and muon experiments are in a unique position to provide this
information. We know how to improve our present knowledge on $P_2$, $xF_3$, $P_1^D$, $F_2$, $q^\nu$, ..., and experiments are underway or planned for the near future to do so.

ii) We have strong indication that structure function measurements on heavy nuclei may not
be used to derive the nucleon structure functions. For example, the sea quark distri-
butions might differ by about 40%. If this is confirmed, then there is work to be done
which might take quite long and would involve large neutrino and muon experiments on $H_2$
and $D_2$. 

iii) The study of scaling violations is one of the most reliable ways to study parton dynamics and to test QCD. Substantial improvements are still possible and new experiments will give much better determinations of $\Lambda$, the gluon distribution and more insight into the question of higher twist contributions.

These experiments are notoriously difficult and there may not be much fun in them any longer. Nevertheless they are important and they should be supported provided a sufficient number of dedicated and persistent physicists is willing to spend their time on them.

REFERENCES

   See also Ref. 1.
4) C. Llewellyn Smith, talk presented at this workshop, to appear in the proceedings Vol. II.
5) See for example, H. Abramowicz et al., Z. Phys. C13, 199 (1982).
6) P. Longo, Charm Prospectives, talk at this workshop.
7) J. Panman, Hadronic neutral currents, talk at this workshop, to appear in the proceedings Vol. II.
8) D.J. Miller, private communication.
Fig. 1 Ratio $F_{2}^{\text{iron}}/F_{2}^{D_{2}}$ versus $x$ as measured by the EMC Collaboration. The dashed region indicates the systematic uncertainty.

Fig. 2 Difference $F_{2}^{\text{iron}} - F_{2}^{D_{2}}$ from EMC data. No account is given to the large (7%) normalization uncertainty between iron and $D_{2}$ measurements.
Fig. 3 Ratio of cross-section on neutrinos and protons as determined by the SLAC-MIT and the EMC experiments.

Fig. 4 The ratio of valence down and up quarks versus x measured by neutrino experiments on hydrogen. The dashed line indicates the measurement of SLAC-MIT at lower energy.
Fig. 5a  Measurement of $R = \sigma_L / \sigma_T$ versus $x$ for the CDHS experiment. ($\nu$) 50 GeV.

Fig. 5b  Measurements of $R = \sigma_L / \sigma_T$ versus $x$ for the EMC experiment (preliminary) and the SLAC-MIT experiment (statistical errors only).
Fig. 6: The slopes $d \ln F_2^N / d \ln Q^2$ for three experiments as obtained from power law fits to the whole $Q^2$-range. The lines are QCD predictions for $\Lambda_{L,0} = 0.2$ GeV.

Fig. 7: Total hadron energy resolution for a hydrogen bubble chamber (BEBC) (solid line). The dashed line shows the expected resolution if an electromagnetic calorimeter would be added within the chamber volume.
LEPTON NUCLEON SCATTERING

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1. Structure functions

As is well known, deep-inelastic scattering measures structure functions. In the case of muon scattering we have $F_1^{(\mu N)}(x,Q^2)$ and $F_2^{(\mu N)}(x,Q^2)$. In the case of neutrino and antineutrino scattering we measure $F_1^{(\nu N)}(x,Q^2)$ ($i=1,2,3$). Despite all successes of QCD, these structure functions cannot be calculated (at present) from first principles. Since these structure functions tell us something about the bound state wave functions of quarks inside nucleons, it is clear that in order to calculate the various $F_i$'s we need some handle on the confinement problem. So far non perturbative effects in QCD have been studied by putting QCD on a lattice. One of the ultimate aims of this procedure should be a calculation from first principles of the $F_i$'s. Such a calculation should presumably be done by calculating matrix elements of Wilson-operators which give moments of the structure functions. From these moments one can than reconstruct $F_i$ approximately. Alternatively one could compare experimental moments with the theoretical ones. As was already mentioned, theorists have not yet been able to accomplish this.

What has been done however is the following. If the structure functions have been measured at a given value of $Q^2$, say $Q_0^2$, it is possible to calculate $F_i(x,Q^2)$ at higher values of $Q^2 > Q_0^2$. In order to do this one may use e.g. the Altarelli-Parisi equations for quark distributions

$$Q^2 \frac{dq(x,Q^2)}{dQ^2} = \frac{\alpha_s(Q^2)}{2\pi} \int \frac{dy}{x} \left\{ q(y,Q^2) P_{qq} \left( \frac{x}{y} \right) + g(y,Q^2) P_{qg} \left( \frac{x}{y} \right) \right\}$$

where in lowest order

$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2f) \ln \frac{Q^2}{\Lambda^2}}$$

with $F$ the number of flavours and $\Lambda$ the well known QCD parameter.

The equations (1) can be systematically corrected for higher order QCD ($O(\alpha_s^3)$) effects. A comparison of the final equations with the $Q^2$ evolution of the measured structure functions gives a value for $\Lambda$. Several experiments at CERN and elsewhere have done this analysis. Results indicate a value for $\Lambda$ in the range 100 - 200 MeV[1]. It is important to try to reduce the error on $\Lambda$ because of the following reason. $\Lambda$ is a fundamental parameter of QCD. When measured in different reactions the same value should
result. A comparison between D.I.S. and for example e⁺e⁻ annihilation data should therefore be done.

A byproduct of the analysis is a determination of the gluon distribution from eq. (1). The CDHS collaboration found at \( Q^2 = 4.5 \, \text{GeV}^2 \) \(^2\):

\[
G(x) = (1 + ax)(1 - x)^b
\]

\[
a = 3.5 \pm 1.0
\]

\[
b = 5.9 \pm 0.5
\]

A problem in the analysis is the presence of so-called higher-twist effects. In terms of moments of the structure functions, they incorporate effects that do not vary as \( \log(Q^2) \) but rather behave as powers of \( Q^2 \). A typical guess for the behaviour of moments is

\[
\int x^{N-1} f(x, Q^2) = M_N \left[ 1 + \frac{4K^2}{Q^2} (1 - N) \right]
\]

where \( K^2 \) can be interpreted as average transverse momentum of the quarks. Some recent theoretical work on these higher twist effects has been done by Ellis, Furmanski and Petronzio\(^3\). Unfortunately the work is not yet in a stage where a systematic experimental analysis of the effects can be made.

2. Hadronic final states

The structure functions give information on the total cross-sections of a virtual photon. It is possible to study in more detail the hadronic final states. From a theoretical point of view it is very hard to give a description of the final state hadrons from first principles. There exist however several models that start from a more phenomenological level. I like to give some attention to the LUND model. It starts off with the idea that the struck quark leaves the nucleon stretching a "rubber band" which mimicks the gluon lines of force. At random points this rubber band may break, producing a new quark and antiquark. The chance that a given quark flavour will be produced in the break up of the rubber band depends strongly on the mass of the produced quark.

One parameter that can be adjusted is the ratio \( V/P \) the relative probability that a quark-antiquark pair ends up as a vector meson or as a pseudoscalar meson. In figure 1, data from the WA25 collaboration\(^4\) are shown for the inclusive hadron distributions for various targets (p, n) and beam (\( v, \bar{v} \)). It is seen that on the whole the model reproduces the data quite well.
This by itself does not mean that the model has been proven correct, or that other models do not reproduce these data. Recently the LUND group has made some predictions on baryon production in the hadronic final state. One effect which is predicted is that \( \Lambda \)'s that are produced at non-zero \( P_T \) with respect to the jet-axis must have a transverse polarisation. Since this prediction depends rather sensitively on the details of the model it would be very interesting to see the effect confirmed or refused by the data.

As is well known from e\(^+\)e\(^-\) annihilation that quarks radiate gluons, one expects the same to happen with the struck quark in deep inelastic scattering. Also this gluon bremsstrahlung effect has been incorporated in the LUND Monte Carlo. In figure 2 results are shown from the EMC. Together with the prediction from two models \(^5\). It can be seen that an explanation of these data needs gluon bremsstrahlung.

Instead of looking at all hadrons in the final state one could also look at inclusive hadron distributions. They are described by quark fragmentation functions \( D_q^h(z) \) or \( D_q^b(z, Q^2) \). The probability to find a hadron with momentum-fraction \( Z \) inside a quark. The \( Q^2 \) evolution of these functions is described by an equation analogous to the equation for the structure functions.

In lowest order the inclusive cross-section factorises in a parton distribution and a fragmentation function.

\[
\sigma^h \propto q(x) \frac{d^k}{q(z)}
\]

Higher order corrections spoil this property \(^6\). There is an indication in the data of the breakdown of factorisation.

There are other effects where the parton picture breaks down. One interesting prediction was made by Berger \(^7\). If one considers the diagram of figure 3 one finds a contribution to the inBreheive \( \pi \) distribution of the form

\[
\int dz \frac{d\sigma}{dy} \frac{dP_T}{dP_T} = \int G_q(x) \frac{1}{yP_T^2 Q^2} |\psi_{\pi}(0)|^2 \left[ \left( 1 - z \right)^{\frac{2}{3}} \left( 1 + (1-y)^2 \right) 
+ \frac{2}{3} (1 - z) \left[ 1 - (\psi - y) \right] (1 - y)^\frac{1}{2} \cos \phi \frac{P_T^2}{Q^2} + \frac{4}{9} (1 - y) \frac{P_T^2}{Q^2} \right]
\]

The \( x,y \) variables are the usual ones as defined in e.g. \( v \)-scattering.
From this the $y$ distribution at high $z$ should show a different behaviour. It would be an interesting test of QCD to see whether the effect can be seen in the data. The interest lies in the fact that we get some insight in the bound state nature of light hadrons.

3. New flavours

With increasing $Q^2$ the sea distribution of the nucleon will change. The amount of heavy flavours $s, c, b ...$ will increase. The evolution equations (1) give a description of this effect. Since these equations only use the longitudinal degrees of freedom they do not give information on the $p_T$ distribution of the produced heavy quarks. A better model which takes these features into account is the photon gluon fusion model. In this model one calculates perturbatively the cross section e.g. for the sub-process

$$\gamma^* + g \to c + \bar{c}$$

which is then folded with the gluon distribution in the nucleon to give the inclusive $c, \bar{c}$ production cross-section.

$$\sigma(\gamma^* N \to c \bar{c} ...) = \int dx G(x) \sigma(\gamma^* g \to c \bar{c})$$

In order to compare with the data a fragmentation model is necessary to give final state charmed mesons and baryons. The semileptonic decays of these particles can be seen as two and three muon final states. In figure 4 data are shown from the EMC where one can see that the photon gluon fusion mechanism gives a very good description of the data, for inclusive charm production.

The same mechanism should work for inclusive bottom production and it would be useful to see whether one could produce free bottom using muon beams.

A related topic is the production of hidden charm and bottom for the production of vector mesons like $J/\psi$ and $Y$. Also here one can construct a photon gluon fusion model. Several calculations have appeared in the literature. In figure 5 a comparison is made between the EMC data on $J/\psi$ production and a model by Baier and Rückl. As can be seen, the agreement with the data is not very good. In the first place there is a problem with the absolute normalisation of the theoretical curves and secondly the shape of the various distributions does not agree well. This may be due to the fact that the wave function that was used in the calculation is too simple.

Also here as with the pion higher twist effects an understanding of the production mechanism would give insight in the bound state nature of hadrons. For this reason experimental data on $Y$ production could be of help here.
4. Weak interaction effects

There is now ample evidence that the standard model of weak- and electromagnetic interactions is in good agreement with the data. An important parameter of the model is $\sin^2 \theta_w$. Deep inelastic scattering experiments offer several ways to determine this parameter. For example a comparison of NC and CC weak cross sections gives a value for $\sin^2 \theta_w$. Using total cross-sections we have the Paschos-Wolfenstein relation

$$\frac{\sigma^{NC}(\nu) - \sigma^{NC}(\bar{\nu})}{\sigma^{CC}(\nu) - \sigma^{CC}(\bar{\nu})} = \frac{1}{2} - \sin^2 \theta_w$$

It is also possible to obtain $\sin^2 \theta_w$ from $\nu_{\mu}e^-$ and $\bar{\nu}_{\mu}e^-$ scattering experiments.

A precise measurement of $\sin^2 \theta_w$ will allow important tests of the standard model. It will also give constraints on unification models.

First of all, a comparison of $\sin^2 \theta_w$ from different experiments offers the possibility to test higher order corrections. Only after these corrections have been applied to the data can one expect agreement. Such tests are important since the standard model is a renormalisable field theory which is capable of making well defined predictions for these higher order corrections.

A second reason why a precision determination of $\sin^2 \theta_w$ is important is that the masses of the $Z$ and $W$ depend directly on it. We have the well known expressions:

$$M_w = \frac{37}{\sin \theta_w} \quad \text{GeV}$$

$$M_Z = \frac{37}{\sin \theta_w \cos \theta_w} \quad \text{GeV}$$

Comparison of the experimentally determined values for $M_w$ and $M_Z$ with the value for $\sin^2 \theta_w$ will again be a test of the standard model. Of course if $\sin^2 \theta_w$ is only known with 10% accuracy the test is not very stringent. There is a more theoretical argument in this respect. The expressions given in (10) are subject to higher order corrections. In order to test these corrections one would like to measure the masses of the $Z$ and $W$ with an error of about 100 MeV or less if it can be done. In order to have a useful comparison based on (10) a knowledge of $\sin^2 \theta_w$ accurate to 1% or less would be very useful.

It has been shown during this workshop that it is possible to determine $\sin^2 \theta_w$ from a measurement of charge and polarisation asymmetries in deep inelastic muon scattering. These asymmetries are due to the interference
between $\gamma$ and $Z$ exchange diagrams. A discussion can be found in the talk by Benvenuti\textsuperscript{[12]}. 

5. Conclusions

There exists now an impressive amount of deep inelastic data. Structure functions have measured both in electromagnetic and weak interactions. These have helped to give a good picture of the quark and gluon distributions inside the nucleon.

It may be worthwhile to try to get a very accurate determination of $\Lambda_{QCD}$ in order to make comparisons with other determinations (e.g. from $e^+e^-$) of this parameters. It will be usefull to study in more detail the bound state effects in $\pi$ production and in the production of quarkonia states. Finally an accurate determination of $\sin^2\theta_W$ will be necessary in order to test the standard model beyond its lowest order approximation.

References

[4] From talk by A. Tenner at this workshop.
[8] For references to models and a comparison with data see: J.J. Aubert et al., CERN-EP 82-153.
Fig. 1
Energy flow in the plane of the event, data from EMC. a) with no cuts, b) with requirements that at least one hadron has $p_T > 2$ GeV. Solid curve in QCD expectation, the dotted is that of non-QCD fragmentation with increased fragmentation $p_T$.

Fig. 2

(a) Sketch of $eN \rightarrow e'X; Q$ labels the exchanged $q^*$ or $W$. The intermediate quark labeled $p'_Q$ is off-shell and timelike.

The initial quark from the incident nucleon carries four momentum $p_N = 2p_Q$. (b) On the left is a diagram showing the disassociation of an off-shell virtual quark into a pion plus $X$.

At large $p_T^2$, its behavior may be represented by the single gluon exchange diagram sketched on the right, in which the quark lines marked with crosses ($\times$) are essentially on-shell. The unshaded oval in the diagram on the right-hand side of fig. 1b represents the unspecified small momentum behavior of the pion wavefunction, represented in this paper simply by the wavefunction at the origin, $\phi_p (r = 0)$.

Fig. 3
Fig. 4
Fig. 5
SPIN STRUCTURE AT THE PARTONIC LEVEL

I : DEEP INELASTIC LEPTON SCATTERING

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ABSTRACT
The fundamental internal structure of hadrons can only be probed fully using polarised beams and targets. We describe some of the essential features that can be studied in electromagnetic and weak charged current reactions and make some comments about Drell-Yan processes.

1. INTRODUCTION

It is totally meaningless to consider spin structure as a separate, isolated subject. The spin quantum number of quark or gluon is an intrinsic and fundamental attribute that plays a deep role in the properties of individual hadrons and in their behaviour when reacting with other hadrons. For this reason my report is written in two sections, the first dealing with leptonic scattering, where one learns, via the lepton probe, about the internal spin structure of the hadrons, and the second, dealing with hadronic reactions, where one uses this information together with perturbative QCD to calculate the experimental observables. The latter, then, constitutes an effective tool for probing and testing the basic QCD elements. As to the former, ultimately of course one will test what one has learnt about the hadrons against the predictions of non-perturbative QCD, but it will probably be some years before that can be done reliably.

The questions that are answered in deep inelastic lepton scattering are: "What is the fundamental internal structure of a hadron? How is it built from quarks and gluons? What is their wave-function, i.e. how, in a hadron of definite helicity, are the momenta and spins of the constituents distributed?"

Unpolarised experiments have already provided an enormous amount of information on such quantities \( u(x,Q^2) \), the number density of "up" quarks with momentum fraction \( x \), to be found in an unpolarised proton when probed by a lepton with \( q^2 = -Q^2 \). Experiments with polarised hadrons teach us about number densities such as

\[
\begin{align*}
\mathcal{P}(x,Q^2), \quad \mathcal{A}(x,Q^2)
\end{align*}
\]

which are the number densities of "up" quarks with spin parallel (\( \mathcal{P} \)) or anti-parallel (\( \mathcal{A} \)) to the helicity of the parent hadron. The usual number density is, of course, related to these:

\[
u(x,Q^2) = \mathcal{P}(x,Q^2) + \mathcal{A}(x,Q^2)
\]

\[ ... \quad (1) \]

*) See page 384.
It must not be forgotten that in order to study the partonic spin dependence one has to have both polarised hadrons and a polarised initial or final lepton beam. This is because the parity-conserving single spin asymmetries all vanish as a consequence of the simplicity of the dynamical mechanism, i.e. one-photon or one-weak boson exchange. For the latter the lepton polarisation is guaranteed since neutrinos are 100% polarised. (There are, of course, parity-violating single spin asymmetries, but they are best thought of as teaching us about the structure of electroweak theory. Some of these are dealt with in the contribution by Soffer).

In the following our main concern is to expose the basic physical ideas and not to look into the detailed dynamics. Thus we shall talk always in terms of the simplest parton model concepts and we shall leave questions as to QCD effects, $Q^2$ dependence etc. to the contribution by Craigie.

2. ELECTROMAGNETIC INTERACTIONS : $p^*p \rightarrow \mu^+\mu^-$

In general, with a polarised nuclear target, there are four independent structure functions $W_1, W_2, G_1$ and $G_2$. They are expected to scale in the following fashion:

$$mW_1(\nu, Q^2) + F_1(x)$$
$$\nu W_2(\nu, Q^2) + F_2(x)$$
$$m^2 G_1(\nu, Q^2) + g_1(x)$$
$$\nu G_2(\nu, Q^2) + g_2(x)$$

... (2)

where $m$ is the nucleon mass and the scaling is in the Bjorken limit.

In the simple parton model we have, in addition,

$$F_2(x) = 2xF_1(x)$$

... (3)

$$g_2(x) = -g_1(x)$$

... (4)

Assuming the validity of these scaling forms one has for the observable quantities $^2$''

a) Unpolarised

$$\frac{d^2\sigma}{d\Omega dE} + \frac{d^2\sigma}{d\Omega dE'} \propto \frac{y + 2(1-y)}{2y} F_2(x)$$

... (5)

where $\Rightarrow$ and $\Rightarrow'$ imply nucleon and lepton helicities parallel or anti-parallel respectively.

b) Longitudinally polarised lepton beam and target:

$$\frac{d^2\sigma}{d\Omega dE} - \frac{d^2\sigma}{d\Omega dE'} \propto (1-y/2) \left[ 2xg_1(x) \right]$$

... (6)

c) Longitudinally polarised leptons, transversally polarised nucleons:
\[
\frac{d^2\sigma}{d\omega dE} - \frac{d^2\sigma}{d\omega dE} \propto \sin(1-y)(1+y/2)[2\xi g_1(x)]/y \quad \ldots (7)
\]

Measurements of these thus give us \( g_1(x) \) and also test the validity of (4) which, like (3), only holds strictly in the simple parton model.

The theoretical interpretation of the above quantities in terms of the quark number densities \( q_i(x) \), \( \bar{q}_i(x) \) is very simple\(^3\):

\[
F_2(x) = x\Sigma q_i(x) \quad \ldots (8)
\]

\[
2\xi g_1(x) = x\Sigma \xi q_i(x) - \bar{q}_i(x) \quad \ldots (9)
\]

Thus the experiments directly yield information on the fundamental quark distributions.

3. **CHARGED CURRENT WEAK INTERACTIONS**: \( W^+ \to \nu \bar{\chi} \)

These reactions are experimentally more difficult than the electromagnetic ones and there is no hope of having a large enough polarised target to do \( W^+ \to \nu \chi \). But to compensate, their theoretical interpretation is simpler. The charged weak current involves only left-handed quarks and right-handed anti-quarks; moreover either a "u" or a "d" quark participates, not both. Thus, in the approximation that the Cabibbo angle is zero, and at \( x \)-values where anti-quarks can be neglected:

\[
\mu^- \text{ on } p \longleftrightarrow u(x) \\
\mu^- \text{ on } p \longleftrightarrow \bar{u}(x) \\
\mu^+ \text{ on } p \longleftrightarrow d(x) \\
\mu^+ \text{ on } p \longleftrightarrow \bar{d}(x)
\]

\( \longleftrightarrow \) means proton helicity \( +\frac{1}{2} \) in the lepton-hadron C.M. We thus see that C.C. reactions with a polarised target measure the spin-dependent quark distributions directly.

4. **Theoretical Models for the Spin-dependent Quark Densities**

In principle, if one could solve the non-perturbative dynamical problem of the binding of three quarks to form a nucleon, one would have available the wave function

\[
\Psi_\Lambda(x_1, \tau_1, \lambda_1; x_2, \tau_2, \lambda_2; x_3, \tau_3, \lambda_3)
\]

for a proton of helicity \( \Lambda \) made up of quarks with momentum fractions \( x_i \), third components of isospin \( \tau_i \), and helicities \( \lambda_i \), from which all the quark
distributions could be calculated directly. We are a long way from the goal, but it is not inconceivable that lattice calculations will begin to yield this sort of information within the next few years.

In the absence of detailed dynamical calculations one resorts to "educated guesses" about the structure of the wave-function, guided by what is known from low energy quark models of the hadron spectrum.

The simplest assumption is that the effective Hamiltonian conserves both spin and isospin, so that the wave-function can have SU(2)Spin × SU(3)Isospin structure. Assuming that the colour wave-function is anti-symmetric, and that we require a symmetric ground state space wave-function, we are forced to seek a symmetric spin × isospin wave-function in order to guarantee overall adherence to the Pauli principle. However the only spin or isospin wave-functions with S=\(\frac{1}{2}\), I=\(\frac{1}{2}\) are of mixed symmetry. For example for a proton, spin up, one could have, for the spin part, in an obvious notation\(^4\),

\[
\chi_{MS} = \frac{1}{\sqrt{6}} \begin{bmatrix} \uparrow \downarrow + \downarrow \uparrow - 2 \uparrow \uparrow \end{bmatrix} \quad \text{... (11)}
\]

or

\[
\chi_{MA} = \frac{1}{\sqrt{2}} \begin{bmatrix} \uparrow \downarrow \downarrow \uparrow \end{bmatrix} \quad \text{... (12)}
\]

When M stands for mixed, and the S, A refer to the symmetry or anti-symmetry under interchange of quarks 1 and 2.

The isospin wave functions \(\phi_{MS}, \phi_{MA}\) look identical, with \(\uparrow\) replaced by "u", \(\downarrow\) by "d".

The only completely symmetric spin × isospin wave-function turns out to be \(\chi_{MS}\phi_{MS} + \chi_{MA}\phi_{MA}\), so one has, for the proton wave-function, the form

\[
\psi_{\lambda=\frac{1}{2}}(x_1, x_2, x_3, r) = \chi_{MS} \phi_{MS} + \chi_{MA} \phi_{MA} \quad \text{... (13)}
\]

which is, even though we did not demand it, an SU(6) wave-function. One then finds for the valence quark distributions in a proton:

\[
\begin{align*}
\rho^u(x) &= \frac{29}{18} f(x) \\
\rho^d(x) &= \frac{7}{18} f(x)
\end{align*} \quad \text{... (14)}
\]

\[
\begin{align*}
u^u(x) &= \frac{1}{18} f(x) \\
\nu^d(x) &= d^u(x) &= \frac{1}{18} f(x)
\end{align*}
\]

where \(f(x)\) is normalised so \(\int_0^1 dx f(x) = 1\).

For the unpolarised distributions we then have
\[ u(x) = 2 \, d(x) = 2f(x) \]  

... (15)

But these distributions, particularly \( u(x) = 2d(x) \), are manifestly unacceptable, as can be seen from the unpolarised data for the ratio of electromagnetic ep to en cross-sections.

Various attempts, none very deep, have been made to improve the theoretical picture. In the "broken SU(6)" model one takes

\[ \gamma_{A=1} = \mathcal{F}_0(x) \chi_{MA} \Phi_{MA} + \mathcal{F}_1(x) \chi_{MS} \Phi_{MS} \]  

... (16)

which leads to ep and en electromagnetic structure functions of the form:

\[ F_2^p(x) = \frac{4}{9} \, f_0(x) + \frac{2}{9} \, f_1(x) + \text{sea} \]

\[ F_2^n(x) = \frac{1}{9} \, f_0(x) + \frac{1}{3} \, f_1(x) + \text{sea} \]  

... (17)

and

\[ 2xg_1^p(x) = \frac{2}{27} \left[ 6f_0(x) - f_1(x) \right] \]  

... (18)

\[ 2xg_1^n(x) = \frac{1}{9} \left[ f_0(x) - f_1(x) \right] \]

(Note that the SU(6) limit, \( f_0 = f_1 \), implies \( g_1^p(x) = 0 \).)

The unpolarised ep and en data give us \( f_0(x) \) and \( f_1(x) \), and one finds\(^5\)

\[ f_1(x) \approx 1.3 \, (1 - x) f_0(x) \]  

... (19)

The polarised proton data of the SLAC-YALE group\(^6\) is shown in Fig (1) and compared with various theoretical models. The parameter displayed, \( A_1 \), is obtained from the experimental asymmetry with longitudinal polarisations [Eqn (6) divided by Eqn (5)], and in the simple parton model is given by

\[ A_1 = \frac{2xg_1(x)}{F_2(x)} \]  

... (20)
The SU(6) result (14) gives $A_1$ independent of $x$. The broken SU(6) model, Eqns (17) (18) and (19) gives a reasonable fit for medium to large $x$, but cannot be correct at small $x$ where the sea is important, and presumably being unpolarised, will dilute the asymmetry. To account for the latter Carlitz and Kaur multiply the R.H.S. of Eqn (18) by an $x$-dependent dilution factor designed to approach 1 as $x \to 1$ and to approach 0 as $x \to 0$ like $\sqrt{x}$, the latter suggested by Regge theory. The prediction is shown as Curve 4 in Fig.(1), and is clearly an acceptable fit at the present level of accuracy. However the prediction involves one free function of $x$ so might not be considered as very significant.

![Graph showing different curves for $A_1$ versus $x$]

2. Current Quarks (Close, 1974).
5. MIT Bag Model (Jaffe, Hughes, 1977).

On the other hand there exists a rigorous sum rule due to Bjorken, which, in the parton model becomes

$$\int_0^1 dx \left[ g_1^p(x) - g_1^n(x) \right] = 1/3 \left| \frac{g_A}{g_V} \right| = 0.418 \pm 0.002 \quad \ldots \quad (21)$$

The dilution factor in ref. (7) was taken as a simple function of $x$ with only one free parameter, which was fixed by satisfying the above sum-rule. So there is some significance in the agreement with the data of Fig.(1).
Much more interestingly, the asymmetries in electromagnetic and in C.C. reactions can be predicted without invoking any further functions (detailed results are given in Kaur⁵), so a future comparison is important. We show below for example a comparison of $2xq^e_1(x)$ for protons and neutrons as given in ref.(5), and the en asymmetry which is predicted to be small, except at $x=1$ where it tends to unity.

None of the above models is particularly convincing, but a knowledge of the detailed internal structure of hadrons must ultimately be of the greatest importance. It is up to the experimentalists to provide this knowledge.

CONCLUSION:

We have explained briefly, how experiments on deep inelastic lepton scattering (electromagnetic or C.C.) with polarised hadron targets provide vital, detailed information about quark distributions in the hadrons. All this was presented at the level of the simple parton model, but eventually questions of the $Q^2$ dependence too will be worthy of examination.

We have not had space to discuss polarised Drell-Yan reactions. It should be noted that detailed predictions exist⁸ for all sorts of two-spin asymmetries i.e. involving both polarised beam and target. More important, and a crucial test of the whole elegant dynamical picture, all single spin asymmetries should vanish. The latter must be tested!

References
1) J.D. Bjorken, Phys. Rev. 148, 1467(1966)
   The proportionality factor in (5), (6) and (7) is : $8\pi^4 E^6 / Q^6$
3) Sec. e.g. : F.E. Close : An Introduction to Quarks and Partons.
4) See Chapter 4 of ref.(3)
6) SLAC-YALE data presented by R.Oppenheim, 5th Intl.
WEAK INTERACTIONS WITH MUON BEAMS

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ABSTRACT

The feasibility of studying weak interactions with muon beams at the CERN SPS has been investigated. The measurements of cross-section asymmetries induced by the interference of the one photon and Z^0 propagators were found to be the best suited for the SPS energy domain. The utilization of the large luminosity ECDMS spectrometer could provide \( \sin^2 \theta_W \) measurements with an error of ± 0.01 and an accurate determination of the muon couplings to the Z^0.

The study of weak interactions can be done profitably with charged leptons at very high energies where the weak cross-sections become considerable. In particular high energy electron proton collision achievable with colliding beam machines such as in the HERA project could produce new heavy leptons coupled to new weak currents and could determine the mass of the W or infer the existence of several Ws through the damping of the charged current cross-section with Q^2. At the CERN SPS the weak force is still dwarfed by the electromagnetic one and the study of its effects remains difficult. Nevertheless it is instructing to see what can be measured with the high quality muon beams available at the SPS along three main topics: exotics, weak charged currents and weak neutral currents.

1. EXOTICS
  1.1 Neutrino Counting

In the accepted theory of lepton-hadron interactions the leptons and quarks are arranged into left-handed doublets and right-handed singlets.

The discovery of the \( \tau \) lepton in 1975\(^1\), which hinted to the existence of a new lepton doublet, was followed in 1977\(^2\) by the discovery of a new quark, the bottom, reinforcing our prejudice that to each lepton doublet there corresponds a quark doublet. The number of doublets, or generations, is not fixed by the theory although the existence of three generations of quarks and leptons has been used\(^3\) to explain in a natural way CP violation.

Experimentally it might be very difficult to produce new generations of charged leptons or of quarks if they are very massive. Neutrinos can also be used to determine the number of generations. Astrophysical considerations\(^4\) limit the number of neutrino types, \( N_\nu \), to 4 or to some very large number \( N_\nu > 10^4 \). Phenomenological arguments\(^5\) set limits on \( N_\nu \) that vary from 10 to 137 according to the assumptions made for the masses of the charged leptons in the new generations.
The most direct determination of $N_\nu$ can be done with the construction of the LEP accelerator through the process

$$e^+ e^- \to \gamma + Z^0$$

(1.1)

which permits to measure the branching ratio of the $Z^0$ to $\nu \bar{\nu}$ which is proportional to the number of neutrino generations.

In fixed target experiments $N_\nu$ can in principle be measured through the production of $\nu \bar{\nu}$ pairs in the Coulomb field of heavy nuclei:7)

$$\mu + A \to \mu + \nu \bar{\nu} + A$$

(1.2)

This reaction is mediated by the Feynman diagrams shown in fig. 1. The first two graphs represent the production of $\nu \bar{\nu}$ pairs via the $Z^0$. The third graph contributes only to $\nu \bar{\nu}$ production via the charged $W$ boson and the contribution of the last graph is negligible since it involves two $W$ exchanges.

A detailed calculation of the cross-sections and of the distributions of relevant kinematical variables has been performed by Barger et al.8). The most striking feature is that the scattered $\mu$ is relatively soft, $<\mu> = 23$ GeV with a beam energy of 280 GeV, contrary to the case of vector meson production, see fig. 2, where the primary muon retains most of the beam energy.

This characteristic can be used to eliminate the only source of background which is given by the production of vector mesons ($\rho$, $\phi$, $\psi$, $\tau$,..) and decaying into $\nu \bar{\nu}$,

$$\mu + A \to \mu + V^0 + A$$

L_{\nu \bar{\nu}}

(1.3)

Unfortunately the cross-section for reaction (1.2) is extremely small $\sim 10^{-11}$ cm$^2$ and cannot be measured with the present generations of synchrotrons unless $N_\nu$ is very large $\sim 10^4$. Furthermore, the cross-section grows with the center of mass energy ($S$) only as $S \propto S$, fig. 3, so that this process will not be measurable even at the Tevatron.

---

Fig. 1: Feynman diagrams for neutrino pair production by muons.
Fig. 2: Final muon energy ($E'$) dependence of neutrino pair production with $N_\nu = 3$ and $E = 280$ GeV. The contributions from vector mesons decays are also shown (from ref. 8).

Fig. 3: Total cross-sections per nucleon for neutrino pair production by muons with $N_\nu = 3$ versus incident muon energy $E$ (from ref. 8).
1.2 Photino Pair Production

Super symmetric theories (SUSY) predict\(^9\) a large number of new particles in particular for each fundamental fermion there should be two scalar particles (i.e. for a muon there should be two spin zero particles the super symmetric muons or Smuons \(\tilde{\mu}\)) to each fundamental vector particle should correspond a spin 1/2 object (i.e. for the photon there should be a SUSY photon called photino \(\tilde{\gamma}\)). Little is known about these particles and it is therefore important to set limits on their production although fixed target experiments with present accelerators are not likely to yield any positive result.

In occasion of this workshop J. Ellis and D. Nanopoulos\(^{10}\) have pointed out that photinos can be pair produced in the Coulomb field of the nucleus in the reaction

\[
\mu + Z \rightarrow \mu + \tilde{\gamma} \rightarrow \mu + Z
\]  

(1.4)

which proceeds primarily via the diagram of fig. 4. This process is analogous to the pair production of neutrinos, fig. 1c, with the W propagator being replaced by a \(\tilde{\mu}\) and the neutrinos by the photinos.

The cross-section \(\sigma(\tilde{\gamma} \tilde{\gamma})\) can be expressed in terms of that for reaction (1.2) \((\sigma(\nu \bar{\nu}))\) as follows\(^{10}\):

\[
\frac{\sigma(\tilde{\gamma} \tilde{\gamma})}{\sigma(\nu \bar{\nu})} = \frac{8\sin^2 \theta_w}{F_\nu} \left[ \begin{array}{c} m_{\tilde{\nu}} \\ m_{\nu} \end{array} \right]^2
\]

with

\[
F_\nu = N_\nu \left[ 4 \sin^2 \theta_w - 2 \sin^2 \theta_w + 1/2 \right] + 4 \sin^2 \theta_w
\]

where \(N_\nu\) is the number of neutrino generations and \(\theta_w\) is the Weinberg angle. Using the present limit on the mass of the \(\tilde{\nu}\) \((m_{\tilde{\nu}})\) of 15 GeV, the world average value for \(\sin^2 \theta_w\) of 0.23 and three generations of leptons we get

\[
\sigma(\tilde{\gamma} \tilde{\gamma}) = 185 \sigma (\nu \bar{\nu}) = 1.85 \times 10^{-39} \text{ cm}^2
\]

in the hypothesis of light photinos, \(m_{\tilde{\gamma}} = 150 \text{ MeV}\).
This cross-section albeit small is measurable with a massive uranium target calorimeter as it has been proposed\textsuperscript{11}) to study the muon production of $\bar{\nu}B$ and the $T$. Conversely the absence of a signal can be used to set a lower limit on $m_\mu^2$ within the assumption for $m_\gamma^2$.

The kinematics of $\gamma \gamma$ production are the same as those for $\nu \bar{\nu}$ production, in particular the interactions have very little hadronic energy deposition and are characterized by a large missing energy since the photinos are expected to escape detection.

The detector need not be particularly sophisticated, the main requirement being a massive calorimeter with good segmentation both lateral and longitudinal to detect the scattered $\mu$ and to withstand intense muon beams ($\sim 10^7 \mu$/sec). A magnetized calorimeter would be optimal since it would provide the best acceptance for measuring the sign and energy of the scattered muon.

The detector\textsuperscript{11}) shown in fig. 5 which consists of a rearrangement of the EMC spectrometer can nevertheless give some useful information for the study of reaction (1.4). Its salient features are an uranium calorimeter with a fiducial mass of 7324 g/cm$^2$, an open air spectrometer and a muon identifier. A typical run of 100 days assuming an incident beam of $2 \times 10^7$ muons/spill with a 2 seconds spill length and 5000 effective spills per day would provide an integrated luminosity of $4.6 \times 10^{32}$ cm$^{-2}$.

---

Fig. 5: Schematic layout of a high luminosity spectrometer with a uranium target calorimeter (from ref. 11).
With a beam energy of 300 GeV this luminosity would yield the following events in function of $m_\mu$

<table>
<thead>
<tr>
<th>$N(\gamma^* \gamma)$</th>
<th>$m_\mu$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>102</td>
<td>17</td>
</tr>
<tr>
<td>53</td>
<td>20</td>
</tr>
<tr>
<td>22</td>
<td>25</td>
</tr>
<tr>
<td>10</td>
<td>30</td>
</tr>
</tbody>
</table>

Since the average scattered muon energy is about 30 GeV it is safe to assume a 50% detection efficiency on the above numbers.

In conclusion the detector proposed\(^{11}\) for the study of multimuon production could be used to increase the limit on the S\text{muon} mass up to 25, 30 GeV.

2. **WEAK CHARGED CURRENT INTERACTIONS OF MUONS**

In neutrino beams the helicity of the beam particles is fixed to be $-1$ (left-handed) for neutrinos and $+1$ (right-handed) for antineutrinos. For muon beams instead the helicity of the beam particles can be adjusted by varying the ratio of the muon momentum $P_\mu$ with respect to the parent pion momentum $P_\pi\(^{12}\)$. Muons with $P_\mu = P_\pi$ correspond to pion decays with the $\mu$ being emitted along the direction of motion of the pion in the pion rest system (forward decays). The helicity of the muon is then $+1$ for $\mu^- (\mu^-_L)$ and $-1$ for $\mu^+ (\mu^+_L)$. Muons with $P_\mu = (m_\mu/m_\pi)^2 P_\pi = 0.57 P_\pi$ correspond to backward decays and the muons have natural helicity, that is $-1$ for $\mu^- (\mu^-_L)$ and $+1$ for $\mu^+ (\mu^+_R)$.

Thus with muon beams the following processes can be studied:

\[
\begin{align*}
\mu^-_L + N &\rightarrow \nu + X \quad (2.1) \\
\mu^+_R + N &\rightarrow \bar{\nu} + X \quad (2.2) \\
\mu^-_R + N &\rightarrow \bar{\nu}_R + X \quad (2.3) \\
\mu^+_L + N &\rightarrow \nu_L + X \quad (2.4)
\end{align*}
\]

The first two reactions are completely equivalent to the standard $V-A$ charged current weak interactions:

\[
\begin{align*}
\nu + N &\rightarrow \mu^-_L + X \quad (2.5) \\
\bar{\nu} + N &\rightarrow \mu^+_R + X \quad (2.6)
\end{align*}
\]

while the other two reactions which cannot be studied with neutrinos are strictly forbidden in pure $V-A$ theories. Therefore they can be used to set stringent limits on the existence of $V+A$ currents as was pointed out by K. Winter\(^{13}\) long time ago.
The interest in right-handed currents (V+A) has been recently revived by the realization that the present V-A (left-handed) character of the weak interaction may be simply the low energy limit of a more complex reality which embodies in a symmetric way both left-handed and right-handed currents\(^{16}\). In models such as the SU(2)_L x SU(2)_R x U(1) the electroweak interaction is generated by a set of gauge bosons \( \tilde{W}_L, \tilde{W}_R \) and B according to the Lagrangian:

\[
\mathcal{L} = \mathcal{L}_{\text{L}} + \mathcal{L}_{\text{R}} + \mathcal{L}_{\text{Y}} = \mathcal{L}_{\text{L}} + \mathcal{L}_{\text{R}} + \mathcal{L}_{\text{Y}}
\]

(2.7)

The left right symmetry is then given by the equality of \( \xi_L \) and \( \xi_R \). The apparent left-handed aspect of the low energy world is attributed to the spontaneous symmetry breaking process which makes the \( W_R \) bosons much heavier than the \( W_L \) bosons.

The mass eigenstates \( W_L \) and \( W_R \) are linear combinations of the unmixed chiral eigenstates \( W_L^{(0)} \) and \( W_R^{(0)} \):

\[
W_L = W_L^{(0)} \cos \xi + W_R^{(0)} \sin \xi
\]

(2.8)

\[
W_R = -W_L^{(0)} \sin \xi + W_R^{(0)} \cos \xi
\]

(2.9)

with

\[
m_R \gg m_L.
\]

Experimentally we are interested in determining two quantities: the mixing angle \( \xi \) and the mass ratio \( \delta = (m_L/m_R)^2 \). The pure V-A world being obtained by \( \delta = 0 \) and \( \xi = 0 \).

The experimental situation on the limits of \( \delta \) and \( \xi \) and on the possibility of improving such limits has been discussed in detail by G. Vesztergombi\(^{15}\) at this workshop. Here we briefly recall the main points of that study.

Neutrino experiments are sensitive to the right-handed currents only through the mixing angle given the inherent left-handness of \( v \) beams. They can therefore set limits only on a combination of the mass ratio and the mixing angle. This is usually achieved\(^{16}\) by comparing the \( y \) distributions (hadronic energy/incoming energy) for neutrino and antineutrinos interactions. For large values of the Bjorken \( x \) variable (i.e. valence quark region), the presence of a right-handed current term will manifest itself as an excess of events at large \( y \).

With muon beams the mass ratio can be measured directly

\[
\frac{\sigma(\mu^- N)}{\sigma(\mu^+ N)} = \left( \frac{m_L^2}{m_R^2} \right)^z
\]

(2.10)
as long as the right-handed neutrino is not too heavy (few GeV). An upper limit of 1\% for the cross-section ratios would give a lower limit of about 250 GeV for the mass of the right-handed W. At present the best limits have been obtained from the beta decay of the muon \cite{17}

\[
m_R > 220 \text{ GeV} \\
|\zeta| < 0.06
\]

which is valid only for very light $v_R$, and from the $K_L-K_S$ mass difference \cite{18}

\[
m_R > 1.6 \text{ TeV}
\]

independently of the mass of the $v_R$ but with considerable theoretical uncertainties. It is worth recalling that an ep machine of the type proposed in HERA is also expected to set limits on $m_R$ of the order of 500 GeV. Hence a measurement of the cross-section ratio would contribute significantly to the present understanding.

The experimental difficulties in performing this measurement at the SPS are overwhelming. The weak interaction cross-section is still about six orders of magnitude lower than the electromagnetic cross-section and the most severe background is given by the decay of the primary $\nu$ inside the hadronic shower produced in low $Q^2$ interactions.

To overcome this background the target calorimeter must be dense in order to provide a large mass with relative short decay path and must have enough granularity in the beam spot to detect the decay of the primary $\nu$ after the shower has been absorbed. The uranium calorimeter of ref. \cite{11} (fig. 5) could be optimized to meet these requirements. Furthermore the presence of the open air spectrometer would be a valuable asset since it could remove the off-momentum muons from the beam spot so that they could be vetoed in a low intensity environment.

As a practical example of background calculation the case of a 200 GeV $\nu$ beam with zero polarization impinging on the uranium calorimeter has been considered. The measurement is restricted to $0.2 < y < 0.8$ and a decay length of one meter was chosen for the scattered muon. The muons decaying in this length are considered undetected and the electron energy produced in the decay is added to the hadronic energy. The muons surviving this cut are considered identifiable since they are out of the hadronic shower. Under these assumptions a signal to background ratio of \% 10\% for $\nu^+$ and 10-20\% for $\nu^-$ was obtained depending on the $y$ of the interaction.

From the analysis of the transition curves of the hadronic showers it will be possible to identify the decay electrons and to eliminate part of the background. The degree of rejection clearly depends on the degree of segmentation of the calorimeter.
Experimentally the following cross-section can be measured

\[ \sigma = \frac{1-\lambda}{2} \sigma_L + \frac{1+\lambda}{2} \sigma_R + \sigma_B \]  \hspace{1cm} (2.11) \]

where \( \lambda \) is the polarization of the muon beam, \( \sigma_L, \sigma_R \) are the cross-sections for left and right-handed currents and \( \sigma_B \) is the normalized background. To a good approximation the background is independent of the beam polarization and measuring (2.11) with different \( \lambda \) (for instance with a 200 GeV \( \mu^- \) beam usable polarizations can be obtained from \( \lambda = +0.95 \) to \( \lambda = 0 \)) it is possible to separate the three contributions.

The proposed uranium calorimeter could be used for a measurement of \( \sigma_L \) but it is doubtful that with such a detector the background could be controlled with the accuracy needed to set a competitive upper limit on \( \sigma_R \).

3. **Weak Neutral Current Interactions with Muon Beams**

In the deep inelastic scattering of charged leptons the weak neutral current interaction introduces a dependence of the cross-section on the charge and polarization of the beam. Given the relative strengths of the weak and electromagnetic interaction the only possible way to observe the weak neutral current with charged leptons is through the interference of the photon and the \( Z^0 \) propagator, fig. 6. The magnitude and properties of this effect have been studied in detail by many authors \(^{19}\). It is amusing to recall that experiments with muon beams were suggested as a method to search for weak neutral currents prior to their discovery.

The interference cross section is given by

\[ d \sigma_{\gamma \mu} \approx d \sigma_{\gamma \mu}^{\text{e.m.}} - \frac{G_F}{\sqrt{2}} \frac{\alpha}{Q^2} \left[ \frac{1}{1+1-y^2} G_1(x) \left( -v_\mu \pm \lambda a_\mu \right) + \left[ 1-(1-y)^2 \right] G_1(x) \left( \pm a_\mu - \lambda V_\mu \right) \right] \]  \hspace{1cm} (3.1) 

![Diagram](image)

Fig. 6: First order contribution to the electroweak asymmetries.
where $v_\mu$ and $a_\mu$ represent the vector and axial coupling of the $\mu$ to the $Z^0$ and $\lambda$ is the helicity of the beam. $G_2(x)$ and $xG_3(x)$ are "interference structure functions" analogous to the well known nucleon structure functions $F_2(x)$ and $xF_3(x)$ but containing the coupling of the quarks both to the $\gamma$ and the $Z^0$:

\[ G_2(x) = 2x \sum_{i=1}^{1} Q_i^2(q(x) + \bar{q}(x)) \quad (3.2) \]
\[ xG_3(x) = -2x \sum_{i=1}^{1} Q_i^2(q(x) - \bar{q}(x)) \quad (3.3) \]

where $Q_i$, $v_i$ and $a_i$ are respectively the charge and the vector and axial coupling of the quark of type $i$ to the $Z^0$.

We recall that the deep inelastic cross-section is given in first order by

\[ d\sigma = \frac{d\sigma}{dQ^2 dv} = \frac{2\pi\alpha^2}{Q^2 v} \left[ \frac{y^2}{1 + R} + 2(1-y) \right] F_2(x, Q^2) \]
\[ = \frac{2\pi\alpha^2}{Q^2 v} \left[ 1 + (1-y)^2 \right] F_2(x, Q^2) \quad (3.4) \]

since $R = q_L/q_T$ is known to be very small. The magnitude of the interference term relative to $d\sigma$ is

\[ \frac{d\sigma_{\gamma Z}^{\pm}(\lambda)}{d\sigma} = \frac{G_F}{\sqrt{2}} \frac{Q^2}{2\pi\alpha} \left\{ \begin{array}{c}
G_2(x) \\
F_2(x) \\
\end{array} \right\} \left\{ \begin{array}{c}
(-v_\mu \pm \lambda a_\mu) \\
(\pm v_\mu - \lambda v_\mu) \\
\end{array} \right\} \\
+ \left[ \frac{1 - (1-y)^2}{1 + (1-y)^2} \right] \frac{1}{xG_3(x)} \left\{ \begin{array}{c}
\frac{G_2(x)}{F_2(x)} \\
\end{array} \right\} \left\{ \begin{array}{c}
(\pm v_\mu - \lambda v_\mu) \\
\end{array} \right\} \\
= K Q^2 \left[ V(-v_\mu \pm \lambda a_\mu) + g(y) a(\pm v_\mu - \lambda v_\mu) \right] \quad (3.5) \]

The constant $K$, equal to $1.79 \times 10^{-3}$ GeV$^{-2}$, determines the size of the effect; about 2% at $Q^2$ of 100 GeV$^2$. For the case of an isoscalar target and in the valence quark approximation the structure function ratios reduce to:

\[ A = \frac{6}{5} \left( a_d - 2a_u \right) \]
\[ V = \frac{6}{5} \left( 2v_u - v_d \right) \quad (3.6) \]

There are two different kinds of cross-section asymmetry that can be measured:

A. Changing the helicity of the beam

\[ A^{\gamma Z}(\lambda_1, \lambda_2) = \frac{\sigma^{\gamma Z}(\lambda_1) - \sigma^{\gamma Z}(\lambda_2)}{\sigma^{\gamma Z}(\lambda_1) + \sigma^{\gamma Z}(\lambda_2)} = \frac{\sigma^{\gamma Z}(\lambda_1) - \sigma^{\gamma Z}(\lambda_2)}{2\sigma_0} \]
\[ = -K Q^2 \frac{\lambda_1 - \lambda_2}{2} \left[ v_\mu A g(y) + a_\mu V \right] \quad (3.8) \]

this asymmetry is manifestly parity violating since it involves only vector, axial-vector combinations of the quark and lepton couplings to the $Z^0$. 
B. Changing the beam charge and helicity

\[
B(\lambda_1, \lambda_2) = \frac{\sigma^+(\lambda_1) - \sigma^-(\lambda_2)}{\sigma^+(\lambda_1) + \sigma^-(\lambda_2)} = -K Q^2 \left[ \frac{\lambda_1 + \lambda_2}{2} a_\mu V + \left( \frac{\lambda_1 - \lambda_2}{2} v_\mu + a_\mu \right) A g(y) \right]
\]

(3.9)

This asymmetry contains both parity violating and parity conserving terms. As we shall see the measurements is most profitably done with right-handed \( \mu^- \) \((\lambda_2 = |\lambda|)\) and left-handed \( \mu^+ \) \((\lambda_1 = -|\lambda|)\) so that

\[
B(|\lambda|) = -K Q^2 g(y) \left[ a_\mu - |\lambda| v_\mu \right] A
\]

(3.10)

In the Glashow Weinberg Salam model (standard model) with the world averaged value of the mixing angle \( \sin^2 \theta_W = 0.23 \), the vector coupling of the \( \mu \) is very small and the asymmetry is essentially parity conserving.

Both types of asymmetry, are very small and their magnitude increases linearly with \( Q^2 \). An apparatus designed to measure these asymmetries must therefore have a good acceptance over a long target in order to provide the required high luminosity, a good selectivity on \( Q^2 \) at the triggering level to overcome the \( 1/Q^2 \) dependence of the cross-section and a high degree of redundancy in the detectors to minimize systematic errors.

The BCDMS spectrometer, utilized in the CERN SPS NA4 experiment, was designed to study inclusive deep inelastic scattering at very large \( Q^2 \) and is therefore particularly well suited for the asymmetry measurements. In fact possible scenarios for measuring both types of asymmetry have been considered in several collaboration meetings dating back to 1977, and a first measurement of the B asymmetry has been recently completed.

In the following we reconsider the feasibility and scientific interest of performing the asymmetry measurements at the CERN SPS in the coming years using this detector.

Before going into the details of the measurements we recall the salient features of the BCDMS spectrometer shown in fig. 7. A more extensive description has been given elsewhere. Briefly it consists of ten iron toroids magnetized to saturation (2 Tesla), eight target sections each five meters long and 12 cm in diameter located in the first supermodules, eighty planes of Multiwire Proportional Chambers (MWPC) which provide the measurement of the scattered \( \mu \) and twenty planes of trigger counters with an annular segmentation which permit a \( Q^2 \) dependent trigger. In addition a set of four hodoscopes is used both to define the beam through the target and to measure its divergence. Finally the whole spectrometer is shielded from the beam halo by a wall of veto counters. The trigger used for data taking required the coincidence of four consecutive trigger planes (11 meter long tracks) with the beam * halo pulse.
3.1 The B Asymmetry

Experimentally this asymmetry is the least demanding since it can be measured with $\mu^-_R$ and $\mu^+_L$ that is with muons coming from the forward pion decays which, therefore, provide intense beam at high energies ($E_\mu \approx 200$ GeV). Furthermore, the size of the asymmetry is about four times larger than for the $A^\pm$ asymmetry.

However, higher order electromagnetic processes introduce an asymmetry which tends to compensate the electroweak term. The major contribution comes from the interference between the one photon and two photon exchanges and between lepton and hadron bremsstrahlung. The size of the correction\textsuperscript{23} is shown in fig. 8 for the measurement of B with 200 GeV muons.

A measurement of the B asymmetry has been performed by the BCDMS collaboration and is described elsewhere\textsuperscript{24}. Here we recall some of the crucial points of the experiment. In this measurement the charge and polarization of the beam are changed by reversing the polarity of all the magnets in the beam line. The field in the spectrometer is also reversed to ensure equal acceptance for the scattered muons.

A reproducibility of the field in the spectrometer with a relative accuracy of $2 \times 10^{-4}$ was obtained by keeping the magnet on the same hysteresis loop with a computer control of the excitation current. Similarly the reproducibility of the field in the magnets used to define the beam energy (Beam Momentum Station, BMS) was kept with a precision of $6 \times 10^{-4}$. The incident beam intensity was maintained approximately constant at $2 \times 10^7 \mu$/spill for $\mu^+$ and $\mu^-$ in order to minimize systematic errors in the corrections for dead time in the flux counting and in the trigger electronics. This condition severely limited the frequency of polarity switches since the yield of $\mu^-$ per proton is about a factor three less than the yield of $\mu^+$ so that a major change in the SPS beam sharing was needed for each polarity switch. Typically the beam polarity was changed three times for each data taking period of about 12 days.
Fig. 8: The B asymmetry from \( \gamma-Z^0 \) interference to first order, calculated for polarization \( \lambda = 0.81 \) and \( \sin^2 \theta_W = 0.23 \) (solid line), and the asymmetry expected from higher order electromagnetic processes at a beam energy of 200 GeV (dash-dotted line).
The data were taken with beam energy of 200 GeV and 120 GeV, the main thrust of the experiment being in the high energy data. The low energy data were taken mostly as a cross-check on systematic errors and radiative corrections.

The asymmetry measurements at both energies are shown in fig. 9 together with a linear fit of the form \( B = a + b g(y) Q^2 \). The results of the fit for the slope parameter \( b \):

\[
\begin{align*}
b_{200 \text{ GeV}} &= [-1.47 \pm 0.37 \text{ (stat)} \pm 0.2 \text{ (syst)}] \times 10^{-4} \text{ GeV}^{-2} \\
b_{120 \text{ GeV}} &= [-1.74 \pm 0.75 \text{ (stat)} \pm 0.3 \text{ (syst)}] \times 10^{-4} \text{ GeV}^{-2}
\end{align*}
\]

are in good agreement with the values of \(-1.51 \times 10^{-4}\) and \(-1.53 \times 10^{-4}\) predicted by the standard model for \( \sin^2 \theta_W = 0.23 \) and with \( |\lambda| = 0.81 \) (200 GeV data) and \( |\lambda| = 0.66 \) (120 GeV data).

The largest sources of systematic errors are due to the leakage of a halo component in the data which is different for \( \mu^+ \) and \( \mu^- \) and to an insufficient accuracy in the reproducibility of the field in the BMS.

A new measurement of the \( B \) asymmetry would benefit from several improvements in the BCDMS spectrometer, in particular the construction of a new set of trigger counters, one per supermodule, which improve considerably the redundancy of the trigger. Furthermore, a new fast decision logic based on the pattern of MWPC hits has been implemented with a reduction of about a factor 10 in the raw trigger rate. As a result of these changes the spectrometer can be operated at much higher luminosities either by increasing the target density or the beam intensity. For instance using a 30 m copper target would increase the luminosity of the spectrometer by a factor four and with the SPS running at 450 GeV it would be possible to increase the beam energy to 250 GeV. In these conditions a typical run of 60 days would yield a measurement of the slope parameter \( b \) with an accuracy of \( \pm 0.08 \times 10^{-4} \text{ GeV}^{-2} \) and, benefitting from past experience, the systematic error could be reduced to \( \pm 0.05 \times 10^{-4} \text{ GeV}^{-2} \).

In the context of the standard model assuming factorization the measured \( b \) slope can be used to determine the only free parameter of the model, \( \sin^2 \theta_W \). The published result of the old measurement is:

\[
\sin^2 \theta_W = 0.23 \pm 0.07 \text{ (stat)} \pm 0.04 \text{ (syst)},
\]

while a new measurement could give an accuracy of

\[
\delta \sin^2 \theta_W = \pm 0.016 \text{ (stat)} \pm 0.01 \text{ (syst)}.
\]

However, the measurement would still be affected by the theoretical uncertainties in the calculations of the radiative corrections which account for a sizeable fraction of the effect itself.
Fig. 9: The measured B asymmetry after radiative corrections at 120 GeV and 200 GeV beam energy vs. $g(y)Q^2 = Q^2 \cdot [1-(1-y)^2]/[(1+y)^2]$ for the 120 GeV data, circles represent data with $Q^2 > 15$ GeV$^2$ and triangles data with $Q^2 > 25$ GeV. Solid lines are straight line fits to the data.
Finally, a high statistics measurement of the $B$ asymmetry could be used to
determine the interference structure function $xG_3(x)$ by subtraction of the two cross
sections\(^{25}\):

\[
\sigma^+(|\lambda|) - \sigma^-(|\lambda|) = - \frac{G_F}{\sqrt{2}} \frac{a}{Q^2} \left[ 1 - (1-y)^2 \right] \times G_1(x)(a_{\mu} - a_{\nu})
\]

for $x$ between 0.3 and 0.7. This measurement is particularly sensitive to
normalization errors between the two data sets requiring a relative accuracy of few
parts in $10^{-4}$ which might not be feasible.

3.2 A asymmetry

This asymmetry was measured for the first time at SLAC\(^{26}\) using polarized
electron beams on a deuterium target and provided the first evidence of parity
violation in weak neutral current interactions.

With the conventional hypothesis of factorization and validity of the quark
parton model QPM the A asymmetry is given by:

\[
A^T = \pm \frac{\Delta \lambda}{2} \frac{6}{5} \left[ a_{\mu} (2 \nu_u - \nu_d) \mp \nu_{\mu} (a_{d-2a_u}) g(y) \right] Q^2
\]

(3.11)

where $\Delta \lambda$ is the net helicity change in the two data taking conditions. To
illustrate the relative importance of the two terms we introduce the explicit
couplings of the standard model:

\[
A^T = \pm \frac{\Delta \lambda}{2} \frac{6}{5} \left[ -\frac{3}{4} + \frac{5}{3} \sin^2 \theta_w \right] \pm \frac{3}{2} \left( -\frac{1}{2} + 2 \sin^2 \theta_w \right) g(y) \right] Q^2
\]

(3.12)

With the standard value of $\sin^2 \theta_w = 0.23$ both terms are negative with the second
term being about 1/4 of the first. In the measurements of $A^T$ the two contributions
subtract and the asymmetry is quite insensitive to the value of $\sin^2 \theta_w$. This is
illustrated in fig. 10 where the asymmetry at fixed $Q^2$ is plotted in function of
$\sin^2 \theta_w$. Hence the measurement of $A^T$ alone is not recommended although it is
experimentally easier given the higher fluxes achievable with $\mu^+$ beams.

On the other hand the measurement of $A^\mp$ by itself would give a competitive
determination of $\sin^2 \theta_w$ and would also provide a confirmation of parity violation
at $Q^2$ values roughly two orders of magnitude larger than in the original SLAC
experiment.

For a model independent analysis of the weak neutral current couplings it is
important to have as many independent determinations as possible of the various
couplings. From the dependence of the A asymmetry, on $y$ introduced by the term $g(y)$
it is in principle possible to separate the two axial-vector and vector combinations.
In practice the resulting errors are rather large but a much better measurement can be
obtained by combining the $A^T$ and $A^\mp$ measurements.
Fig. 10: $A^\pm$ asymmetries at $Q^2 = 100$ GeV$^2$ and $\Delta \lambda = 1.0$ versus $\sin^2 \theta_W$. 
The size of these asymmetries is directly proportional to \(\Delta \alpha\) and \(Q^2\) hence the choice of the running conditions depends on two conflicting requirements, obtaining a large statistics of events at large \(Q^2\) (100-20 GeV\(^2\)) and retaining a sufficiently large \(\Delta \alpha\). The first condition requires intense beams at high energy while changing the helicity of the beam requires increasing values of the parent pion energy relative to the energy of the muon beam, so that the yield of muons per interacting proton quickly decreases with increasing muon energy. The situation is of course worse for the \(A^-\) measurement since the yield of energetic \(\pi^-\) is less than for \(\pi^+\).

With the SPE operating at 450 GeV it is feasible to measure \(A^-\) with a beam energy of 200 GeV, a \(\Delta \alpha\) of 1.0 and an integrated flux of \(1.6 \times 10^{13}\) muons at each beam condition. A Monte-Carlo calculation based on this integrated flux on a 30 meter copper target in the BCDMS spectrometer predicts \(8 \times 10^6\) reconstructed interactions in the kinematic domain \(Q^2 > 30\) GeV\(^2\), .2 < x < .8, .2 < y < .85 where the acceptance of the detector is well behaved.

Assuming the standard model with \(\sin^2 \theta_W = 0.23\) the Monte-Carlo calculation gives the asymmetries for \(A^+\) and \(A^-\) plotted in fig. 11 in function of \(Q^2\). The errors are purely statistical and the points are not randomized. A linear fit to these points gives a \(Q^2\) slope of \((0.33 \pm .11) \times 10^{-4}\) for \(A^+\) and \((-0.46 \pm -0.11) \times 10^{-4}\) for \(A^-\) that is a raw signal of 3 to 4 standard deviations.

In the standard model assuming factorization and universality we can determine \(\sin^2 \theta_W\) from a fit to (3.11) with an accuracy of \(\pm .10\) for \(A^+\) and \(\pm .01\) for \(A^-\). From the combined fit to \(A^+\) and \(A^-\) the following axial coupling combinations can be determined in a model independent way

\[
\begin{align*}
\mu & \quad \text{SLAC ed 26) } \\
\frac{a}{d} & = -0.37 \pm 0.04 \\
\frac{v}{d} & = -0.06 \pm 0.05
\end{align*}
\]

Assuming the quark couplings known these values determine completely the couplings of the muon:

\[
\begin{align*}
a & = -0.5 \pm 0.05 \\
v & = -0.04 \pm 0.04
\end{align*}
\]

The systematic errors in the case of the \(A^-\) asymmetry are less demanding than for the B asymmetry since the only change during the data taking is the setting of the pion channel. This however will affect the composition of the halo in the beam and to some extent the beam phase space. Furthermore, the polarization of the beam must be known accurately since the size of \(A^\mp\) is directly proportional to \(\Delta \alpha\). An accuracy of 10% on \(\Delta \alpha\) propagates an error of \(\pm 0.005\) for \(\sin^2 \theta_W\), similarly a systematic uncertainty of 10% introduces again a systematic error of \(\pm 0.005\).
Fig. 11: Monte-Carlo predictions for $A^\pm$ measurements with $\sin^2 \theta = 0.23$, $E_\mu = 200 \text{ GeV}$, $\Delta \lambda = 1.0$ and $1.6 \times 10^{18}$ muons on a 30 meter long copper target.
polarization of the M2 beam line has already been measured with 200 GeV energy for the measurement of the B asymmetry. In this workshop F.L. Navarra\textsuperscript{27}) presented a detailed plan for measuring and monitoring the polarization of the muon beam with an accuracy of ± 0.05 which is sufficient for the proposed accuracy on \(\sin^2 \theta_W\). Finally since no other part of the detector or of the beam line is changed it is relatively easy to maintain the apparatus stable for the period of the measurement (~100 days).

3.3 Beam Requirements for \(A^*\) Measurements

The best estimates for muon yields with the SPS operating at 450 GeV are based on some old measurements of muons yields and pion production yields\textsuperscript{28}).

<table>
<thead>
<tr>
<th>SPS Energy (GeV)</th>
<th>(E_g\ (\text{GeV}))</th>
<th>(E_\mu\ (\text{GeV}))</th>
<th>(&lt; \lambda &gt;)</th>
<th>Yield (\mu/\text{proton})</th>
</tr>
</thead>
<tbody>
<tr>
<td>450 GeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>220\textsuperscript{+}</td>
<td>200</td>
<td>-0.8</td>
<td>1.6 (10^{-5})</td>
<td></td>
</tr>
<tr>
<td>300\textsuperscript{+}</td>
<td>200</td>
<td>+0.1</td>
<td>2.8 (10^{-6})</td>
<td></td>
</tr>
<tr>
<td>220\textsuperscript{-}</td>
<td>200</td>
<td>+0.8</td>
<td>6.1 (10^{-6})</td>
<td></td>
</tr>
<tr>
<td>300\textsuperscript{-}</td>
<td>200</td>
<td>-0.1</td>
<td>1. (10^{-6})</td>
<td></td>
</tr>
<tr>
<td>212\textsuperscript{+}</td>
<td>200</td>
<td>-0.9</td>
<td>8. (10^{-6})</td>
<td></td>
</tr>
<tr>
<td>212\textsuperscript{-}</td>
<td>200</td>
<td>+0.9</td>
<td>3.1 (10^{-6})</td>
<td></td>
</tr>
</tbody>
</table>

where the yields for \(<\lambda> = 0.9\) have been estimated from Monte-Carlo calculations of the muon yield versus polarization.

The required integrated muon flux of \(1.6 \times 10^{12}\) could be obtained with the following beam conditions:

<table>
<thead>
<tr>
<th>(&lt; \lambda &gt;)</th>
<th>Proton/Pulse</th>
<th>Days</th>
<th>Integrated Protons</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\mu^-)</td>
<td>0.9</td>
<td>5.2 (10^{12})</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>-0.1</td>
<td>5.2 (10^{12})</td>
<td>65</td>
</tr>
<tr>
<td>(\mu^+)</td>
<td>-0.9</td>
<td>3.2 (10^{12})</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>+0.1</td>
<td>3.2 (10^{12})</td>
<td>35</td>
</tr>
</tbody>
</table>

assuming an overall efficiency for data taking of about 70% which was found realistic in the past.

The instantaneous beam intensities are rather low, at most \(1.3 \times 10^7\) \(\mu/\text{sec}\) for \(\mu^+\) with \(< \lambda > = -0.9\) and a spill length of 2 sec, and will not pose any problems for beam counting or in the performance of the hardware. It is therefore advantageous to maintain a constant intensity of protons per pulse so that the operation of the SPS will not be affected by the changes in polarization.
With the standard 100 days of operation per year of the SPS for fixed target physics the \( A^\pm \) measurement could be done within one calendar year and the \( A^0 \) with somewhat less time. The overall cost in protons is of \( 2.2 \times 10^{18} \) for \( A^- \) and \( 0.8 \times 10^{18} \) for \( A^0 \).

### 3.4 Two Measurements of \( B \)

An interesting alternative consists in making two measurements of the \( B \) asymmetry at two different beam polarizations \( \lambda_1 \) and \( \lambda_2 \). From the values of the fitted slopes in function of \( Q^2 \cdot g(y) \):

\[
\begin{align*}
b_1 &= -(a_\mu - \lambda_1 v_\mu) K A \\
b_2 &= -(a_\mu - \lambda_2 v_\mu) K A
\end{align*}
\]

(3.13)  
(3.14)

is possible to obtain a model independent relation between the vector and axial vector couplings of the muon:

\[
v_\mu = \frac{a_\mu - \frac{b_1 - b_2}{b_1 \lambda_1 - b_2 \lambda_2}}{b_1 - b_2}
\]

(3.15)

This relation is independent of the validity of the QPM and is also independent on the parameter \( \rho \) which measures the relative strength of the weak neutral current and charge current interaction. In the previous discussion a value of \( \rho = 1 \) was implicitly assumed in the definition of the constant \( K \). In the standard model (3.15) determines \( \sin^2 \theta_W \):

\[
\sin^2 \theta_W = \frac{1}{4} - \frac{1}{4} \frac{b_1 - b_2}{b_1 \lambda_1 - b_2 \lambda_2}
\]

(3.16)

Using the same beam conditions as for the \( A^\pm \) measurements and utilizing the same integrated \( \mu \) flux of \( 1.6 \times 10^{12} \mu \), the measurements of \( B \) at \( \lambda_1 = 0.9 \) and \( \lambda_2 = -0.1 \) would yield the following values for the \( \mu \) couplings:

\[
\begin{align*}
a_\mu &= -.5 \pm .04 \\
v_\mu &= -.0 \pm .06
\end{align*}
\]

and an accuracy on \( \sin^2 \theta_W \) of \( \pm 0.03 \) but without any assumption on the value of \( \rho \) or on the validity of the QPM. These values are however still sensitive to the theoretical uncertainties involved in the radiative corrections to the data.

Finally it is important to notice that an experiment carried out to measure the \( B \) asymmetry at two different beam polarizations cannot in practice give also a measurement of \( A^\pm \) since the strategy of data taking is quite different for the two cases in order to minimize the systematic errors.
4. PROSPECTIVES FOR ASYMMETRY MEASUREMENTS

It is difficult to foresee the relevance of a combined A^+, A^- measurement which would give results about two years after completion of data taking considering the huge quantity of data to be processed, \( \sim 50 \times 10^6 \) interactions. This would mean 1987-1988 for final results, just before the foreseen LEP operation. Furthermore, the operation of the pp colliders at CERN and at Fermilab should by then have detected the Z^0 and measured its mass with a few percent accuracy.

Nevertheless, accurate determination of \( \sin^2 \theta_w \) will still be relevant even after the Z^0 has been discovered and its mass measured at LEP since they will permit to check higher order weak contributions and thus prove the renormalizability of the theory. Grand unified theories that include the standard model as a low energy limit also make predictions which are very close to the experimental values for \( \sin^2 \theta_w \).

A sharpening of the experimental errors is extremely important\(^{29} \) to test these theories. The threshold of interest for new determinations of \( \sin^2 \theta_w \) seems to be about \( \Delta \sin^2 \theta_w \approx 0.01 \) but again it should be remembered that different experiments will have different systematic errors and theoretical uncertainties so that many independent determinations of \( \sin^2 \theta_w \) will still be valuable.

For instance the asymmetry measurements will provide a \( \sin^2 \theta_w \) using interactions at very high \( Q^2 \) and high \( x \) in a well definite kinematic domain of \( x \) and \( Q^2 \). The experiments with neutrino beams have little control of the \( x \) and \( Q^2 \) region used for the measurement since inclusive weak neutral current interactions contain only one well measured variable, the hadronic energy. Furthermore, in these experiments the determination of \( \sin^2 \theta_w \) depends on the measurement of the ratio of neutral to charged current interactions both for neutrinos and antineutrinos:

\[
\frac{1}{2} \sin^2 \theta_w = \frac{R - rR}{1 - R}
\]

with
\[
R = \frac{\sigma_{\nu N}}{\sigma_{\bar{\nu} N}}, \quad \bar{R} = \frac{\sigma_{\bar{\nu} N}}{\sigma_{\nu N}}, \quad r = \frac{\sigma_{\nu c}}{\sigma_{\bar{\nu} c}}
\]

The most important theoretical uncertainties involve the size and composition of the non strange component of the sea which is sampled differently by neutral currents (flavour conserving) and charged current (flavour changing) interactions, and the effects of scaling violations.

In the asymmetry measurements the contribution of the sea is small because the interactions are at \( x > 0.2 \) and the error on the correction is negligible. Similarly scaling violations appear in the same way in the numerator and denominator and cancel out from the final asymmetry. Finally the higher order weak contributions affect differently the \( \sin^2 \theta_w \) determination from neutrino interactions and from the A^\pm measurements so that the two independent measurements would be largely complementary.
Finally it has been recently pointed out by Sehgal\textsuperscript{30}) that the determination of the axial-vector, vector combinations of the quark muon couplings which are measured with $A^\pm$ can put severe constraints on theories like the left right symmetric model which have more than one $Z^0$.

In summary the asymmetry measurements can still contribute to our understanding of weak neutral currents and to test the standard model in a more stringent way.

CONCLUSIONS

In the context of this workshop we have considered what could be done with muon beams among three major topics: exotics, weak charged current and weak neutral currents. The first two topics require a construction of a massive target calorimeter with fine segmentation that could also be used to study the muon production of the $T$ and $D\bar{D}, B\bar{B}$ pairs. With such a detector the limit on the mass of the scalar muon could be increased from 15 GeV to 26 GeV, by studying photino pair production in the field of the nucleus. Weak charged current interactions could also be detected and their cross-section measured. A limit on the existence of right-handed currents as implied by the left right symmetric models is much harder to achieve since the measurement requires the control of the background to a degree which might not be realistic to obtain. For both experiments the Tevatron could provide a serious competition since the factor two increase in energy with respect to CERN will be a very valuable asset and the BFP detector\textsuperscript{31}), already scheduled to run, could do a good job.

The weak neutral current interactions can still be studied quite profitably at the CERN SPS with the BCDMS spectrometer. The experience gained in the measurement of the charge asymmetry "B" could be utilized in the measurement of the parity violating asymmetries $A^\pm$ thus establishing parity violation in weak neutral current interactions at a $Q^2$ about two orders of magnitude larger than in the first measurement at SLAC. This measurements using a well tested apparatus would provide a determination of $\sin^2 \theta_W$ with an error of $\pm 0.01$ and with theoretical uncertainties which are quite different and in many respects smaller than with the traditional neutrino experiments. Finally the concept of $\nu - e$ universality could be tested in a new $Q^2$ regime and new more accurate constraints would be provided both for the standard model and for larger models which incorporate the standard model as a low energy limit. The measurement of the $A^\pm$ requires a good control of the systematics in the beam conditions and in the detector. Clearly the experiment is not first generation and the factor two increase in energy at the Tevatron could not offset the advantage of a well tested beam and a particularly well suited detector.

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CHARGED CURRENT WEAK INTERACTION OF POLARIZED MUONS

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(Paper was presented by G. Vesztergombi)

ABSTRACT
The polarization of the muon beam can be used to test the presence of right-handed couplings in charged current interaction of muons in process $\mu^+ N \rightarrow \nu^+ X$. The experimental feasibility and the limits which can be obtained on the mass of right-handed intermediate boson are discussed.

1. INTRODUCTION
At first glance it seems to be hopeless to detect charged current weak interaction of muons, because the typical electromagnetic cross-sections are about a million times larger even at an incoming muon energy of several hundred GeV. One should not forget, however, some remarkable merits of the muon beam.

a) Energy
Due to the kinematic properties of pion decay the average energy of muons is 3 times higher than the one of neutrinos. This may turn out to be rather important. On one hand, the weak cross-sections are linearly proportional to the beam energy and on the other hand the energy can be critical in presence of thresholds. In addition, the incoming muon energy can be preselected which provides more flexibility in the study of threshold phenomena.

b) Helicity
Due to their extremely small (if any) mass the helicity of neutrinos is uniquely predetermined. In case of muons one can select helicity at will. This provides an unique possibility to look for such type of weak interactions which are impossible in case of neutrinos as it was noticed by K. Winter. Namely, if the pion momentum is denoted by $p_\pi$ then the decay muon with momentum

$$p_{\mu}^{\text{FORW}} \approx p_\pi$$

(forward decay in $\pi$-system)

will have "unnatural" helicity (i.e. opposite to the helicity of the neutrino with the same lepton number). One can get "natural" helicity selecting muon momenta

$$p_{\mu}^{\text{BACK}} \approx \left(\frac{m_\mu^2}{m_\pi^2}\right) p_\pi$$

(backward decay in $\pi$-system).

Thus if one is interested in normal left-handed interactions then the muon beam energy should be lowered relative to the parent pion energy. Even in this case it remains about a factor two higher than the average neutrino energy from the same pion decay.

c) Beam handling
Beam phase space can be measured easily. The well collimated muon beam spot can reduce by order(s) of magnitude the required lateral size of the target and the interaction vertex is well identified.

Severe difficulties compensate the flexibility of muon beam.

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i) One needs an extremely good (~$10^{-6}$) hardware rejection against events which have a muon in the final state in order to catch weak fishes from the QED ocean.

ii) The final state is rather complicated. In absence of neutrino detection the relevant kinematic information should be extracted from the analysis of hadronic shower. With modern experimental techniques these problems can be overcome in most of the kinematical range, thus at least in some areas muon experiments can challenge and/or complement neutrino experiments.

2. RIGHT-HANDED CURRENTS

The theoretical interest for weak effects with "unnatural" right-handed polarization can be summarized in the following way:

a) The dominantly V-A structure of weak interactions is well established at present energies but the search for deviations should still proceed.

b) The standard SU$_L$(2) x U(1) model is highly asymmetric and unaesthetic.

c) Right-handed neutrinos and intermediate bosons seem to be one of the simplest candidates which can "bloom" in the desert between 100 GeV and the grand unification mass ($^2$).

In the following we discuss the experimental possibilities to search for right-handed neutrinos by muon beam in the framework of SU$_L$(2) x SU$_R$(2) x U(1) model. We start with a "manifestly right-left symmetric" Lagrangian where $W_L$ and $W_R$ are coupled to V-A and V+A currents, respectively:

$$I_W = \frac{g}{2\sqrt{2}} \left[ (V-A) \cdot W_L + (V+A) \cdot W_R + H.C. \right]$$

where e.g. $(V \mp A)^\text{lep}_\mu = \gamma_\mu (\pm \gamma_5) \mu$ or $(V \pm A)^\text{had}_l = \bar{U}_l (\pm \gamma_5) d$. The combinations $(V + hA)^\text{lep}$ and $(V + hA)^\text{had}$ represent leptonic and hadronic currents having non-vanishing matrix elements between only definite helicity states. For simplicity, here and in the next we neglect masses and Cabbibo or KM angles ($h = \pm 1$). That is in a given vertex the transition is prohibited, for example between $\mu^\text{had}_R(h = \pm 1)$ and $\nu^\text{lep}_L(h = \mp 1)$.

The left-right symmetry of $I_W$ however is broken by an asymmetric vacuum. The Higgs potential and the vacuum expectation values of the Higgs-fields are arranged to yield to mass eigenstates which are linear combinations of unmixed chiral eigenstates,

$$\begin{align*}
W_1 &= W_L \cdot \cos \xi - W_R \cdot \sin \xi \\
W_2 &= W_L \cdot \sin \xi + W_R \cdot \cos \xi
\end{align*}$$

for definiteness $M_2 \gg M_1$.

The modified Lagrangian reads

$$I_W = \frac{g}{2\sqrt{2}} \left\{ \left[ (V-A) \cos \xi -(V+A) \sin \xi \right] W_1 + \left[ (V-A) \sin \xi + (V+A) \cos \xi \right] W_2 + H.C. \right\}.$$ 

In case of left-handed $\nu^\text{lep}_L$ neutrinos (and also $\mu^\text{lep}_L$) the $(V+A)$ leptonic current does not give any contribution, in contrast with the hadronic current because $(u, d)$ quarks are occurring always in left-right symmetric combinations inside the nucleons. Thus one gets the "left-handed" effective four-fermion Lagrangian in the form:

$$I_{\text{LEFT}} = \frac{g^2}{8} \left\{ (V-A)_{\mu^+ \mu^-} \cos \xi [ (V-A)_{\mu^+ \mu^-} \cos \xi - (V+A)_{\mu^+ \mu^-} \sin \xi ] + (V-A)_{e^+ e^-} \sin \xi [ (V-A)_{e^+ e^-} \sin \xi + (V+A)_{e^+ e^-} \cos \xi ] \right\}$$

x) At present energies $Q^2$ dependence is negligible.
After some rearrangements one obtains

$$
\text{L}^{\text{LEFT}} = \frac{g^2}{8} \left\{ (V-A)_{\text{lep}}^+ (V-A)_{\text{had}}^+ \left[ \cos^2 \frac{2\phi}{M_1^2 - M_2^2} \right] - (V-A)_{\text{lep}}^+ (V-A)_{\text{had}}^+ \sin \phi \cos \left[ \frac{1}{M_1^2} - \frac{1}{M_2^2} \right] \right\}.
$$

This interaction can be studied by standard neutrino scattering because by default left-handed neutrino (and right-handed antineutrino) beams are available.

Assuming however the existence of right-handed $\nu_R$ neutrinos the situation will be reversed and one should retain only $(V+\nu)^{\text{lep}}$ leptonic currents which provide the effective four-fermion Lagrangian for right-handed neutrino $(\nu_R^+)$ scattering:

$$
\text{L}^{\text{RIGHT}} = \frac{g^2}{8} \left\{ (V-A)_{\text{lep}}^+ (V-A)_{\text{had}}^+ \left[ \sin^2 \frac{2\phi}{M_1^2 - M_2^2} \right] + (V+A)_{\text{lep}}^+ (V-A)_{\text{had}}^+ \sin \phi \cos \left[ \frac{1}{M_1^2} - \frac{1}{M_2^2} \right] \right\}.
$$

The cross-section calculations are reduced to the evaluation of matrix elements which has the general form:

$$
A \left( h_{\text{lep}}, h_{\text{had}} \right) = \left\langle \left\{ \frac{3}{8} \left[ (V + h_{\text{lep}}^A)^+ (V + h_{\text{had}}^A) \right] \right\} \right.
$$

In this notation the differential cross-section can be written as

$$
\sigma_{\text{LEFT}}^\nu = \left| A \left( -1; -1 \right) \right|^2 c_{\text{LL}}^2 + \left| A \left( -1; +1 \right) \right|^2 c_{\text{LR}}^2 = \sigma_{\text{+}}^\nu c_{\text{LL}}^2 + \sigma_{\text{-}}^\nu c_{\text{LR}}^2
$$

$$
\sigma_{\text{RIGHT}}^\nu = \left| A \left( +1; +1 \right) \right|^2 c_{\text{RR}}^2 + \left| A \left( +1; -1 \right) \right|^2 c_{\text{RL}}^2 = \sigma_{\text{+}}^\nu c_{\text{RR}}^2 + \sigma_{\text{-}}^\nu c_{\text{RL}}^2
$$

where the meaning of $\sigma_{ij}$ is self-explanatory and

$$
c_{\text{LL}} = \frac{\cos^2 \phi}{M_1^2 - M_2^2}; \quad c_{\text{RR}} = \frac{\sin^2 \phi}{M_2^2 - M_1^2}; \quad c_{\text{LR}} = \frac{\sin \phi \cos \phi \left( \frac{1}{M_1^2} - \frac{1}{M_2^2} \right)}{c_{\text{RL}}}.
$$

Some representative diagrams corresponding to different terms are shown in Figure 1.

After trace calculations one can get $\sigma_{ij}$. In general case they consist of two parts which are $i \leftrightarrow j$ symmetric in helicities:

$$
\sigma_{ij} = \left| A \left( h_i, h_j \right) \right|^2 = h_i h_j K_1(p_k) + (1 + h_i h_j) K_2(p_k)
$$

where $K_1$ and $K_2$ represent definite kinematic functions of particle momenta. Due to the fact that in our calculations the masses are neglected $K_1$ and $K_2$ are depending only on the CM-energy and CM-scattering angle which is equivalent to the scaling variable $y$. Thus there remain only two possibilities

i) $h_i h_j = +1$ yields $\frac{d\sigma}{dy} \propto 1$

ii) $h_i h_j = -1$ yields $\frac{d\sigma}{dy} \propto (1 - y)^2$

Of course, one has $x \equiv 1$ for "elastic scattering" on quarks. From these the usual procedure gives for charged current scattering on isoscalar nuclei

$$
\sigma_- (x, y) = \sigma_+ (x, y) \propto q(x) + (1 - y)^2 \overline{q}(x)
$$

$$
\sigma_+ (x, y) = \sigma_- (x, y) \propto \overline{q}(x) + (1 - y)^2 q(x)
$$

where $q(x)$ and $\overline{q}(x)$ represent the quark and anti-quark distribution inside target nuclei.

In the general case the muon beam consists of $\mu_L^-$ and $\mu_R^-$ components. Thus the charged
current cross-section for negative muon beam with polarization $\lambda$ can be written as a sum

$$\sigma^{L} = \frac{1 - \lambda}{2} \sigma_{\text{LEFT}} + \frac{1 + \lambda}{2} \sigma_{\text{RIGHT}} = \frac{1 - \lambda}{2} \sigma_{-}^{2L} + \frac{1 + \lambda}{2} \sigma_{+}^{2L} + \sigma_{+}^{2R} + \sigma_{+}^{2R} \cdot$$

It is worth to remark that the left-right mixing term is independent of muon polarization, in accordance with the fact, that it is parity conserving. Of course, this left-right symmetry can be broken by mass terms and for too heavy $\nu'$ the $\sigma_{\text{RIGHT}}$ part would be zero due to energy conservation.

For completeness, we write down the differential cross-sections in a more explicit way:

$$\frac{d^{2}\sigma^{L}}{dxdy} = \frac{1 - \lambda}{2} \sigma_{L} + \frac{1 + \lambda}{2} \sigma_{R} \cdot \sigma_{RL} \propto \frac{1 - \lambda}{2} \left[ q+(1-y)^{2} \right]^{2} \left[ \left[ q+(1-y)^{2} \right] c_{RL} \cdot \right]^{2} \frac{d^{2}\sigma^{R}}{dxdy} = \frac{1 + \lambda}{2} \sigma_{L} + \frac{1 - \lambda}{2} \sigma_{R} \cdot \sigma_{RL} \propto \frac{1 + \lambda}{2} \left[ q+(1-y)^{2} \right]^{2} \left[ \left[ q+(1-y)^{2} \right] c_{RL} \cdot \right]^{2}$$

where the transition $\mu^{-} \leftrightarrow \mu^{+}$ is formally achieved by substituting $\lambda \leftrightarrow -\lambda$ and $q(x) \leftrightarrow \bar{q}(x)$. One gets the corresponding neutrino cross-sections simply by setting $\lambda = \pm 1$:

$$\frac{d^{2}\sigma^{\nu}}{dxdy} = \sigma_{L} + 0 + \sigma_{RL} \propto \left[ q+(1-y)^{2} \right] c_{RL}^{2} \frac{d^{2}\sigma^{\bar{\nu}}}{dxdy} = \sigma_{L} + 0 + \sigma_{RL} \propto \left[ q+(1-y)^{2} \right] c_{RL}^{2} \cdot$$

In summary, the muon cross-sections consist generally of 3 parts: the parity violating piece includes pure left- and right-handed contributions, the parity conserving part contains their mixing which is within our approximation independent of $\lambda$. In the case of neutrino scattering the pure right-handed term is lost. The remaining terms contain $M_{2}$ in $\sin(\xi)M_{2}$ and $\sin^{2}(\xi)\nu_{2}$ combinations. Thus it is practically impossible to deduce any limit on the right-handed intermediate boson mass, $M_{2}$ from neutrino scattering.

3. PRESENT LIMITS ON RIGHT-HANDED PHENOMENA

A number of partial reviews have been published on this topic (see Section 3-7). One can derive limits for mixing angle $\xi$ and ratio $\delta = M_{2}/M_{1}$ from existing experimental data in the following interactions: $\mu$-decay ("direct, inverse"): $\beta - \nu$, non-leptonic decay of strange particles and high energy $\nu$ scattering. These measurements can be classified (see Table 1) according to the following criteria:

a) sensitivity to massive right-handed neutrinos,
b) they give bounds on $\xi$, the mixing angle,
c) they give bounds on $\delta = M_{2}/M_{1},$
d) special assumptions (if any) are required about hadron structure.

Theoretical and experimental effort has been concentrated in the low energy leptonic and semi-leptonic area. By definition they were not sensitive to massive (greater than 1 GeV/c$^{2}$) neutrinos due to the lack of energy to produce them.
3.1. Pure leptonic processes

All the classical parameters are more or less sensitive to the (V-A) structure of muon decay. Latest compilation is shown in reference$^5$. The Michel parameter of energy spectrum gives a limit on mixing angle
\[ |\xi| \leq 0.06. \]

The angular asymmetry $\xi_{PM}$ of electrons emitted from polarized muon decays defines an ellipse\(^4\) with axis $x$ and $y$
\[ |x| = |\delta - \xi| \leq 0.23 \quad \text{and} \quad |y| = |\delta + \xi| \leq 0.115. \]

Inverse muon decay (i.e. $\nu e$ scattering) measurements are preferring (V-A), but their accuracy is not good enough to deduce stringent limits on (V+A) parameters\(^8\).

From Figure 2 which was taken from Sakurai's review based on talk of Strovink in Blacksberg conference one can deduce that pure leptonic processes can allow as low as 220 GeV mass for $M_\nu$ at mixing angle less than 0.06.

3.2 Semi-leptonic processes

Longitudinal polarization of electrons in pure Gamow-Teller nuclear beta decay is found to be equal\(^9\) to
\[ (-c/v) \cdot p_{\beta}^{GT} = 1.001 \pm 0.008. \]

This gives a bound on the parameter $y$: $|y| \leq 0.09$.

Angular asymmetry of electrons from decay of polarized $^7$Ne nucleus\(^10\) defines a hyperbola like area in $(\delta, \xi)$ plane shown in Figure 2.

The semi-leptonic bounds are shrinking considerably the $(\delta, \xi)$ domain allowed by pure leptonic processes but the minimal bound on $M_\nu$ is increased only up to about 250 GeV.

3.3 High energy neutrino interactions

$\bar{v}$-scattering on nucleons is very sensitive to right-handed currents in the high-$y$ region, and bounds are valid whatever the mass of right-handed neutrinos. The CDHS experiment\(^11\) yields a bound on mixing angle:
\[ |\xi| \leq 0.095 \quad (90 \% \ C.L.). \]

It does not however give a significant constraint on $\delta = M_1^2/M_2^2$ mass ratio.

3.4 Non-leptonic weak processes

Large enhancement factors for right-handed currents are found in hadronic weak processes but for their derivation additional assumption on hadron structure are necessary. Though this assumptions can be well founded, due to the complexity of hadrons one can not exclude the existence of other possible phenomena which can interfere with left-right symmetric weak effects distorting their appearance. Due to the absence of neutrinos either in the initial or in the final state these bounds are independent of right-handed neutrino mass. Only the right-handed intermediate boson mass does affect the matrix elements.

3.4.1 Hyperon decays: $\Lambda \rightarrow N\pi$, $\Sigma \rightarrow N\pi$, $\Xi \rightarrow \Lambda\pi$, $\Omega \rightarrow \Xi\pi$

I. I. Bigi and J. M. Frere\(^12\) argue, that "left-right couplings introduce a correction factor $(1 - 120 \sin \xi)$ into the factorizable contribution to the $\Delta I = 3/2$ amplitude for P-wave decays of hyperons". They use the observed departure from pure left-handed current
contribution as upper limit for the mixing angle

\[ \left| \sin \xi \right| \leq 1/120 \] (no limit for \( \delta \)).

According to M. Denis \(^7\) the applicability of factorization is questionable because it is neglecting the effect of soft gluons. In addition, right-handed effects are expected to give similar contribution to each process which is not the case.

### 3.4.2 \( \mathbf{K} \to 3\pi \) decay

J.F. Donoghue and B.R. Holstein\(^{13}\) say: "The most stringent bounds come from the deviation from PCAC predictions in K decays both for \( \Delta I = 1/2 \) and \( \Delta I = 3/2 \). In the limit of no mixing

\[ M_2 > 300 \text{ GeV} \]

(\( \approx \delta < 1/20 \)).

If the right-handed quark mixing angles are equal to their left-handed counterparts and \( M_2 \) is larger then \( \sin \xi < 0.004 \). These limits however are also very model dependent because they rely e.g. on the bag-model.

### 3.4.3 \( K^0 - \bar{K}^0 \) mass difference

G. Beall et al.\(^{14}\) gets \( \delta < 1/430 \) corresponding to \( M_2 > 1.6 \) TeV. M. Denis\(^7\) taking into account t-quark and "would be Goldstone" effects can remain however within the experimental limits if

\[ \delta \approx 0.15 \quad (M_2 \approx 210 \text{ GeV}). \]

### 3.5 Overall conclusion from present data

Neglecting the controversial non-leptonic processes the best fit to low energy data obtained by Maalampi et al.\(^5\) provides \( M_1/M_2 = 0.22 \) or in terms of upper limits

\[ M_1/M_2 < 0.29 \quad \text{and} \quad |\xi| < 4.2^\circ \] (68.3 % C. L.)

which means \( M_2 > 275 \text{ GeV} \) in case of \( M_1 = 80 \text{ GeV} \). There are experiments in progress to improve limits arising from \( \mu \) or \( \tau \)-decay. No experimental attempt is known, however, to get limits on \( M_2 \) mass in case of massive right-handed neutrinos. Therefore it would be important to perform experiments with right-handed \( \mu \) beams which could give unique results on \( (\delta, \xi) \) independently from \( \nu_R \) mass and free from hadronic structure assumptions. Of course, \( \nu_R \) mass should be within the kinematically allowed limits of \( \nu_R \) scattering. Thus observation of the production threshold would provide exact value of \( m_{\nu_R} \) unattainable for other experiments.

4. EXPECTED BOUNDS FROM \( \mu \) EXPERIMENTS

#### 4.1 No-mixing

In order to get a feeling for the experimental sensitivity, we discuss some special cases in detail. If the mixing angle \( \xi \) is so small that one gets

\[ c_{RR} \gg c_{RL} \]

then the formula shows that there is no practical possibility to extract information on right-handed currents from \( \nu \)-scattering. Thus \( \mu \) scattering provides unique possibility to measure \( M_2 \) directly i.e. one can discover the right-handed current even in total absence
of left-right interference. One can perform 2 measurements at different muon polarizations, for example, taking $\lambda_o = 0$ and $\lambda = \lambda = 0.9$ one gets:

$$N_o = \text{Monitor}_o \cdot \frac{1}{2} \left[ \frac{1}{M_1^4} + \frac{1}{M_2^4} \right] \left[ q(x) + (1 - \gamma)^2 q'(x) \right] = \text{Monitor}_o \cdot \frac{1}{2} \left[ \sigma_L + \sigma_R \right]$$

$$N_1 = \text{Monitor}_1 \cdot \frac{1}{2} \left[ \frac{1 - \lambda}{M_1^4} + \frac{\lambda}{M_2^4} \right] \left[ q(x) + (1 - \gamma)^2 q'(x) \right] = \text{Monitor}_1 \cdot \frac{1}{2} \left[ (1 - \lambda) \sigma_L + \lambda \sigma_R \right].$$

Introducing notations: $\delta^2 = \frac{\sigma_R}{\sigma_L} = \frac{\sigma_1 - (1 - \lambda) \sigma_0}{(1 + \lambda) \sigma_0 - \sigma_1}$ one can solve this system of equations because one expects $\sigma_R \ll \sigma_L$ which implies $\sigma_1 \approx (1 - \lambda) \sigma_0$. Error propagation gives

$$\partial (\delta^2) = \frac{1}{2 \lambda} \frac{1}{\sigma_0} \left[ \frac{\partial \sigma_1}{\partial \sigma_0} - \frac{\partial \sigma_0}{\partial \sigma_0} \right] \approx \frac{1 - \lambda}{2 \lambda} \sqrt{\frac{1}{N_o} \frac{1}{N_1} + \frac{1}{N_o} \frac{1}{N_1}} \frac{1}{K (1 - \lambda)},$$

where $K = \text{Monitor}_1 / \text{Monitor}_0$ denotes the relative number of incoming muons with $\lambda$ and $\lambda_o$ polarization, respectively. For $K = 4$ and $\lambda = 0.9$ one gets numerically

$$\partial (\delta^2) = \partial (\frac{M_1^4}{M_2^4}) \approx 0.1 \sqrt{\frac{1}{N_o}}$$

which means that $N_o = 100$ events can produce one standard deviation limit on right-handed mass $M_1 / M_2 < \sqrt{2 \delta / \rho} = 0.316$ corresponding to $M_2 > 250$ GeV. It seems to be an easy experiment. Don’t forget, however, that in order to improve this limit by a factor of 2 one requires $(2^2)^2 = 256$ times more muon (i.e. running time).

### 4.2 Right-handed boson is extremely heavy

If $M_2$ is so large that $c_{RR} \ll c_{RL}$ then the muon scattering is reduced formally to the neutrino one. Even in this case the muon beam has the advantage that the normal weak interaction will be suppressed by a factor of $(1 - \lambda) / 2$ relative to the mixing term. Within our approximation measurements with $\mu^+ \mu^-$ and $\mu^- \mu^-$ beams provide

$$\sigma^- = \frac{1 - \lambda}{2} c_{LL}^2 \left[ q(x) + (1 - \gamma)^2 q'(x) \right] + c_{RL}^2 \left[ q(x) + (1 - \gamma)^2 q(x) \right]$$

$$\sigma^+ = \frac{1 + \lambda}{2} c_{LL}^2 \left[ q(x) + (1 - \gamma)^2 q'(x) \right] + c_{RL}^2 \left[ q(x) + (1 - \gamma)^2 q(x) \right].$$

In case of magnetic field reversal (i.e. beam conjugation) one finds $\lambda^+ = - \lambda^- = \lambda$.

It is worth to define the combination

$$D(x) = \frac{\sigma^- - (1 - \gamma)^2 \sigma^+}{\sigma^- - (1 - \gamma)^2 \sigma^+} = \frac{(1 - \lambda) c_{LL}^2 \overline{q} + 2 c_{RL}^2 q}{(1 - \lambda) c_{LL}^2 q + 2 c_{RL}^2 \overline{q}} \approx \frac{\overline{q}}{q} + \frac{2}{1 - \lambda} \frac{c_{RL}^2}{c_{LL}^2},$$

where one can neglect $c_{RL}^2 \overline{q}$ relative to the first term if $\delta^2 < (1 - \lambda)^2 / 2$. In this case the mixing angle is given by the formula:

$$\delta^2 \approx \frac{c_{RL}^2}{c_{LL}^2} = \left( D(x) - \overline{q}/q \right) \frac{2}{1 - \lambda}$$

That is the sensitivity is increased by a factor of 20 in muon case relative to the neutrino one if the muon polarization is equal to $\lambda = 0.9$, which makes the experiment less sensitive to the error in $\overline{q}/q$ ratio determination.
5. EXPERIMENTAL DETECTION OF CHARGED CURRENT EVENTS

5.1 Rates

The cross-section for charged current process \( \mu^+ N \rightarrow \nu_\mu X \) is \( \sigma = 0.62 E_\mu \times 10^{-38} \text{ cm}^2/\text{muon/mucleon} \). The rate of interaction at 200 GeV on lead (uranium) target is then about \( 0.8 \times 10^{-9} \) events/muon/meter (\( \sim 1.4 \times 10^{-9} \)). A moderate flux of \( 10^7 \) muons/burst yields \( 10^4 \) events in 10 days on a lead (uranium) target of 10 m (6 m). The production rate by itself is therefore high enough to allow an investigation of the process. We should not however forget about the polarization factor of \( (1-\lambda)/2 \) as \( \lambda \) will generally be about .9.

5.2 Signature

The final state is characterized by three features which can be used against potential backgrounds:

i) the absence of muons in the final state

ii) a large missing energy

iii) a hadronic shower at high \( Q^2 \).

As the \( Q^2 \) distribution of events with large missing energy clearly plays a key role in the measurements, the detector should have a good angular resolution.

5.3 Backgrounds

The main contributions to the background arise from events with fake muon interactions, such as muon decay in the initial state, or events where the scattered muon is undetected because it is soft or decays.

i) Muon decay in the initial state

There is only an electromagnetic shower at a rate of \( 8 \times 10^{-6} \) decays/muon/meter. These events will be strongly suppressed by requiring a hadronic shower with \( Q^2 > 1 \text{ GeV}^2 \).

ii) Undetected final muon

a) Decay of the final muon

According to Monte Carlo calculations, a cut on the transverse momentum of the hadronic shower in the final state reduces the ratio background/signal to a few percent.

b) Loss of soft final muons

Such events are eliminated by a request of a large missing energy in the final state.

5.4 Triggering

A trigger would require:

i) A large local energy deposition \( y > .2 \) which is readily obtained by the calorimeter threshold.

ii) No muon in the final state. One can check that there is no muon with energy less than \( .8 E_{\text{BEAM}} \) by inserting a beam analysis magnet and muon identifier after the calorimeter.

iii) A missing energy requirement \( y < .8 \) combined with muon veto will reduce the trigger rate to the level of \( 10^{-5} \) events/incoming muon.

The final event selection is performed by an off-line analysis imposing the high \( Q^2 \) requirement. Thanks to the length of the proposed calorimeter we can estimate the remaining background by selecting events when the hadronic shower is well separated from the eventual electron shower at the decay of the scattered muon.
5.5 Detector

The detector should consist of two parts: a dense, fine grained calorimeter and a veto-system to identify the surviving muons. The veto-system can be built from standard elements. The fine granularity can be achieved by a novel design based on scintillating fibres.

The parameters of a possible uranium calorimeter are summarized below:

- Uranium plate thickness: 1.5 millimeter
- Scintillating fibre diameter: 0.5 millimeter
- Number of plates: 6000
- Average density: 14.4 g/cm³
- Total length: 12 m = 17280 g/cm²
- Lateral width: 40 cm
- Lateral segmentation: 1 millimeter
- Longitudinal segmentation (x,y) interleaved: 8 millimeter
- Number of read-out channels by 2×2 fibres: 1200000 channels

If one uses lead instead of uranium then all the above parameters should be rescaled by the density factor \( \rho_u / \rho_{\text{lead}} \).

By this detector 1 day running with \( \lambda_1=0 \) and 4 days with \( \lambda_1=0.9 \) can provide a bound

\[
M_2 \gtrsim 250 \text{ GeV} \quad (68.3 \% \text{ C.L.})
\]

In case of \( \lambda_1=0.95 \) after 150 days \( (1.5 \times 10^{13} \text{ incoming } \mu_\text{R}^\text{in}) \) it is possible to reach

\[
M_2 \gtrsim 450 \text{ GeV} \quad (68.3 \% \text{ C.L.})
\]

In order to realize this theoretical possibilities significant developments are required in the fibre read-out technology which would make feasible the digitization of the information from about one million optical channels. Some preliminary studies would be very useful by the help of the uranium calorimeter proposed by the EMC collaboration\(^{15}\) for bb studies.

\[\star\star\star\]

REFERENCES

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Figure 1: Representative $SU_L(2) \times SU_R(2) \times U(1)$ diagrams

Figure 2: Low-ended bounds on right-handed current parameters
HADRON PRODUCTION IN DEEP INELASTIC M UON SCATTERING

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Workshop on Fixed Target Physics at SPS

Report to which the following persons contributed:
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V. Eckardt, J. Favier, C. Gössling, J. Nassalski, P. Renton, N. Schmitz,

ABSTRACT
Future possibilities of physics with the final state hadron system in muon
scattering are considered in the light of work done so far at the SPS and
planned for the Tevatron.

1. INTRODUCTION

The physics interest in the study of the hadronic final state in muon scattering
is twofold.

(a) - A study of production mechanisms.
(b) - A study of fragmentation and radiative QCD jets.

The existing experiments which are of primary concern when considering muon
scattering in the years \( \geq 1985 \) are:

(a) - e^+e^- annihilation

(b) - W(\bar{W})\bar{N}

(c) - \nu\bar{\nu}N

Petra, Pep
BEBC, Fermilab 15' 
NA2 (SPS)
NA9 (SPS)
NA28 (SPS)
E665 (Tevatron)

In general lepton scattering is complementary to e^+e^- experiments and there
are some aspects of QCD tests which demand data from both. The interest of a
comparison with e^+e^- data at similar energies lies not in rivalry but the
necessity to confront QCD with a wide spectrum of pertinent data so that a
quantitative determination of ostensibly equivalent parameters may be made in
different reactions. However, lepton scattering experiments have an advantage in the
definition of the parton direction and identity.
Neutrino scattering\(^1\)
may be considered in much the same light as muon
scattering. Both define the struck parton jet well although the neutrino does
marginally better with the diquark system and antineutrinos are the only reliable
source of d quark fragmentation functions. However neutrino scattering suffers in
general fragmentation and QCD studies from several major defects.

(a) - Lack of energy necessary to separate adequately 1, 2 and 3 parton fragmentation
systems.
(b) - Lack of statistics.
(c) - Lack of definition of the momentum and direction of the exchanged virtual boson.
(d) - Lack of charged particle identification.

By far, the most relevant "competition" to any future work at the SPS is provided
by the experiment NA2 (SPS), from which illustrative data will be used in this report,
by NA9, NA28 (SPS) which are running SPS experiments with a rather complete acceptance
and charged particle identification and by E665 which for brevity can be described as
the Tevatron version of NA9. Compared to NA2, NA9 and E665 (as presently proposed)
have a more complete detection and particle identification system but are lower
luminosity experiments partly due to target length limitations and partly due to
limitations in the streamer chamber repetition rate.

In the rest of this report we will consider the current physics interests\(^2\) in
the light of present data and the possibilities of the above experiments. Following
the evident needs a possible apparatus for 1985 will be described. In addition the
indirect measurement of \(B\bar{B}\) production through its multimuon final states will be
considered. This report is by definition a summary and fails to do justice to the
detailed work performed by the members of the subgroup which was presented in the
parallel sessions of this workshop.

2. QUARK PARTON MODEL

The basis of all discussion of deep inelastic scattering is the Quark Parton
Model illustrated in fig. 1. Within this model the production mechanism is expected
to be well described by the photon quark interaction and the unknowns under study in
hadron production are the various fragmentation functions of quarks \(D^q(z)\) and of
diquarks \(D^{qq}(z)\). In muoproduction for \(x_{Bj} < 0.05\), scattering is from the
quark antiquark sea (see fig. 2) and there is expected to be essentially an equal
number of positive and negatively charged hadrons produced. For higher \(x_{Bj}\) the
charge 2/3 u quark dominates at the level of 90%. These characteristics can be seen in
the data\(^3\) illustrated in fig. 3 where the z weighted distributions are shown for
each charge in 3 different \(x_{Bj}\) regions.
Fig. 1: Conventional QPM picture of Deep Inelastic lepto production of hadrons

Fig. 2: Fraction of different quarks participating in the scattering as a function of $x_{Bj}$
Fig. 3: Distributions of positive and negative hadrons as a function of $Z$ for three different $x_{Bj}$ regions in muon scattering.

A further detail of the fragmentation parameters is for example the production ratio between vector and pseudoscalar mesons. Recent data\textsuperscript{4)\textsuperscript{)}} are shown in fig. 4 in which a comparison between $\pi^0$ and $\phi$ production is made. At $z = 1$ the data are equal and this provides a measure of $a_v/a_\phi$ since at $z = 1$ only direct production is possible by definition. The resultant value $a_v/a_\phi = 1.0 \pm 0.3$ (stat) \pm 0.4 (syst) differs from the value 3 expected from spin counting. If this were a mass effect then a measurement of $K^0/\bar{K}$ would be illuminating. NA9 may provide this measurement for which particle identification is necessary.

Baryon/antibaryon production has been seen to contribute $\sim 10\%$ of the hadrons in the fragmentation process however the exact production mechanism is as yet obscure. A clue that gluons may be relevant is provided by some preliminary data\textsuperscript{4)\textsuperscript{)}} on the $p_T$ dependence of the ratio $p/(\text{all +ve})$ and $\bar{p}/(\text{all -ve})$ shown in fig. 5. These data contain $\sim 2000$ identified protons and antiprotons and are based on $\sim 500k$ muon scatters from NA2. NA9 will have a better identification but many fewer events and a similar total number of identified protons and antiprotons is expected. One can therefore conclude that a definitive study of baryon production needs good particle identification but also higher statistics ther offered by NA9, E665.
Fig. 4: Comparison of production of $\rho^0$ and $\pi^0$ mesons in muoproduction

Fig. 5: The ratio of (p/all-ve) and ($\bar{p}$/all-ve) hadrons as a function of $P_T^2$
3. QCD CORRECTIONS TO FRAGMENTATION

(Report of W. Stockhausen to Parallel Sessions)

Beyond the parton model leading order QCD corrections modify the fragmentation functions $D^{H}(z)$ such that they acquire a $Q^2$ dependence $D^{H}(z, Q^2)$ which is described by a set of Altarelli-Parisi evolution equations\(^5\). Although scale breaking has been observed in $e^+e^-$ production its interpretation is complicated by the plethora of heavy quark decays. In neutrino scattering $Q^2$ dependence is only seen for $W < 4$ GeV\(^6\). In muon scattering, data with statistical and systematic errors at the 10% level, exist and the $Q^2$ dependence is seen to be weak\(^7\). The data are shown in fig. 6 and, in anticipation of the next point, are shown for fixed $x_{Bj}$.

In the hadronic final state, strong next to leading order effects are expected to appear as a breakdown of the factorisation, between the variables $x_{Bj}$ and $z$, which is present in both the QPM and leading order QCD. This appears as an $x_{Bj}$ dependence (fig. 7) of the fragmentation function at fixed $Q^2$. Quantitative model estimates of

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**Fig. 6**: $Q^2$ dependence of fragmentation yields for 5 different $z$ values in four bins of $x_{Bj}$. The solid curve is a QCD calculation [8] the dashed lines represent the Quark Parton Model.
Fig. 7: $x$-dependence at fixed $Q^2$ of fragmentation for 5 different $z$ values

the QCD corrections have been made\(^8\) and rough agreement with the data is seen, however the large number of independent fragmentation functions which contribute to unidentified hadron data give many degrees of freedom. Furthermore, the data and the models can be reduced (fig. 8) to a dependence on a single variable $W^2$ which, within errors, requires no residual dependence on either $x_{Bj}$ or $Q^2$. Note that this breakdown of factorisation is one of the few observable next to leading order QCD effects, it is not present in $e^+e^-$ annihilation.

In addition to the classical perturbative QCD effects there are expected to be significant higher twist effects. In general these are 'edge of phase space' effects and lead to the dependence of the fragmentation on $y = v/E$. Within the models of Berger\(^9\) this can be understood as the observation of a very high $z$ pion forcing the quarks of the mass shell and thus inducing a non-zero longitudinal photon coupling. Also some recent calculations\(^10\) suggest that observable effects should be present in $\rho^+\rho^-$ production.

It is clear that in this field the confrontation with QCD is not yet really discriminative. Advances are possible in muon physics since the systematic errors on the measurement of $v$ are adequate however the charged pions must be identified to reduce the number of fragmentation functions in the model calculation and to avoid problems from "mass effects". NA9 will not have high enough statistics nor will E665. This is a clear field for a new experiment, run with high luminosity, at several different energies to look at the $y$ dependence as well.
4. PRODUCTION FROM HIGH A NUCLEI

(Report from C. Coignet to Parallel Session)

4.1 How does fragmentation work?

As sketched in fig. 9, fragmentation, in the laboratory frame, is expected to take place over a long distance of the order of \( z \sim 100 \text{ fm} \). If this is the situation then differences in the hadrons produced from different nuclei provide information on the nature of confinement and the interaction of fragmenting quarks with nuclear matter. Within the model of Bialas and Bialas \(^{11}\) there is a relationship

\[
\frac{1}{N} \frac{dN}{dz} A_2 \xrightarrow{\text{high } z} \sqrt{qN} \quad \frac{1}{N} \frac{dN}{dz} A_1 \xrightarrow{\text{high } \gamma_{\text{cms}}} \sigma_{\text{eff}}
\]

Data have been presented by NA2 \(^4\) on a comparison between hadrons produced on Hydrogen, Carbon and Copper targets. A publication on these data is in preparation but they, surprisingly for some people, indicated that the fragmenting quark at high energies takes little note of its surroundings, this is illustrated by plots as a function of \( \gamma \) and \( p_T^2 \) in figs. 10 and 11. There are also more recent ideas \(^{12}\) which might expect enhancement of the parton reinteraction probability if gluons are emitted.
Fig. 9: Sketch of virtual photon interaction with a quark in a nucleus

4.2 Nature of the photon interaction

The detection and study of the hadronic debris resulting from lepton scattering on nuclei has been strongly advocated\textsuperscript{13}) as a means to study the nature of the virtual photon interaction. This line of thought has been given new impetus by the observation\textsuperscript{14}) of the anomalous behaviour of the ratio between iron and deuterium nuclei. If indeed this phenomenon can be related to an increase of the $q\bar{q}$ sea then an increase in the production of strange and charm meson pairs would be expected for high $A$. On the other hand if the effect is related exclusively to virtual pion states a change in the $K/\pi$ ratio would be expected.

The presently approved program within the NA28 proposal is for $\sim 10$ days exploratory work with high $A$ nuclei. If these were used with $^{13}$Cs in the streamer chamber at 20 atmos they would yield $\sim 10$ K deep inelastic events. These would not provide a study of anything but the gross features. A "reasonable" experiment with a series of high pressure targets ($^{113}$Xe, $^{88}$Kr, $^{40}$Ar, $^{32}$Ne, $^{4}H$, $^{4}He$) would consist of $\sim 50$-$60$ days running, with a resultant $\sim 20$ K statistics on several targets. It would not be necessary to modify the present NA9 apparatus.

5. QCD JETS

The conventional diagrams relevant to QCD jet production are shown in fig. 12. In any discussion of jets it should be remembered that the QCD process e.g. fig. 12 a) is a bremsstrahlung type of process peaked at zero degrees and therefore any observation of jets is necessarily in the tails of various kinematic distribution ($p_T^2$). The behaviour of $p_T^2$ with kinematics is expected to be given by\textsuperscript{15})

$$< p_T^2 > \sim a_s(Q^2) \cdot \mu^2,$$
Fig. 10: Comparison of hadron yields from hydrogen copper and carbon targets as function of c.m.s. rapidity \( y^* \) for two different ranges in \( v \).

Fig. 11: As fig. 10 but as function of \( p_T^2 \).
Fig. 12: Diagrams for QCD jet production.

the dependence on $W^2$ coming from the phase space for gluon emission, such behaviour is observed\textsuperscript{16}). In contrast the $p_T$ associated with the fragmentation of any parton is not expected to change and this is the limiting resolution. (Unfortunately our apparatus is not sensitive to direct partons). Given these contrasting behaviours it is clear that there is an advantage in going to high energies. This is illustrated in fig. 13 where the tails in $\sum p_T^2$ are compared for two different data sets with a mean $W$ differing by a factor 2. The tail is clearly much more pronounced in the higher energy data set. In this higher energy range it is then possible (fig. 14)\textsuperscript{17}) to observe jet like energy flow structures if a $p_T$ cut is applied to the data.

At the present time there is still a lot to learn about QCD jet structures, among the questions for Deep Inelastic Scattering are:

(a) How does the diquark target jet behave as a function of $W^2$ for $W^2 > 100$ GeV\textsuperscript{2}? This should be answered by NA9.

(b) How does the event structure vary as a function of $W^2$ up to energies equal to that of Petra and Pep? This can be answered by E665 at CMS energies up to $W^2 = 1400$ GeV\textsuperscript{2} but not at the SPS where the limiting muon energy is 325 GeV.

(c) What are the flavour and charge properties of the jet structures. This will be difficult in either of NA9/E665 as presently conceived because of lack of statistics.

(d) How do the jet structures behave in topology, flavour etc. as a function of $x_{Bj}$? Can the transition from $qg \rightarrow q\bar{q}$ be seen?

Again as for (c) NA9 and E665 seem to be short of statistics and there appears to be a clear case for an improved high luminosity, good particle identification muon experiment.
Fig. 13: $\Sigma p_T^2$ for two data sets with different energy compared with Quark Parton and QCD model calculations.

Fig. 14: Distribution of energy flow (a) with no cut on $p_T$ (b) with cut of $p_{T_{\text{max}}}^2 > 2 \text{ GeV}^2$. 
6. HEAVY FLAVOUR PRODUCTION
(Report of C. Gössing to Parallel Sessions)

Charm production by muons is well described by the photon gluon fusion model which is based on the diagram shown in fig. 12(b). The experimental studies have been performed by the NA218\(^{18}\) and BFP19\(^{19}\) experiments at SPS/FNAL energies. The technique detects the semi-leptonic charm decays via observation of extra final state muons and uses a calorimetric target to signal the missing neutrino energy. The only bar to the measurement of the upsilon production and of bottom hadron production is luminosity. The extension of this proven technique to the heavier quark systems has been studied in the working group and a report prepared\(^{20}\) which is included after this contribution. The proposed apparatus will of course be sensitive to exotic unexpected multimuon final states and would provide a limit on the production of super symmetric photino particles\(^{21}\).

The direct detection via hadron decay has been considered and rejected. It does not provide the statistics required for a study of production and fragmentation.

7. PHOTON DETECTION

7.1 Single Photon Production
Measurements of \(\pi^c\) production\(^{22}\) are strongly complementary to charged hadron production. Single photons (not products of \(\pi^c\) decay) are complete jets in themselves. In muon scattering the interference between the Bethe-Heitler and Compton amplitudes fig. 15 is proportional to the cube of the muon charge and is therefore different for \(\mu^+\) and \(\mu^-\). Analysis of NA2 data is at present under way. It is necessary to await the results before judging on a future program.

7.2 2 \(\gamma\) Physics
(Report of G. Smadja to Parallel Sessions)

In principle very forward \(\pi^c/\eta^c\) production can proceed by the Primakoff effect (fig. 16) in which the virtual photon \((Q^2)\) interacts with the Coulomb field of a heavy nucleus. Since \(Q^2 < 0\) it is necessary to go to high energies to satisfy the coherence conditions. At lower energies the technique has been used at \(Q^2 = 0\) to determine the \(\pi^c/\eta^c\) lifetime\(^{23}\).

The process has been recently calculated\(^{24}\). It has been shown that the hadronic wave functions involved in the form factor \(F_{\pi\gamma}(Q^2)\), fig. 17a, and the conventional charged pion form factor \(F_\pi(Q^2)\), fig. 17 b, are related such that a measurement of the strong coupling is obtained which is independent of the uncalculable functions.

\[
a_s(Q^2) = \frac{1}{4\pi Q^2} \frac{F_{\pi\gamma}(Q^2)}{|F_\pi(Q^2)|^2}
\]
Fig. 15: Interference of Bethe-Heitler and Compton diagrams for single photon production.

Fig. 16: Sketch of Primakoff process.

Fig. 17: The form factors $F_{\pi Y}$ and $F_{\pi}$ calculated using factorization between QCD and the hadronic wave functions $\phi$. 
Highish values of \( Q^2 \) are required but as shown in fig. 18 the experiment is statistically feasible out to \( Q^2 > 2 \text{ GeV}^2 \). \( F_{\pi}(Q^2) \) is known out to several GeV².

The technical problem is to operate the photon detector as close as possible to the muon beam. It is conceivable that this type of extension might provide some competition for \( e^+e^- \) storage rings in the field of 2 photon physics.

8. THE APPARATUS

In section 3 and 5 it was pointed out that the current NA9 experiment and the E665 experiment at Fermilab (as presently conceived) failed to satisfy the need for good statistics in the study of fragmentation and jet production. The limitations come from the target length 1 m and the repetition rate of the SC which limit final physics samples for \( \approx 1 \) year running to 50-100 K events.

Fig. 18: Yield of events from the Primakoff process as a function of \( Q^2 \). The statistical errors are indicated.
The obvious question as to whether a significant factor in luminosity (5–10) can be achieved with a modern design for a detector and with a larger target has been considered. The answer presented in an accompanying document [25] is unequivocally positive.

The solution presented involves a TPC as a vertex detector and ring imaging Cerenkov counters for charged particle identification. The total cost in a preliminary estimate would be \( \approx 1/10 \) of a Lep detector and the construction time \( \approx 2 \) years. The solution studied is probably not unique and may not be the best but demonstrates clearly that the technology is not a limitation.

9. CONCLUSIONS

We have considered hadron production by muons in the light of existing experiments. The fields examined and conclusions presented in the report are:

- QCD corrections to fragmentation – high statistics, good particle identification required – needs new experiment.

- Study of Quark fragmentation mechanism using nuclear targets – needs \( \approx 1 \) year SPS dedicated running – no new experiment required.

- Study of QCD jets – while study of \( W^2 \) dependence requires Tevatron E665 a detailed high statistics study is also required with good particle identification either at Tevatron or SPS.

- Heavy flavour production – Extension of current calorimeter/muon detection techniques to bottom quark system needs luminosity and good calorimeter.

- Photon detection provides access to interesting 2\( \gamma \) production mechanisms.

- The high luminosity good particle identification experiment alluded to above is eminently practical.

As a final conclusion it seems clear that hadron production by muons has shown its worth in comparison to a priori competitive experiments. It seems to be a suitable candidate for membership of the club of second phase SPS experimental physics.
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A STUDY OF BEAUTY AND CHARM MUOPRODUCTION AT THE SPS

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DESY⁴, Lancaster⁴, Liverpool⁴, Rutherford¹

ABSTRACT

We propose an experiment to study beauty and charm muoproduction via semi-leptonic decays into multi-muon final states. The apparatus for the experiment is based on the EMC Forward Spectrometer (NA2) with a factor ~ 500 increase in luminosity. The measurements proposed include the study of upsilon and B-anti-B production and will provide for a much improved experimental limit on the amount of D⁺ - D⁻ mixing. From a comparison of the charm decays into 2 and 3-muon final states it is proposed to make a direct measurement of the intrinsic charm content of the nucleon. We also comment on possible studies of rare charm and beauty decays into multi-muon final states.

1. INTRODUCTION

A study of charm production by muons through multimuon events has been very fruitful for the insight it provides into QCD, via the Photon-Gluon Fusion model¹, the measurement of the charm contribution to the nucleon structure function F2, the measurement of the gluon distribution of the nucleon and the charm quark fragmentation function. It would be very interesting to repeat these measurements through the production of bound and unbound beauty particles. The higher masses of beauty quarks leads to a shorter distance scale and all the models applied to charm production should work better. For example, the colour singlet model of Berger and Jones² has some difficulty in describing inelastic J/ψ production³. This uses an explicit non-relativisitic wave function and would be expected to work better for beauty quarks which are a factor of ~ 3 heavier than charmed quarks.

In proposing this experiment we draw heavily on our experience with the European Muon Collaboration apparatus (NA2) where in addition to 907 bound charm events and 2950 di and trimuon decays of open charm, 1upsilon candidate and 3 wrong-sign trimuon events were observed. The upsilon candidate yielded a cross-section x branching ratio measurement for 280 GeV muons of σB = 2.5 ± 2.5 x 10⁻³⁸ cm²³. The BCDMS experiment (NA4) also performed an upsilon search and produced an upper limit for 280 GeV of σB < 1.3 x 10⁻³⁸ cm²⁶. Thus, for the calculations presented here, we assume a cross-section for upsilon production of σB = 1.0 x 10⁻³⁸ cm².
The wrong sign trimuon events ($2\mu^+\mu^+\mu^+$ events and $1\mu^+\mu^-\mu^-$) were interpreted
\[ \mu^+ N + \mu^+ \to \bar{B} B X \]
\[ \to \mu^+\nu + \text{hadrons} \]
\[ \to \mu^+\nu + \text{hadrons} \]
and
\[ \mu^+ N + \mu^+ \to \bar{B} B X \]
\[ \to \bar{D} + \text{hadrons} \]
\[ \to \mu^-\bar{\nu} \]
\[ \to \mu^-\bar{\nu} + \text{hadrons} \]
\[ (\mu^+\mu^+\mu^+) \]
\[ (\mu^+\mu^-\mu^-) \]

These events were estimated to contain a background of 2 events from $\pi$ or $K$ decays in the hadronic showers from conventional deep inelastic scattering events. Taking the mean semileptonic branching ratios for charm and beauty decay to be 10%, gave a measured cross-section of $5 \pm 5 \times 10^{-3}$ cm$^2$ [5).

Alternatively these events could be interpreted as originating from charm production with weak interaction mixing changing the $D$ to a $\bar{D}$ or vice-versa. Thus,
\[ \mu^+ N + \mu^+ (D^+ \text{ or } D^0) \bar{D}^0 X \]
\[ \to D^+ \]
\[ \to \mu^+\nu + \text{hadrons} \]
\[ (\mu^+\mu^+\mu^+) \]
and
\[ \mu^+ N + \mu^+ (D^- \text{ or } \bar{D}^0) D^0 X \]
\[ \to \bar{D}^+ \]
\[ \to \mu^-\bar{\nu} + \text{hadrons} \]
\[ (\mu^+\mu^-\mu^-) \]

From this an upper limit of 20% (90% confidence level) was set on the probability of $D^+\to\bar{D}^+$ mixing by assuming that this was the dominant process [5].

In order to perform a definitive experiment to study these processes we propose an apparatus with a factor of 500 improvement in luminosity over the NA2 experiment. A Uranium target calorimeter is proposed to decrease the background contamination from delayed events arising from $\pi$ or $K$ decays. We choose to use an open spectrometer of the type used by the EMC NA2 experiment [6]. Whilst this type of spectrometer has lower luminosity than a continuous target apparatus of the BCDMS [7] or BFR [8] type the better resolution allows the reduction of background processes which are a serious
problem in this type of experiment\(^9\). The apparatus proposed uses most of the existing pieces of equipment from the EMC Forward Spectrometer with improvements in the beam region to allow the measurement of low \(Q^2\) events. With this setup we believe that it will be possible to separate events coming from \(B^0\) mixing and \(B\rightarrow J/\psi K_S^0\) production by using a combination of the decay muon transverse momentum and the missing energy carried away by the neutrinos.

2. APPARATUS

Fig. 1 shows a schematic plan of the proposed forward spectrometer system. As mentioned above this is based on the EMC (NA2) spectrometer which is fully described elsewhere\(^6\). Here we discuss the main features of the new pieces of hardware and the modifications to the existing experimental setup. These are in general not major changes as we foresee that the experiment should run within the existing EMC area in EHN2.

In order to minimise the effects of \(\pi/K\) decay and to maximise the target luminosity we propose to use a Uranium Sampling Total Absorption Calorimeter (STAC) of the kind used by NA2\(^{10}\). In order to retain the same resolution as in the iron calorimeter of NA2 the sampling has been chosen to be similar with 0.8 cm thick Uranium sheets interspersed with 0.7 cm sheets of scintillator. The mean density of material in such a calorimeter is 10.6 g/cm\(^3\) as compared to 6.1 g/cm\(^3\) in the NA2 STAC. Thus we estimate that the residual \(\pi/K\) decay contamination will be \(\approx 35\%\). Whilst this level of background is rather large it can be calculated and is separable from the charm and beauty signals via the differences in missing energy and transverse momentum as it tends to peak at small missing energy and very low values of \(P_T\).

For an 8 m target the corresponding total target length is 8459 g/cm\(^2\). Allowing 5 absorption lengths at the end of the STAC to absorb hadronic showers, the effective total target length becomes 7324 g/cm\(^2\) which gives a factor of 5 increase in target length over the NA2 experiment.

The NA2 data was taken in a single 10-day running period which was reduced to an effective data-taking period of only 4 days. During this period the NA2 apparatus was run with a mean beam intensity on target of \(1.5 \times 10^7\) muons per pulse and a spill length of around 800 ms. The apparatus envisaged here has been modified to run at an intensity of \(1.0 \times 10^8\) muons per pulse with a 2 second spill.

To obtain clean pattern recognition when running under these conditions and at the same time improve the tracking efficiency in the region close to the beam we purpose to use 3-stage wire chamber detection distributed regularly along the spectrometer axis. This consists of a large area drift chamber to cover wide angle tracks; a medium sized MWPC with the beam region made insensitive to cover the region from around 7 cm to 25 cm from the beam; and a small beam proportional chamber to reconstruct tracks within the beam region (radius \(\leq 7\) cm). To achieve this the following improvements/modifications are foreseen:
Fig. 1: Schematic plan of the proposed apparatus
a) The drift chambers upstream of the Forward Spectrometer Magnet (FSM) denoted W1 and W2 have been replaced by 2 mm wire-spacing multwire proportional chambers (MWPC) P1 and P2. This will provide unambiguous pattern recognition in this region where the soft photon and electromagnetic backgrounds make drift chamber operation very difficult at high beam fluxes.

b) MWPC's POC, P3A/B have been added at the exit of the FSM aperture to improve the tracking efficiency close to the beam.

c) The NA2 Cerenkov counter (C2) has been replaced by an iron wall which will act as a filter for soft and electromagnetic background which is generated downstream of the target and also shields the trigger hodoscope H2 and the drift chambers W4/5 which are mounted directly behind it.

d) The drift chamber W3 situated behind the FSM has been reinforced by the addition of the drift chamber module W1. This provides momentum determination for the outgoing muon track(s) by using only the track information from the detectors in front of the iron wall.

e) MWPC's POD and P4/5 have been added in the region covered by W4/5 to allow for improved low angle muon detection and to provide a lever-arm from POC to POD for momentum determination of tracks in the beam region. P4/5 are interleaved with the drift-chamber modules W4/5.

f) The existing detectors in the beam region are further reinforced by the MWPC POD and the Hodoscopes BHC,D,E,F to allow the detection of small angle scattered muons from low Q² events.

Two basic triggers are proposed for the apparatus. The first, Trigger 1 requires a cluster multiplicity of > 2 in each of the trigger hodoscopes H1, H2 and H3 with target pointing in the vertical plane imposed by matrix coincidences between the hodoscopes H1, H2, H3 and H4. Horizontal target pointing will be demanded between the hodoscopes H1 and H2. To trigger on lower Q² events the Small Angle Interaction Trigger (SAIT) developed for experiment NA28\(^{12}\) will be utilised. Thus Trigger 2 will require the SAIT trigger plus a vertical target pointing track in H1234 and a horizontal target pointing track in H12. We estimate that these triggers will achieve levels of around \(10^{-8}\) per incident muon giving a trigger rate of \(\approx 100\) events per spill which is a rate which can be handled by the EM data acquisition and monitoring system. These triggers are a factor of \(\approx 2\) more efficient in accepting \(> 2\) muon events than the original NA2 triggers gaining a factor of 2 increase in luminosity.

Most of the proposed apparatus exists and has been run successfully for experiments NA2 and NA9. The new detectors which will be required are the hodoscope H2, the MWPC's P3A/B, the beam proportional chamber POE and the Uranium STAC.
3. PHYSICS INTEREST OF THE EXPERIMENT

With the apparatus discussed above and 40 days of data-taking the estimated luminosity of the experiment will be raised by a factor of around 500 over the existing NA2 multi-muon data (assuming a 70% data-taking efficiency). By combining this increase with the experimental results from the NA2 experiment we have calculated the event yields for charm and beauty production listed in Table 1. Using these numbers as a guide we now go on to discuss the principal physics topics covered by the experiment.

3.1 Upsilon Production

Measurements of the cross-sections for upsilon production will be of particular interest to see if, as one would naively expect, perturbative QCD calculations for this process are more successful than for the $J/\Psi$. Apart from the expected improvement due to moving to a higher quark mass there are many unanswered questions relating to the applicability of the higher order QCD graphs for the photon-gluon fusion process. These were invoked to try to explain the production of "inelastic" $J/\Psi$ events ($Z < 0.95$) which were seen by NA2 in roughly equal numbers to the "elastic" events ($Z > 0.95$) which can be well represented by the leading order graph. The models\(^3\) achieved only limited success for the inelastic $J/\Psi$'s and it would be of special interest to see if upsilon production exhibits a similar behaviour. The estimated number of events for this experiment should allow the study of the $Q^2$, $\nu$, Z and $P_T$-dependences of upsilon production which should provide a good basis for testing these ideas.

3.2 B-\bar{B} production

The study of open beauty production is also interesting and with this experiment definitive measurements can be made. Fig. 2 shows the total photoproduction cross-section ($Q^2 = 0$) calculated in leading order photon-gluon fusion together with the NA2 data points for open charm and beauty production. The calculations assume a simple counting-rule glue\(^13\) and take 1.5 GeV and 5.0 GeV for the charm and beauty quark masses respectively. The charm data are well described by the model and the NA2 measurement for B-\bar{B} production is also consistent with such a model. Clearly, as in the case of hidden or bound beauty discussed above the same arguments relating to the quark mass apply here and it would be of considerable interest to be able to establish a common production mechanism for both open and bound beauty quark systems.

The shape of the curve for the beauty cross-section in the threshold region is very sensitive to the hard gluon component of the nucleon whereas the large $\nu$ region is more sensitive to the beauty quark mass. This experiment is designed to work in the threshold region and is therefore more sensitive to the former. We note that any experiment using the higher energy muon beam foreseen at FERMILAB will have difficulty in studying this region and will be sensitive primarily to the large $\nu$ region. Thus
Table 1
Event yields for charm and beauty particle production
(after analysis cuts)

<table>
<thead>
<tr>
<th>Flavour</th>
<th>Final State</th>
<th>No of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beauty</td>
<td>Upsilon</td>
<td>~ 300</td>
</tr>
<tr>
<td></td>
<td>3-muons</td>
<td>~ 1000</td>
</tr>
<tr>
<td>B-\bar{B}</td>
<td>4-muons</td>
<td>~ 50</td>
</tr>
<tr>
<td></td>
<td>5-muons</td>
<td>~ 5</td>
</tr>
<tr>
<td>J/\psi</td>
<td>Z &gt; 0.95</td>
<td>2.5 x 10^5</td>
</tr>
<tr>
<td></td>
<td>Z &lt; 0.95</td>
<td>2.5 x 10^5</td>
</tr>
<tr>
<td>Charm</td>
<td>2-muons</td>
<td>1.4 x 10^6</td>
</tr>
<tr>
<td>D-\bar{D}</td>
<td>3-muons</td>
<td>5.0 x 10^6</td>
</tr>
</tbody>
</table>
Fig. 2: $\sigma_{\gamma p} \rightarrow$ heavy Quarks (nb) vs $\nu$ (GeV). The data points are EMC measurements taken from ref.3) and the curves are the Photon-Gluon Fusion Model predictions discussed in the text.
the two sets of measurements would be complementary and would provide a complete study of the subject. Here again, the projected event yield will allow an investigation of the \( Q^2 \), \( \nu \), \( Z \), \( P_T \) and angular dependences of the cross-sections for \( B \to \bar{B} \) production in this region.

In addition to the wrong-sign trimuon signal discussed above we estimate that we should see \( \sim 50 \) events in which the initial \( B \to \bar{B} \) pair decays to produce a 4-muon final state and \( \sim 5 \) events with 5-muons. Here the additional muons come from the decay of primary \( B \) mesons. Such additional events will prove valuable in helping to understand the processes by which \( B \)-mesons are produced and decay.

3.3 \( D^* \to D^0 \) Mixing

Theoretically the amount of \( D^* \to D^0 \) mixing is expected to be very small\(^{14} \). The present experimental limits are at the level of \( \sim 5\%\(^{15,16,17} \). By using the 1000 wrong-sign trimuon events from this experiment we anticipate that we will be sensitive to \( D^* \to D^0 \) mixing at the level of \( \sim 0.1\% \).

Fig. 3 shows the summed \( P_T^z \) distributions calculated for the decay muons coming from respectively \( B \to \bar{B} \) decay and from the \( D^* \to D^0 \) charm decay scheme discussed earlier. The curves come from the Photon-Gluon Fusion model for the region \( Q^2 > 0.1 \) GeV, assuming a minimum decay muon energy cut of 10 GeV. The two processes have very different dependences and at large \( P_T^z \) beauty decay dominates. By assuming that all of the signal at high \( P_T^z \) is from \( B \bar{B} \) production and parameterising the lower \( P_T^z \) region we can set a fairly precise limit on the amount of the total signal which could have come from \( D^* \to D^0 \) mixing.

3.4 Charm Studies

The copious production of final states containing charmed particles allows a significantly improved measurement of the content and distribution of the charm quarks inside the nucleon.

Earlier publications\(^{3,5,11,15} \) have shown that the production yields are well described by the Photon-Gluon Fusion Mechanism\(^1 \) but to date only upper limits have been set on the intrinsic charm content of the nucleon\(^{15} \). The reason for the latter was that the limit had to be derived using the NA2 charm dimuon signal only, as the luminosity meant that there were too few trimuon events to make a sensible comparison. The larger luminosity of the proposed experiment will provide a much improved study of this subject and will allow a clean separation of photon-gluon and intrinsic charm effects.
Fig. 3: Comparison of the sum $p_T^2$ distributions for decay muons coming from $D^+$ and $B$ decay.
Intrinsic charm is observed when one charmed quark fragments in the current fragmentation region and the other fragments in the target fragmentation region. The dimuon events have a contribution from this process which is expected to be significant in the medium to large $x$ region ($x > 0.3$). In the trimuon case however the events detected have both decay muons in the current fragmentation region so that intrinsic charm cannot contribute to this signal. Thus the difference between the charm dimuon and trimuon production rates at large $x$ allows a direct measurement of the intrinsic charm content of the nucleon.

The luminosity of this experiment will allow the hadronisation of heavy quarks to be studied in a much more direct way than has been possible in the past. By separating the forward and backward charm-jets in the 3-muon event sample one can study the contributions from hadronisation in both the $c\bar{c}$ system and the system including the spectator quarks in the nucleon. Deviations from the fragmentation seen in a clean $c\bar{c}$ environment such as that of $e^+e^-$ physics are expected. The high statistics also allow the study of the $W$-dependence of the hadronisation process which to date has not been possible.

By assuming a photon-gluon fusion production mechanism for elastic ($Z > 0.95$) $J/\psi$ production the gluon distribution for the nucleon can be determined. In view of recent data from the EMC which suggest that there may be differences between bound and free nucleon quark and gluon distributions it would be of particular interest to compare the gluon distribution derived from the EMC iron data with that from Uranium which is proposed here.

3.5 Rare Charm Decay Modes

In this section we briefly discuss a few additional measurements of charm decay which we estimate this experiment will be able to either measure or set upper limits on. In each case the decay mode is rare and to date no experimental measurement exists.

The NA2 experiment set an upper limit of $1.4 \times 10^{-2}$ (90% confidence level) on the branching ratio for the pure leptonic decay of a D-meson into a muon and a neutrino. Current theoretical estimates place the branching ratio in the region of $10^{-3}$ depending upon which particle(s) mediate the decay. Given the luminosity of this experiment we can improve the NA2 limit to $\lesssim 10^{-3}$ which will provide a very useful constraint on the particle(s) which mediate the decay.

The signature for these events is a dimuon in which a small amount of energy ($< 50$ GeV) is deposited in the STAC together with a large missing energy ($E_{\text{miss}} > 70$ GeV). The backgrounds to the signal come from a small residual acceptance for semi-leptonic decays ($D \to Ku\nu$) and from elastic $\tau$ lepton pair production. Both of these processes are calculable and are to some extent separable so that, given the current theoretical estimate of the branching ratio some leptonic events may be seen.
3.6 Other Possibilities

In addition to its ability to run with very high beam fluxes the apparatus described in this document has a large acceptance over a very wide kinematic region. Taking into account the improvements in the small angle region coming from the SAIT and the proposed MWPC system, the spectrometer has excellent single-muon acceptance for the kinematic region

\[ 0.10 < Q^2 < 200 \text{ GeV}^2, \quad 0.0003 < x < 0.8 \]

As this is a substantially larger kinematic region than that covered by any previous counter experiment we would like to point out that this provides an excellent opportunity to perform measurements of the nucleon structure function F2 and attempt to resolve some of the unanswered questions about the relative importance of higher twist effects and the A-dependence of the bound nucleon cross-sections. Such experiments would require around 17 days of data-taking per target running under similar conditions to those foreseen here. Apart from the Uranium STAC target it would be possible to extend the measurements by using liquid or passive heavy targets.

CONCLUSIONS

We propose an experiment to study beauty and charm muoproduction via semi-leptonic decays into multimuon final states. Using a slightly modified version of the existing EMC forward spectrometer and a Uranium target we can obtain a factor of 500 improvement in luminosity over previous measurements in this field.

This luminosity will enable detailed studies of upsilon and beauty meson production and provide valuable tests of the applicability of leading and higher order QCD production mechanisms of heavy quark states. By a detailed study of wrong-sign trimuon events we can substantially improve the experimental limit for amount of D^*\text{+} - D^*\text{-} mixing.

The copious production of charm dimuon and trimuon events will enable detailed studies of the hadronisation of heavy quarks and a comparison of the two signals provides an excellent way of investigating the intrinsic charm content of the nucleon. Elastic J/ψ production off the Uranium target will allow us to investigate the possibility of a variation in the gluon distribution with nuclear target. We propose also to measure pure leptonic decay rate of the D meson.
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IDEAS FOR A HIGH LUMINOSITY MUON PHYSICS DETECTOR WITH COMPLETE PARTICLE IDENTIFICATION

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ABSTRACT

Modifications of the existing EMC-NA9 spectrometer at the SPS muon beam by using a Time Projection Chamber (TPC) as vertex-detector and Ring Image Cerenkov (RICH) counters allow at least a factor 5 increase in luminosity and provide complete hadron identification. The compactness of the new detectors gives space for future 4π coverage for neutral particle detection.

1. INTRODUCTION

The existing EMC spectrometer\(^1\) at the SPS muon beam (Fig. 1) was conceived in 1974\(^2\). It uses the then available best technology for particle identification (multicell gas Cerenkov counters, aerogel Cerenkov counter, time of flight hodoscopes) covering the kinematical range of produced particles as completely as possible. As vertex detector a streamer chamber with inserted target of 1 m length is in use. Neutral particle detection is possible within the forward kinematical range \((\cos \theta_p)\) with a lead-glass calorimeter. For the study of hadrons produced in deep inelastic muon scattering especially in quark or gluon jets one is aiming for higher luminosities with complete charged and neutral particle identification\(^3\).

On the basis of acceptance studies using Monte-Carlo events we discuss the possibility to achieve this aim by using very modern detection devices:
- a TPC as vertex detector and as particle identifier for momenta below \(\approx 1\) GeV;
- liquid and gas ring image Cerenkov counters for a complete identification of charged particles in the momentum range from 0.7 GeV/c to maximum momentum.

The compactness of RICH detectors gives space in the vertex part of the spectrometer for implementation of e.m. and/or hadron calorimetric devices. The expected performance concerning the possible luminosity, estimates of the influence of background events, cost and timescale estimations are discussed.

2. ACCEPTANCE STUDY

As input for acceptance studies a sample of MC events generated according to the Lund model\(^4\) within the kinematical limits for the scattered muon of \(4 < Q^2 < 200\) GeV/c\(^2\), \(15 < y < 260\) GeV, \(E > 25\) GeV, \(\theta_{\text{Lab}} > 0.5^\circ\), \(40 < W^2 < 400\) GeV\(^2\) and \(0 < \omega/E < 0.9\) was used. The EMC-NA9 standard running conditions of 280 GeV incoming positive muons, vertex magnet field +1.5 Tesla, forward spectrometer magnet field -1.5 Tesla and the 1/2 degree trigger were applied.
Fig. 1  1981 set-up of the EMC-NA9 experiment with a streamer chamber (SC) vertex detector, multicell gas Cerenkov counters (C0, C1, C2), aerogel Cerenkov counter (CA), time of flight hodoscopes (F1,2,3,4) and lead glass array (LG).
As reference planes for the acceptance description the wire chamber planes behind the vertex magnet (PV2) and behind the forward spectrometer magnet (W3) are taken (see Fig. 1). To simplify the description two angles $\phi$ and $\theta$ as defined in Fig. 2 are used. They are given by connecting the impact point of a track on the reference plane with the centre of the target. Otherwise the EMC coordinate system is used:

- $x$: beam direction (pos. downstream)
- $y$: horizontal axis (pos. downstream left)
- $z$: vertical axis (pos. up).

![Diagram showing definition of acceptance angles $\phi$ (horizontal) and $\theta$ (vertical)](image)

**Fig. 2** Definition of acceptance angles $\phi$ (horizontal) and $\theta$ (vertical)

The resulting hit pattern at the vertex exit and the forward spectrometer exit are shown in Figs. 3 and 4 respectively. The corresponding distributions of momenta as a function of the horizontal deflection $\phi$ and the vertical deflection $\theta$ are shown in Figs. 5 and 6 behind the vertex and Figs. 7 and 8 behind the forward spectrometer. The momentum cutoff at about 0.5 GeV behind the vertex magnet and about 3 GeV behind the forward spectrometer magnet is due to the magnetic field settings.

![Hit pattern of MC tracks at PV2 behind the vertex magnet](image)

**Fig. 3** Hit pattern of MC tracks at PV2 behind the vertex magnet.

![Hit pattern of MC tracks at W3 behind the forward spectrometer magnet](image)

**Fig. 4** Hit pattern of MC tracks at W3 behind the forward spectrometer magnet.
Fig. 5 Momenta of tracks as function of horizontal deflection $\phi$ downstream of the vertex spectrometer

Fig. 6 Momenta of tracks as function of vertical deflection $\theta$ downstream of the vertex spectrometer

Fig. 7 Momenta of tracks as function of horizontal deflection $\phi$ downstream of the forward spectrometer

Fig. 8 Momenta of tracks as function of vertical deflection $\theta$ downstream of the forward spectrometer
3. **VERTEX MAGNETIC FIELD**

The performance of a Time Projection Chamber (TPC) as vertex detector or as photon detector in a Ring Image Cerenkov counter (RICH) is crucially dependent on the absence of field components perpendicular to the electron drift direction which is given by \( \vec{v}_{dr} \parallel \vec{E} \parallel \vec{B}_z \). For example the Lorentz angle \( \alpha = |\vec{v}_{dr} \times \vec{B}_t| / |\vec{E}| \) with standard values \( |\vec{v}_{dr}| = 5 \text{ cm/sec}, |\vec{E}| = 0.5 \text{ kV/cm} \) and assuming \( |\vec{B}_t| = 0.01 \text{ Tesla} \) produces after a 40 cm drift an offset of 4 mm (= 10 mrad).

In principle for the TPC vertex detector it is always possible to correct for Lorentz drifts by using the field map of the vertex magnet. The same is true for \( \vec{B}_t \) components out of the RICH-TPC plane. In the plane \( \vec{B}_t \) components are destructive for electrons drifting near the TPC walls and therefore have to be avoided. The actual field configuration of the EMC vertex magnet is to a good approximation radially symmetric\(^5\). In Figs. 9, 10, 11 are shown respectively the main field component \( B_z \) along the beam (x coordinate), the \( B_y \) component at \( y = 50 \text{ cm} \) as a function of \( x \) and the \( B_x \) component measured along the beam. The position of the inner coil boundary is indicated (± 1 m from the centre) as well as the position of the target, the TPC and the liquid RICH counter. The residual \( B_x, B_y \) components within the volume defined by the poles amounts to about 0.05 Tesla.

Possible magnet modifications to reduce \( B_x \) and \( B_y \) are under study\(^6\). These are:
- close the now open pole region by introducing iron plugs which can be shaped adequately. The possible maximum \( B_z \) field changes in this case from 1.5 Tesla to 2.3 Tesla;
- adding of compensating coils near the inner coil edges;
- widening of the magnet aperture but leaving the polepiece gap at 1 m distance.

Independent of the envisaged modifications we assume in the following no principal hindrance to the TPC vertex detector performance within the inner volume of the magnet. Nevertheless, the arrangement of RICH-TPC's inside the magnet has to be radially symmetric to avoid \( \vec{B}_t \) components in the plane of the TPC.

4. **THE TPC VERTEX DETECTOR**

A high multiplicity event taken from NA9 streamer chamber hydrogen data is shown in Fig. 12 looking onto the bending plane (x-y plane). On average a multiplicity of 6 tracks outside the beam region was measured. Taking into account the event topology the TPC shape was chosen as shown in Fig. 13 and put inside the 2 m\(^2\) pole region. The target of 1.5 m length and 7 cm\(^2\) is inserted protruding 30 cm upstream and ending 40 cm before the end of the TPC cage to give enough tracking length also for tracks emerging from the target end. The beam region is decoupled from the TPC over the whole length by a pipe of 10 cm\(^2\).
Fig. 9  $B_z$ component of the vertex magnet field along x at $y=z=0$ cm

Fig. 10  $B_y$ component of the vertex magnet field along x at $y=50$ cm and $z=0$ cm

Fig. 11  $B_x$ component of the vertex magnet field along x at $y=z=0$ cm
Fig. 12  Streamer chamber event taken from NA9 - Data on Hydrogen

Fig. 13  TPC shape in the bending plane. The liquid RICH counter is arranged at the downstream end of the TPC
Fig. 14  Layout of the TPC field cage. The outer surface of the beam pipe is also covered with potential strips.

Fig. 15  Layout of the TPC end plate.
A possible layout of the TPC field cage with two boxes of 30 cm height and drift distance, each away from the -6kV central plane, is shown in Fig. 14.

The TPC end plate construction with pad rows of varying density in x and y (near the target) and adapted to the event topology is shown in Fig. 15. The sense wires at +3.7 kV having 4 mm pitch and separated by the field wires at +0.4 kV are spanned in y direction 4 mm above the pad rows at 0kV. A further 4 mm above the sense/field wire plane is built a 2 mm pitch gridwire plane (or mesh) at 0kV. A third wire plane with 2 mm pitch is spanned 8 mm above the gridwires. It is acting as trap for incoming electrons by application of +100/-100 volts pairwise which are switched to 0 volts during the event recording. A summary of the main TPC parameters is given in Table 1. The $\Delta \rho / \rho^2$ momentum resolution achievable with the proposed layout is comparable to the resolution of the existing streamer chamber:

- TPC resolution $\Delta \rho / \rho^2 = 0.5\%$ to 1\% per GeV/$c^2$ \cite{7},
- streamer chamber resolution $\Delta \rho / \rho = (1+p)^2 \%$ \cite{1}

### Table 1

Main Vertex TPC Parameters

- height 2 x 300 mm
- length 1550 mm
- width 600/1450 mm conically shaped with 42.5° acceptance in the bending plane
- target 1500 mm long, 70 mm\* inserted in the TPC
- TPC field cage -6kV with beam pipe of 100 mm\*
- sense wire spacing 4 mm
- 21 pad rows with 8 x 8 mm\* pads (5 x 8 mm\* near the beam)
- row distance varying from 100 mm to 40 mm
- pressure 1 atm, gas mixture 80% Argon, 20% methane
- gate wire plane in front of the grid wire plane to avoid production of ions if no trigger takes place
- resolution: in $y \approx 250$ µm, in $z \approx 1$ mm (with 2 to 5 cm drift per µsec and with a 60 nsec clock readout), in $x$ defined by 4 mm sense wire pitch
- readout time $\approx 15$ µsec
- $z$ coordinate loss near the end plates $\approx 10$ mm if the trigger is formed in 500 nsec
- two track separation 2 x 2 cm\*
- $\Delta \rho / \rho^2 \approx 0.5\%$ proportional to $\sqrt{BL^2/N}$ with $L =$ track length and $N =$ number of pad crossings
5. PARTICLE IDENTIFICATION WITH THE VERTEX TPC

The mean track length of about 1 m within the TPC gives a mean number of 1 m/4 mm = 250 samples from the CCD or FADC electronics connected to the sensewires to provide a $\Delta E/\Delta x$ measurement with an accuracy of about $\sigma(\Delta E/\Delta x) = 5\%$.

The upper limits for identification with a $3\sigma$ separation are then $7$:

- $e/\pi < 8$ GeV/c
- $\pi/K < 0.75$ GeV/c (and 4 to 10 GeV/c)
- $K/p < 1.3$ GeV/c.

The lower limits are determined by the 3.5 cm radius target size. At 90° track angle, protons of less than 230 MeV/c (pions of less than 60 MeV/c) are trapped within the target material.

6. THE VERTEX LIQUID RICH DETECTOR

Particles with momenta greater than $\sim 750$ MeV/c are identified by a liquid RICH detector situated close to the downstream end of the TPC (Fig. 13) with a $\phi$ acceptance of about $\pm 42^\circ$. The radial arrangement takes into account the actual radially symmetric vertex magnet field and avoids $\vec{B}_z$ components in the RICH-TPC plane. Radial $\vec{B}_z$ components produce a Lorentz angle deviation which has to be corrected. The use of 1 cm C$_6$F$_{14}$ (FC72) radiator and 14 cm photon driftspace from the quartz window to the 4 cm thick RICH-TPC gives an overall thickness of about 20 cm. A possible modular arrangement of RICH-TPC's as shown in Fig. 16 takes into account increasing particle density towards the beam region which itself is deadend out. The inner modules about the bending plane have 10 cm driftlength ($\sim 2$ usec read out time), top and bottom modules have 2 x 15 cm drift length ($\sim 3$ usec) with only one detection grid in the middle. The outer modules have 40 cm driftlength ($\sim 8$ usec). The overlap with respect to the vertex-TPC size helps to detect the rings of $\sim 25$ cm$^2$ also for tracks leaving the vertex-TPC at the edges. The expected identification limits are $8$:

- $4\sigma-\pi/K$ - separation from 0.2 to 4.5 GeV/c,
- $4\sigma-K/P$ - separation from 0.7 to 8 GeV/c,

of which the lower limit is defined by detection of at least 3 photoelectrons.

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Fig. 16  Layout of the photon detector modules of the vertex RICH
7. THE GAS RICH DETECTORS

One gas RICH detector filled with C$_3$H$_2$(FC87) downstream of the vertex magnet with $\phi$-acceptance of $\pm$ 10° and one downstream of the forward spectrometer magnet filled with 50%/50% Neon/Argon mixture and of $\phi$-acceptance of $\pm$ 2.5° provide the identification of high momentum particles.

The TPC photon detector, modular shaped according to increasing particle density like in the case of the liquid RICH-TPC's, cover the detector entrance windows. The beam region is deadend out.

Parameters of the TPC-photon detectors are summarized in Table 2.

Table 2

Parameters of the RICH photon detector TPC's

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>- depth 40 mm</td>
<td></td>
</tr>
<tr>
<td>- size variable as function of particle densities to adapt total readout time (&lt; 10 nsec)</td>
<td></td>
</tr>
<tr>
<td>- gas mixture methane, isobutane and TMAE</td>
<td></td>
</tr>
<tr>
<td>- detection grid 4 mm pitch</td>
<td></td>
</tr>
<tr>
<td>- with 60 ns time digitisation the spatial resolution in electron drift direction is $\approx$ 1 mm</td>
<td></td>
</tr>
<tr>
<td>- quartz window towards the radiator volume</td>
<td></td>
</tr>
<tr>
<td>- gating grid in front of the OkV grid with $\approx$ 1.5 mm pitch</td>
<td></td>
</tr>
<tr>
<td>- sensitive amplifiers ($\approx$ 0.1 $\mu$A)</td>
<td></td>
</tr>
</tbody>
</table>

A spherically built mirror array of 2.5 m radius at 1.25 m distance behind the TPC's is used as focusing element in the vertex gas RICH detector. Similarly a mirror array of 10 m radius at 5 m distance is used behind the TPC's of the forward gas RICH detector. Assuming $N_0 = 100$ $cm^{-1}$ one expects about 40 photoelectrons per ring in the vertex gas RICH and about 22 photoelectrons in the forward gas RICH.

The identification limits are $^8$ for the vertex gas RICH detector:

$4\theta$-H / K - separation from 2.5 to 20 GeV/c,

$4\theta$-K/P - separation from 9.5 to 35 GeV/c.

Assuming a dominant contribution to the error of the Cerenkov angle measurement from chromatic aberration $^9$ and taking as dispersion for the Neon/Argon mixture the value $\Delta$n = 0.12 $\times$ 10$^{-5}$ the identification limits of the forward gas RICH are:
40-π/K - separation from 7.2 to 128 GeV/c,
40-K/P - separation from 25.5 to 270 GeV/c.

Lower limits are in each case fixed by the 3 photoelectron condition. The identification performance of all RICH detectors are summarized in Table 3. Fig. 17 shows the matching in momentum of identification in the vertex part of the proposed layout.

Table 3
Identification parameters of RICH counters

<table>
<thead>
<tr>
<th></th>
<th>LIQUID RICH C$<em>{6}F</em>{14}$ (FC72)</th>
<th>VERTEX GAS RICH C$<em>{5}F</em>{12}$ (FC87)</th>
<th>FORWARD GAS RICH 50% Neon/50% Argon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiator length N$_0$ in photo electrons (β=1, N$_0$=100cm$^{-1}$)</td>
<td>1 cm 20</td>
<td>1.25 m 40</td>
<td>5 m 22</td>
</tr>
<tr>
<td>γ threshold</td>
<td>1.6</td>
<td>17</td>
<td>48</td>
</tr>
<tr>
<td>40-π/k-separation</td>
<td>0.2-4.5 GeV/c</td>
<td>2.5-20 GeV/c</td>
<td>7.2 - 128 GeV/c</td>
</tr>
<tr>
<td>40-k/p-separation</td>
<td>0.7-8 GeV/c</td>
<td>9.5-35 GeV/c</td>
<td>25.5 - 270 GeV/c</td>
</tr>
<tr>
<td>Dominant contrib. to resolution δθ</td>
<td>radiator thickness</td>
<td>chromatic aberration</td>
<td>chromatic aberration</td>
</tr>
<tr>
<td>Focusing type</td>
<td>proximity focussing</td>
<td>geometric focussing</td>
<td>geometric focussing</td>
</tr>
</tbody>
</table>

Fig. 17 Matching of identification of the vertex detector system
Fig. 18  Results of the background event study by Atkinson et al. (Ref. 10)

8. BACKGROUND EVENTS

An extensive study\textsuperscript{10} of the handling of background events in a gas RICH
detector to be used in the CERN SPS OMEGA spectrometer was done by simulation of
identification of MC event tracks. Size and kinematical conditions within that
detector are very similar to the discussed vertex and forward gas RICH detectors.
The study shows that the identification efficiency does not drop from nearly 100% for
 multiplicities of background tracks below about 40 within a sensitive time of the TPC
photon detector of 3 \(\mu\)sec (Fig. 18). EMC data contain the average one halo muon
background track per 6 streamer chamber pictures taken with 1 \(\mu\)sec sensitive time
each.

9. POSSIBLE LUMINOSITY

A comparison of the actual (1982) luminosity for data taking on hydrogen and the
possible luminosity with the proposed spectrometer layout (Fig. 19) is done in Table 4.
An increase of at least a factor 5 seems to be achievable.

10. COST AND TIMESCALE ESTIMATIONS

The electronics cost for the vertex-TPC detector with 21 pad rows x 130 pads on
average per row gives 2730 pad channels. Plus 400 sense wire channels the total
channel number for 2 TPC endplates is 6260. All channels equipped with CCD's or
FADC's of channel price 300 SFR per channel give a total electronics cost of \(\approx 1.9\) MSF.
The TPC mechanics cost scaled down from a LEP detector TPC is 0.5 MSF. So the total
TPC cost sums up to \(\approx 2.5\) MSF.
Fig. 19  The new EMC experimental setup. For the description of non indicated parts, see Fig. 1 and Ref. 1.
A cost estimate for the three RICH detectors also obtained by scaling down from LEP detector costs gives in total 1.5 MSF, so that the proposed layout seems realisable for about 4 MSF. No cost for any vertex magnet modification is included.

A timescale estimation is given by taking timescales for the corresponding LEP detector prototype construction which are proposed to be 2 to 3 years.

**Table 4**

Comparison of luminosity parameters for μ-p scattering

<table>
<thead>
<tr>
<th>parameter</th>
<th>1982</th>
<th>future</th>
</tr>
</thead>
<tbody>
<tr>
<td>- target</td>
<td>1 m Hydrogen</td>
<td>1.5 m Hydrogen</td>
</tr>
<tr>
<td>- trigger</td>
<td>1/2 degree</td>
<td>1/2 degree</td>
</tr>
<tr>
<td>- effective spill</td>
<td>1.6 sec</td>
<td>1.6 sec</td>
</tr>
<tr>
<td>- primary intensity</td>
<td>55 x 10^{11} ppp</td>
<td>150 x 10^{11} ppp</td>
</tr>
<tr>
<td>- deep inelastic events</td>
<td>5 x 10^{-7}/muon</td>
<td>7.5 x 10^{-7}/muon</td>
</tr>
<tr>
<td>- muon energy</td>
<td>280(400)GeV</td>
<td>320(450)GeV</td>
</tr>
<tr>
<td>- vertex detector dead time</td>
<td>100 msec/20%</td>
<td>~ 10 μsec/0%</td>
</tr>
<tr>
<td>- recorded events</td>
<td>3 to 4/pulse</td>
<td>21/pulse</td>
</tr>
<tr>
<td>- luminosity factor</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>- good events</td>
<td>10 to 20%</td>
<td>~ 20%</td>
</tr>
<tr>
<td>- analysis</td>
<td>SC picture analysis in 8 laboratories</td>
<td>filmless</td>
</tr>
</tbody>
</table>
11. CONCLUSIONS

A high luminosity muon physics detector is feasible by using a TPC type vertex detector and RICH detectors for particle identification. The modification cost is about 10% of the cost of the existing apparatus and the construction time is about 2.5 years. The main advantages are:

- luminosity increase at least a factor 5,
- full range charged particle identification,
- very high identification granularity given by RICH detectors, (4 x 4 mm$^2$ in comparison to now 120 x 120 mm$^2$ at 3 m distance from the vertex) which allows identification of dense track topologies within jets,
- true 3 dimensional tracking in the vertex detector which provides nonambiguous track pattern recognition,
- filmless straightforward analysis of vertex detector data,
- lots of space for neutral detector devices in the proximity of the target to allow small size/low cost calorimetry over the full solid angle.

12. Acknowledgement

Thanks to V. Eckardt, H.E. Montgomery and T. Ypsilantis for discussions.

***

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HADRONIC FINAL STATES IN $\nu$ AND $\bar{\nu}$ EXPERIMENTS

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Abstract
An overview is presented of the experimental possibilities of the study of fragmentation in the BEBC bubble chamber, exposed to neutrino and antineutrino beams. Comparisons are made with other techniques: muon-hadron and electron-positron experiments. Possible improvements of BEBC are discussed that will improve our knowledge of the fragmentation.

1. INTRODUCTION

In the past, fragmentation processes have been studied in the BEBC bubble chamber, filled with $H_2$ and $D_2$ and using both $\nu_\mu$ and $\bar{\nu}_\mu$ as test particles. Since the study of fragmentation by the counter experiments in the same beam line has been restricted to subjects like dimuon search, and no definite plans for the continuation of these studies exist at the moment, the present discussion will be confined to BEBC. The features and possibilities of the bubble chamber and its filling liquids will be analyzed; a comparison will be made with other techniques like muon-hadron and $e^+e^-$ experiments.

For a continuation of the BEBC program in the second half of this decade, a number of experimental improvements have been suggested:

1. Construction of a forward spectrometer;
2. Construction of a calorimeter inside BEBC;
3. Implementation of methods of holographic photography;
4. Increase of statistics of the present experiments.

The impact of such improvements will be discussed in the coming sections.

2. THE STUDY OF FRAGMENTATION

The quantities important for the study of the fragmentation process are: fragmentation functions and their integrals in dependence of the parameters $W$ and $Q^2$, Feynman $x$ distributions etc. In the present bubble chamber experiments, the measured quantities have to be corrected for the energy of the invisible neutral particles, for measurement errors and, in the case of deuterium, for the uncertainty due to Fermi motion. The corrections are
generally made by means of Monte Carlo calculations in which the uncertainties are incorporated. The computations result in smearing factors which have to be applied to the measured data. It is the uncertainty of these factors, rather than their size which contributes to the systematical uncertainty of the final result. Fig. 1a shows the fragmentation function for negative hadrons (the leading charge) in the $\bar{\nu}$ interaction. The smearing functions are shown for hydrogen and deuterium in figs. 1b and 1c. Under the present conditions the detection probability for $\gamma$'s in BEBC amounts to nearly 20%. The Monte Carlo program utilizes this value.

![Fragmentation function of negative hadrons in $\bar{\nu}p$ interactions (left). Smearing functions for hydrogen and deuterium (right).](image)

The resulting curves show values in the neighbourhood of 1 in the region of small and medium values of the fragmentation parameter $z = E_h/\nu$, but show large fluctuations in the region of high $z$. It must be noted that the values of the smearing function are strongly dependent upon the distribution under study, so that large fluctuations indeed give rise to important uncertainties. The measurement of the fragmentation function in the high $z$ region is of great importance, for instance for the study of higher twist effects.

If fragmentation functions of positive particles are measured, the identification of protons plays a significant role. Protons may be reliably identified in the bubble chamber by means of a bubble density estimate for momenta up to 1 GeV/c. For higher momenta again corrections have to be applied for the underestimate of the proton energy if this particle is mistaken for a pion. The smearing curves show larger deviations from 1 in the
low z region than the ones displayed in figs. 1b and 1c.

Fig. 1c shows larger smearing factors than fig. 1b because of the Fermi motion in the deuteron. The difference, however, is not very large due to the predominance of the energy uncertainty over the Fermi motion. The high peak in the curves is due to measurement errors rather than to energy uncertainty: For an event with a particle with high z, nearly all energy is visible. However, measurement errors of the muon and the fast particle lead to a transverse momentum non-balance which, by the energy correction algorithm, is translated into a positive energy correction.

Figs. 1b and 1c also show the results of a 100% detection efficiency for γ's. This would be the approximate situation if an internal photon calorimeter were installed in BEBC. The figures, indeed, show smearing factors much closer to 1 for both hydrogen and deuterium, over a large region of z. The high peak at the end of the interval is not dramatically reduced, since it is not caused by energy mismeasurement. It should be pointed out that the presented curves have been calculated with the present energy correction algorithm (Bonn method). It is conceivable that in presence of the calorimeter more powerful algorithms may be designed which may disentangle the energy loss from the transverse momentum measurement error. However, in this case a new uncertainty will take over as the most important one: the uncertainty due to neutrons and undetected neutral strange particles. Then, real progress may only be obtained by a reduction of the depth of the fiducial volume that will decrease the measurement errors. The smearing factor could be considerably flatter in that case. This reduction would come in addition to the one caused by the calorimeter itself and could appreciably reduce the number of useful events by ca. 40%.

3. THE EXPERIMENTAL PROGRAM

We now turn to the experimental program of possible future BEBC experiments. The question has to be answered which problems in fragmentation are best answered by neutrino experiments employing the bubble chamber technique. For this purpose we shall divide the fragmentation process into three phases:

1. The primordial stage;
2. The quark-gluon fragmentation;
3. The decay of resonances.

4. THE PRIMORDIAL COLLISION

There are specific problems of the lepton-quark primordial collision that can be studied better in ν̅-hadron interactions than in μ-hadron or in e⁺-e⁻ interactions. This is due to the fact that a) ν and ν̅ test on the flavour of the accelerated quark, b) the u and d quark participate at equal
footing in $\bar{\nu}$ and $\nu$ experiments and c) that there are two diquark systems (uu and ud) in hydrogen and three in deuterium (uu, ud and dd) left over after the collision. As an example, fig. 2 shows Bjorken x distributions of $\Lambda$ production in $\nu$ and $\bar{\nu}$ interactions. The bubble chamber is specifically suited for the study of neutral strange particles, for which it has a nearly unbiased acceptance and therefore yields an optimal detection possibility of the strange flavour. Figs. 2a and 2b show a difference in x-distribution which indicates a larger contribution of the quark sea to the $\Lambda$ production by antineutrinos than by neutrinos. Indeed, the $\bar{\nu}$ may react with an $\bar{s}$ quark of the sea; the remaining s quark may have the right colour to combine with a ud-diquark to produce a $\Lambda$ hyperon.

\begin{figure}[h]
\centering
\includegraphics[width=0.7\textwidth]{fig2}
\caption{x-distributions of $\bar{\nu}$ and $\nu$-neutron events with $\Lambda$ production.}
\end{figure}

In the present experiments 3% of all charged current events show a $\Lambda$ decay, 5% a $K^0$ decay. It is clear that for a continued study of strange particle production the experiments need higher statistics, independent of further technical improvement of the bubble chamber.

Also charmed particles occurring in the final state of a neutrino interaction point directly to the primordial collision. Probably, the charmed quark is too heavy to allow the creation of $c\bar{c}$ quark pairs in the course of
the fragmentation of the colour string. In $\nu/\bar{\nu}$ reactions the charm production mechanism may be studied as well as the type of particle produced: $D, D^*, F, \Lambda_c, \Sigma_c$ etc.

For the detection of charmed particles in BEBC, the application of holographic methods is highly needed. A hydrogen run in BEBC with 40,000 charged current events would yield 260 detectable charmed particles if the spacial resolution were 100 $\mu$m. With a resolution of 50 $\mu$m the number would be increased to 1000. The experiment could yield information about the like-sign muon problem, inclusive reactions, $x$-distributions and fragmentation functions. It cannot be foreseen, however, which fraction of the data can be fully evaluated, for instance by 3-constraint fitting. Part of the events will be lost by the presence of too many neutral particles. It is clear that holography in BEBC combined with an internal calorimeter would considerably improve the situation.

5. THE QUARK-GLUON FRAGMENTATION

For the measurement of fragmentation functions of different particles, especially for the search for mass dependence of the fragmentation functions, particles must be individually identified in the bubble chamber. Proton-pion separation is limited to momenta below 1 GeV/c, as indicated before. Pion-kaon separation is nearly impossible under the present conditions. The detection of neutral strange particles facilitates the study of a limited number of processes. Fig. 3 shows the fragmentation functions and the Feynman $x$ distributions of $K^+\pi^-$ and $K^-\pi^+$ produced in $\nu$-deuterium interactions.

The availability of a calorimeter in BEBC would open up new possibilities for the study of fragmentation. Particles like $\eta, \omega$ and $\pi^0$ could be identified by individual $\gamma$-detection. The identification of protons would become possible by kinematical fitting in a far greater percentage of the cases if most neutral outgoing particles can be detected. According to an analysis made by J. Schneps it will also become possible to recognize most of the rescattering events in deuterium (events where both baryons are involved in the reaction) by making use of a kinematical algorithm. This algorithm works best with a maximum amount of information about neutral particles.

A special problem is the identification of neutrons for which the calorimeter only yields very limited facilities. At a limited rate, neutrons can be detected by secondary interactions in the chamber. Also the neutron energy may be measured for a fraction of the events. Fig. 4 shows the result of a Monte Carlo calculation, showing the secondary interaction rates for $n, K^+$ and $\bar{n}$ as a function of particle momentum, as being produced in charged current $\bar{\nu}n$ interactions. The vertical scale and the
Fig. 3  Fragmentation functions and $x$ Feynman distributions for $K^*(892)$ in $\nu$ interactions.

Fig. 4  Fraction of charged current $\bar{\nu}n$ events with a secondary interaction in BEBC as a function of particle momentum. Percentages refer to integrated values.
integral values show fractions of the charged current events in the $\bar{\nu}n$ channel. It becomes clear from the figure, that neutron detection is possible for neutrons of a few GeV/c. At higher momenta there is a strong $n-K^0$ ambiguity. Antineutrons may never be detected in this way.

Among the problems to be investigated with the bubble chamber are the study of charge flow in the fragmentation process, soft gluon effects (transverse momentum balance in the colour string) and the polarization of hyperons. For most of the problems a better particle identification and a better determination of total and individual energies would be desirable.

A number of problems in fragmentation can better be investigated in $\nu$-nucleon and $e^+e^-$ collisions. Here higher hadronic centre of mass energies and $Q^2$ values are needed than can be obtained in $\nu/\bar{\nu}$ interactions at the present beam energies. Among these problems is the question of correlation in rapidity between $K\bar{K}$, $B\bar{B}$ and $A\bar{A}$ pairs. A long range of rapidity must be available to find these correlations. Also first and higher order QCD effects in fragmentation (hard gluon effects) will only be important at higher hadronic energies than can be obtained in neutrino experiments with sufficient statistics. The same is true for hard gluon jets that probably are very rare at the present energies.

For the study of this part of the program, a bubble chamber would have to be equipped with good tools for the identification of particles going forward in the hadronic centre of mass. For this purpose a forward spectrometer would be appropriate. As being pointed out, however, the specific problems on hand can better be studied at higher centre of mass energies, the need of a forward spectrometer in BEBC is therefore strongly reduced.

6. RESONANCE DECAY

An important problem in the study of fragmentation processes is the distinction between particles that are directly created in the quark-gluon fragmentation and those that originate from directly produced resonances. As discussed in the previous section, the detection is possible of both $K^0$ and $K^0$ ($= K^0\pi$). In this way the ratio can be measured between vector meson and pseudoscalar meson production in the fragmentation process. With the present methods, identification is possible of $\Lambda^{++}$, $\Delta^0$, $Y^*$, $K^*$ and $\rho^0$. More possibilities would exist if more $\gamma$'s can be identified.

7. THE FERMILAB PROGRAM

Fermilab has higher energy, the bubble chamber will be equipped with holography and possibly with a calorimeter. However, the statistics is low and there seems not to be a real competition with the CERN program.
8. CONCLUSIONS

1. $\sqrt{v}$ experiments in BEBC yield interesting results, mainly by the dis-entangling of the primordial process.
BEBC has good detection facilities; the ability of particle identification is limited.

2. Of the possible improvements of BEBC, the construction of an internal $\gamma$-calorimeter and the implementation of holographic equipment seem most rewarding.

Acknowledgements

The author is indebted to dr. Jack Schneps and dr. Gunnar Ingelman for clarifying discussions.
\textbf{\( \nu_\tau \) PRODUCTION}

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\section*{ABSTRACT}

The possibilities for the production of beams of \( \nu_\tau \) and the detection of their interactions are reviewed.

\section*{1. INTRODUCTION}

It is important to establish the existence of the \( \nu_\tau \) as a distinct particle.

It is known that:

\[
\nu_\tau \neq \bar{\nu}_e \quad \text{and} \quad \nu_\tau \neq \bar{\nu}_\mu
\]

from the equality of the \((e\nu)\) and \((\mu\nu)\) branching ratios of the \( \tau \). From the absence of the decay modes

\[
\begin{align*}
\tau \rightarrow e\gamma & \quad \text{B.R.} < 6.4 \times 10^{-7} \\
\tau \rightarrow \mu\gamma & \quad \text{B.R.} < 5.5 \times 10^{-7}
\end{align*}
\]

there is indirect evidence against the equality, of \( \nu_\tau \) with \( \nu_e \) or \( \nu_\mu \) respectively. More direct evidence comes from accelerator produced neutrino beams:

\[
\begin{align*}
\nu_\tau & \neq \nu_\mu \quad \text{Bubble chambers at FNAL and CERN} \\
\nu_\tau & \neq \nu_e \quad \text{FNAL emulsion experiment.} \\
\nu_\tau & \neq \nu_e \quad \text{BEBC Beam Dump experiment 1979} \\
& \quad \text{(excluded at 90\% C.L.)}
\end{align*}
\]

However what is still lacking is a demonstration that \( \nu_\tau \) interact to produce \( \tau \) leptons (as \( \nu_e \) and \( \nu_\mu \) were shown to produce \( e \) and \( \mu \) respectively).

If beams of \( \nu_\tau \) were available then other physics aims would be to test \( \nu_\tau, \nu_\mu, \nu_e \) universality and to study the structure of the \( \nu_\tau \) interaction via the \( \tau\tau \) polarization. However for this physics known \( \nu_\tau \) fluxes and large numbers of interactions are required.

\section*{2. PRODUCTION OF \( \nu_\tau \) BEAMS}

Among the mechanisms which have been suggested are the following

(a) Dilepton production by the Drell-Yan mechanism

\[
p + N \rightarrow \tau^+ \tau^- + X \\
\begin{array}{c}
\nu_\tau \nu_n \\
\end{array}
\]

Because of the large mass of the \( \tau \) the production rates are expected to be \( \approx 10^{-8} \) \( \nu_\tau \)/proton.
(b) Beauty production

\[ p + N \rightarrow b + \bar{b} + X \]

Because of the smallness of the beauty production cross sections this process is only expected to yield \( \sim 10^{-7} \nu_\tau / \text{proton} \).

(c) F meson production

\[ p + N \rightarrow F + \bar{F} + X \]

\[ \nu_\tau \]

\[ \bar{\nu}_\tau \text{ etc.} \]

The yield of \( \nu_\tau \) from this process depends upon several factors. The decay \( F + \nu_\tau \) has not been observed but the absolute decay width can be predicted from the \( \pi \)-decay rate.

\[ \Gamma(F + \nu_\tau) = \frac{G^2 f^2 p \pi^2 (1 - m_\tau^2)^2}{8\pi m_F^2} \]

Hence

\[ \text{B.R.} \ (F + \nu_\tau) = \frac{t \Gamma}{\Gamma} \]

where \( t \) is the mean life of the \( F \), which on the basis of the few \( F \) mesons observed, is measured to be

\[ t = (2.9^{+1.8}_{-0.9}) \times 10^{-13} \text{ s} \]

and therefore \( \text{B.R.} \ (F + \nu_\tau) = (1.4^{+0.8}_{-0.4})\% \)

For the purpose of calculating rates I have used the traditional BR of 3\%, however the data indicates this may be optimistic.

Since \( F \) production cross sections are not well known it is usually assumed that \( \sigma_F / \sigma_D \) is given by the relative probability of the produced charm quark picking up an \( \bar{s} \), rather than a \( \bar{d} \) antiquark. From fragmentation studies in \((e^+ e^-)\) annihilations and lepto production this probability is estimated to be 0.2. The cross section \( \sigma_D \) is measured in the beam dump experiments to be \( \sim 17 \mu b \) and a differential cross section of the form

\[ E \frac{d^2 \sigma}{dp} = e^{-2P_x} (1 - |x|)^\lambda \]

has been assumed.

It is obvious from the above that the estimates of \( \nu_\tau \) production rates are subject to wide uncertainties.
3. DETECTION POSSIBILITIES

It must be borne in mind that, using a copper production target, the total rate of \( \nu_\tau + \bar{\nu}_\tau \) charged current interactions may be only a few percent of the total number of (prompt plus non-prompt) charged current interactions. Powerful detection techniques are therefore essential.

3.1 High Resolution Bubble Chamber

The use of holography seems to be the only possibility of achieving adequate resolution over a large volume. Tests which are being carried out for BEBC and for the FNAL 15-foot Bubble Chamber indicate that a resolution of 50 \( \mu \text{m} \) maybe obtainable over a large fraction of the visible volume.

Seventy percent of all \( \tau \) decays are one-prongs and therefore their detection is crucial. This means the detection of a kink and this can be characterised by the observation of an impact parameter or distance of closest approach \( \delta \). Calculations performed for a Fermilab proposal (2) show that if \( \delta > 100 \mu \text{m} \) can be detected then 30% of all 1-prong \( \tau \) decays would be observed. For decays into three or more prongs the efficiency should be much greater. Therefore an overall detection efficiency of \( \approx 40\% \) should be obtainable.

3.2 Kinematic Properties of \( \tau \)-decay

Charged current \( \nu_\tau \) events would have characteristics very different from \( \nu_\mu \) and \( \nu_e \) interactions and these can be exploited, probably in conjunction with high resolution photography, to isolate the signal.

3.2.1 "Balanced" Neutral Current Events

Most \( \nu_\tau \) charged current interactions involve no charged lepton in the final state. They thus have the topologies of neutral current interactions. However the energy and transverse momentum carried off by the final state neutrino are much less in the \( \nu_\tau \) events. Tests based on these features have been proposed (3).

3.2.2 Missing \( p_T \) in \( e\nu\bar{\nu} \) and \( \mu\nu\bar{\nu} \) events

Albright, Schrock and Smith (4) have proposed a selection based on the net transverse momentum \( p_T \) in a plane normal to the neutrino beam direction and the angles \( \phi_{\mu H}, \phi_{\mu H} \) between the transverse momentum of the hadrons and the lepton and net \( p_T \) respectively. \( p_T > 1 \text{ GeV/c}, \phi_{\mu H} > 90^\circ \) and \( \phi_{\mu H} > 120^\circ \) they obtain an acceptance of 22% for \( \nu_\tau \) interactions against only 0.9% for \( \nu_\mu \) charged current events.

In a contribution to this Workshop W. van Doninck and C. Wilquet have applied the technique of Multivariate Discriminant Analysis to this problem. Events of the type \( \tau \rightarrow \mu\nu\bar{\nu} \) and \( \nu_\mu \) charged current events were generated by a Monte Carlo method and each event was characterised by a number of kinematic variables, including those mentioned above. The analysis programme then determines the "canonical variable", formed from a combination of the input variables, which shows the maximum separation between the two event families.
The results are shown in fig. 1. It can be seen that for the same acceptance as the Albright et al. selection, the background from $v_{\mu}$ events is much lower. The points B and C represent different selection criteria put forward in two Fermilab proposals to search for $v_{\tau}$. The power of the discriminant analysis is evident and it can of course be applied to other decay modes of the $\tau$.

3.2.2 Discrete hadronic decay modes

Among the other distinctive decay modes of the $\tau$ are those into the resonances $A_1$ (7%) and $\rho$ (22%). The search would be made in neutral current type events. By requiring large transverse momentum of the resonance relative to the other hadrons in the event the background from neutral current interactions can be minimised.

4. BACKGROUNDS TO DECAY EVENTS

Charged current interactions of $v_{\mu}$ and $v_{e}$ can be eliminated as a source of background by the detection of the final state electron or muon. The backgrounds therefore come from the neutral current sample.

4.1 Strange Particle Production

The decay of $K^+$ or $\Sigma^+$ produced in neutral current interactions of $v_{\mu}$ and $v_{e}$ could simulate a $\tau$-decay event. However the rate of strange particle production is low
(\(\sim 5\%\) for \(\mu^+\) and \(\sim 2\%\) for \(\Sigma^+\)) and the \(k^\pm, \Sigma^+\) are predominantly of low momenta, whereas produced \(\tau\) will have momentum \(\sim 50\) GeV/c. If we require therefore a momentum of greater than 5 GeV/c and a decay within 1 cm of the vertex then we can estimate a background of approximately 3\% from \(\Sigma^+\) and 0.2\% from \(k^\pm\) given the level of \(\nu_\tau\) production assumed.

4.2 Charmed Particle Production

Single charmed particle production in neutral current interactions is forbidden. However associated production can occur via coupling to a \((c\bar{c})\) pair in the quark-antiquark Sea. The charmed content of the sea has been estimated to be (5-10)% and therefore the contribution of this channel to the total neutral current rate is \(\sim 10^{-3}\). This gives an estimated background from this source of \(\sim 3\%\) relative to the expected signal.

4.3 Close Interactions

Since heavy liquids are used with interactions lengths of \(\sim 125\) cms (Ne/H₂) or 60 cm (freon) there will be large numbers of interactions within 1 cm of the vertex. If the probability of interaction within 1 cm is (1-2)% and if there are on average 4 charged hadrons per event, then there will be approximately three times as many interactions as detected \(\tau^\pm\) decays. However there are several ways in which this background could be reduced to a manageable level. Firstly most interacting hadrons are of low momentum and a minimum momentum could be required; secondly the interaction must have the appearance of a decay i.e. correct charge and no evaporation stubs; thirdly the candidate decay should be azimuthally opposed, around the beam direction, to the other hadrons.

In conclusion therefore it appears that the background problems will not be insurmountable provided there is a good efficiency for detection of \(\tau\)-decays.

5. INTERACTION RATES

If we take for example BEBC as detector with a fiducial volume of 17m³ and a filling of heavy neon (\(\rho = 0.71 \) gm/cm³) and use the production parameters given in section 2 then we obtain the interaction rates given in the following table. The distance \(\ell\) is from target to detector and 400m corresponds to the present beam dump facility. A proton energy of 450 GeV has been assumed.

<table>
<thead>
<tr>
<th>(\ell) (m)</th>
<th>400</th>
<th>200</th>
<th>100</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\nu_\tau) cc events per (10^{18}) protons</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td>7.4</td>
<td>16.5</td>
<td>26.3</td>
<td></td>
</tr>
</tbody>
</table>
A conceivable experiment would therefore be a run of $10^{19}$ protons, with the chamber at 50m from the dump. This would yield 166 $\nu_\tau$ and 81 $\bar{\nu}_\tau$ charged current events. Good resolution holography should be possible over a small volume chamber and therefore approximately 100 $\nu_\tau$ decays would be detected. A proposal similar to this was put forward by D.R.O. Morrison in 1981.

6. COMPARISON WITH FERMILAB

An extensive programme of beam dump experiments is in preparation at FNAL. The design recently adopted consists of 9m of solid iron magnets followed by a very large superconducting magnet (50 Kgauss field and 8.4m in length). The facility is designed to shield a 32-inch bubble chamber at 58m, the 15-foot bubble chamber at 160m and an electronic experiment (E656) at 300m. The experiments should begin in 1986 and a proton energy of 800 to 1000 GeV will be used. I have therefore compared similar facilities at FNAL and at CERN, and have assumed an $5^{1/3}$ increase of the F production cross section with energy.

- FNAL 15-ft BC at 160m = 58 → 1000 GeV
- BEBC at 400m, 450 GeV = 29 → 800 GeV
- Small chamber at 50m at FNAL = 11 → 1000 GeV
- same chamber at CERN (450 GeV) = 6 → 800 GeV

However it should be noted that the comparison is per proton and that because the machine repetition rate at FNAL is five times lower than at CERN, the comparisons per unit time are less favourable to FNAL.

7. CONCLUSIONS

It is clear that for the construction of new facilities FNAL has the advantage of higher energies. However if current developments in holography permit (as is hoped) 50µm resolution over 12m$^3$ of BEBC and if the F production cross sections and branching ratios become sufficiently well known to predict reliable and appreciable event rates then a run using BEBC and the existing beam dump facility to detect the $\nu_\tau$ could be justified before 1986.

8. ACKNOWLEDGEMENTS

My thanks are due to Paul Bostock who wrote the programme to calculate the $\nu_\tau$ event rates. I am also grateful to D.R.O. Morrison and W. Venus for useful discussions.
REFERENCES

NEUTRINO OSCILLATIONS AT CERN

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This subject was worked out in a subgroup with contributions from the members of the P150 and P178 proposals, specially Baton, M. Neveu, A. Grant and B. Pietryck.

I. INTRODUCTION

There is neutrino oscillation when there is a transition between a neutrino of a given species and a neutrino of another species. As we believe in the existence of three kinds of neutrinos at least: $\nu_e$, $\nu_\mu$, $\nu_\tau$, one can have three ways of oscillation among neutrinos:

\[ \nu_e \leftrightarrow \nu_\mu \leftrightarrow \nu_\tau \]

The same being true among antineutrinos. In principle neutrinos and antineutrinos may behave differently: this is CP violation. But at our present level of sensitivity, CP is most probably conserved and we will treat neutrinos and antineutrinos on the same footing.

1.1 Principle of the search

Oscillations among neutrinos lead to an anomaly in the evolution of the beam. Two methods can be envisaged to find an effect:

- disappearance method

The flux decreases faster than normal when going away from the target.
Through a given area, the flux decreases faster than $1/R^2$. This is best tested with 2 detectors positioned at 2 different distances along the beam.

- appearance method

In a beam of a given flavor ($\nu$) one looks for neutrinos of a new flavor ($\nu_e$, $\nu_\tau$) at a distance from the target. One needs a good estimate of the initial contamination.

1.2 Phenomenology of oscillations

The probability of oscillation between 2 $\nu$ flavors is:

$$P = \sin^2 2\theta \sin^2 \frac{R}{L}$$

where $\theta$ is the mixing angle between the neutrinos, $R$ is the distance over which the oscillation is measured, $L$ is the oscillation length:

$$L = 2.5 \frac{E(\text{MeV})}{\Delta m^2(\text{eV}^2)} \text{ (m)}$$

with $\Delta m^2 = m_1^2 - m_2^2$

$m_1$ and $m_2$ being the masses of the mass eigenstates $\nu_1$, $\nu_2$. Oscillations among 3 neutrinos will start with one channel first, and we will only treat oscillations among two neutrino species. To have oscillations one needs:

- $\Delta m^2 \neq 0$ different $\nu$ must have different masses, at least one neutrino must be massive.
- $\theta \neq 0$ there must be mixing between lepton generations.

1.3 Theory

GUT's (grander than SU_5) suggest that:

- $\nu$ masses are to be expected
- the lepton number is unlikely to be conserved. Then GUT's like oscillations, but they do not give strict predictions:
the masses are model dependent with the loose constraints:

\[ 10^{-5} \text{eV} \lesssim m(\nu) \lesssim 10 \text{eV} \]

the favored mixing by analogy with quarks, seems to be between \(\nu_\mu\) and \(\nu_\tau\).

1.4 Present limits

All channels starting with \(\nu_e\), \(\nu_\mu\), \(\bar{\nu}_e\), \(\bar{\nu}_\mu\) have been investigated so far, usually as by-products of general neutrino interaction studies. The results come from very low energy (\(\bar{\nu}_e\) at reactors), low energy (\(\nu_e\bar{\nu}_\mu\) at LAMPF) medium energy (Gargamelle) or high energy (emulsion, 15'BC, \(\bar{\nu}_e\)BC).

The overall picture is given in Fig. 1, which is expressed in terms of the 2 independent parameters chosen to describe the oscillation: \(\sin^22\theta\) and \(\Delta m^2\). Channels involving \(\nu_e\), leave less room for oscillations than the channel \(\nu_\mu \leftrightarrow \nu_\tau\) favored by the theory.

1.5 Rules for improvement

There are 3 independent channels, each of them must be studied thoroughly. Concerning the sensitivity in the two parameters:

- the upper limit on \(\Delta m^2\) varies very slowly with the statistics of the search \((\sqrt{N})\), and it varies like \(E/R\). To improve on \(\Delta m^2\) one must lower \(E\), or increase \(R\).

- the limit in \(\sin^22\theta\), on the contrary, depends essentially on the statistics: it varies like \(\sqrt{N}\).

The rule is then: find a \(\nu\) beam, put a detector (or two) at a large distance and accumulate as many events as possible.

At CERN there are plenty of \(\nu\) sources; used as so, or not. We will consider different cases:
- a new experiment in the PS beam
- a $\nu_e$ beam pointing to BEBC
- an experiment in the SPS beam
- new beams extracted from the SPS.

Two of these possibilities have been worked out in detail in two pending proposals: P150 for the $\nu_e$ beam, P178 for the present SPS beam.

II. SEARCH FOR HEAVY NEUTRINOS IN THE PS BEAM

At low energy it has been suggested (U. Amaldi) to use the neutrinos produced in the beam feeding the AA or stored in the AA. This seems particularly interesting for the $\nu_e$ component coming from $\mu$ decays. In the PS beam there are already three experiments, searching for oscillations with existing detectors: COH and CHARM use the disappearance method between 2 distances along the $\nu_\mu$ beam, BEBC looks for the appearance of $\nu_e$.

One could envisage to improve the search in this beam with a heavy, fine grain, two detector experiment.

Instead, it is suggested to use this beam to search for neutrinos with mass in the range 1-100 MeV.

2.1 Decays of heavy neutrinos

In this mass range neutrinos called $\nu_H$ may decay into $e^+e^-\nu_e$ with life times which allow an experimental investigation:

$$\tau = 2.2 \times 10^{-6} \left( \frac{m_\mu}{m_\nu} \right)^5 \frac{1}{|U_{He}|^2} \quad (s)$$

$m_\mu$ and $m_\nu$ are the $\mu$ and $\nu_H$ masses respectively, and $|U_{He}|^2$ is the coupling strength between $\nu_\mu$ and $\nu_e$.

Such neutrinos may originate from oscillation of the initial $\nu_\mu$. Because the masses are very much apart, the oscillation length is tiny, and the overall effect is an admixture of a $\nu_H$ component in the dominant $\nu_\mu$ beam, in the
5. SPIN PHYSICS

A lot of activity has been devoted to spin physics during that workshop and is summarized in a report [19].

5.1 A Spin Test of QCD

The physics motivation is clear and ambitious. Due to the vector nature of QCD, the helicity of partons is conserved throughout perturbative QCD scattering processes. Only mass terms and more generally scalar interactions can flip it.

Elementary scattering processes have neat spin properties. For instance colliding $q$ and $\bar{q}$ couple only if their helicities are opposite.

This behaviour of spin in elementary QCD processes can be read from the hadronic spin behaviour provided one knows the relation between the spin orientations of the hadron and of its constituents. In the case of the proton and the $u$ quark this is known from SLAC $e^+p$ scattering. Fig. 17 shows how the leading $u$ quark has a tendency to carry the spin of the proton. The $d$ quark in the proton is harder to measure; it will be obtained from $e^-n$ scattering in the near future. One will therefore know the "dilution" of the spin of the constituent in the nucleon.

Hard scattering of polarized particles can be represented by a very transparent formula, simply deduced from the unpolarized case. Cross sections are just replaced by cross section asymmetries and normal structure functions by polarized structure functions (i.e. the difference of parton populations with parallel and antiparallel spin orientation relative to the nucleon spin). This gives:

$$\Delta_{AB} C_{AB} = \sum_{a,b} \int \frac{d\Omega}{4\pi} \int d^4x \frac{d\Delta^a_A(x)}{d\Delta^b_B(x)} \Delta_{ab} \langle f | e^2 \Delta_f^{ab} (x, Q^2) \rangle$$

with $C_1 (x, Q^2) = \sum_f e^2 \Delta_f^{ab} (x, Q^2)$

5.2 First Problems

Perturbative QCD predicts that any single spin effect vanishes.

However strong spin effects are exhibited by the simplest experiments [20]. For instance Fig. 18 shows the polarization of inclusively produced hyperons. It is quite large up to high $p_T$ where QCD processes should dominate. Various explanations, involving final state interactions or various types of disguised scalar terms, have been put forward [21] and, as it is, this result cannot be used now as a counterproof of QCD.

A crucial test would be to align one spin in the initial state and see whether or not this polarization is transmitted to the final one. One should therefore study double spin processes. But, in the hyperon case for instance, the theoretical prediction is not unique since several processes can compete to produce these high $p_T$ hyperons.

5.3 Technical Assessment

In order to study the feasibility of such experiments one should adopt realistic numbers for polarized beams, targets and the relevant set ups.
For beams we have already seen that only a polarized accelerated beam can provide much intensity: $10^{10}$/sec, as a conservatory estimate, versus a few $10^8$ for a $\Lambda \rightarrow p$ beam.

For target we will adopt also a conservative choice: 20 cm of irradiated NH3 ($p_{\text{eff}} = 0.18$) leaving for the future most performing solution like LiD ($p_{\text{eff}} = 0.35$).

Table 1, from the report by N.S. Craigie et al. [19] indicates what one can expect for most of the interesting processes: the field is clearly very broad.

One personal remark however is that many numbers, for instance luminosities and acceptances, in that list are still somewhat overestimated or stretched to values which look hardly realistic, and therefore I feel that a new iteration, with a critical input from the groups explicitly or implicitly quoted as candidates, is necessary to reach a fully realistic program.

In photoproduction the field is limited by the technical impossibility to get helicity states. One must therefore concentrate on transversally polarized photons and study the azimuthal asymmetries in the production of pairs or quarks, due either to higher order corrections or to the mass in the case of heavy quarks. For instance the azimuthal distribution of $c\bar{c}$ pairs produced by transversally polarized $\gamma$ [22] is probably measurable in experiments of high sensitivity, like a beam dump where the muons from semi-leptonic decay are selected at high $p_L$ and/or $p_T$ in such a way that they remember closely the parent quark direction.

In conclusion, a very important work on the feasibility of polarization experiments has been started and should go on. Magnificent achievements in polarized sources, targets and acceleration have already been reported.

6. **INTERMEDIATE ENERGIES: EXCLUSIVE PROCESSES**

In the past elastic or exclusive scattering at intermediate energies was an important activity in high energy physics. The decline of Regge-type phenomenology led to some loss of interest in such processes. However it is becoming clear now that, in the QCD picture, coherent effects, simply reflecting the fact that partons are bound in the nucleon, cannot be ignored and may even be a source of information on this bound state. The exclusive limit is therefore an interesting and critical region from this point of view and, even if not much activity is presently devoted to this field, one should leave the door open to future works.

As noticed during the workshop [23] quite spectacular behaviours arise at SPS energies for exclusive processes. For instance Fig. 19 shows the energy behaviour of $d\sigma/dt$ at fixed large value of for elastic $pp$ scattering: after the steep fall at low energy, it flattens out in the ISR domain. At low energy the parametrization is consistent with the CIM diagram (Fig. 20a and legend) ; at high energy it seems to favour the multiple scattering processes (Fig. 20b). The transition is within the SPS energy domain.

If one compares $p\bar{p}$ and $pp$ elastic scattering one observes another dramatic effect, shown in Fig. 21. The very precious behaviour of $p\bar{p}$ [24] compared to $pp$ could indicate that CIM type processes are unimportant for $p\bar{p}$. Other not understood features are the
This experiment would improve substantially on the Gösgen result, in the region of low mixing angles. A previous BEBC result on $\nu_e \rightarrow \nu_\tau$ was based on 100 events, the present one would gather 1300 events.

3.3 NA14 beam

For completeness it has been pointed out (D. Treille) that the NA14 beam is also an enriched $\nu_e$ beam with

$$\frac{\nu_e + \bar{\nu}_e}{\nu_\mu + \bar{\nu}_\mu} \sim 0.2$$

The CERN territory extends behind this beam, such that one could install an experiment $\sim 2$ Km away from the target. With a 100 ton detector, this would give after one year of data taking a limit:

$$\sin 2\theta \Delta m^2 < 1.5 \text{ eV}^2$$

quite good in this channel.

IV. THE JURA PROPOSAL (P178).

This proposal uses the present SPS $\nu_\mu$ beam

4.1 Philosophy of the search

This experiment is the only one to look at the same time at oscillations, with the appearance and the disappearance methods. Being a fine grain detector it can identify electrons either from $\nu_e$ or $\nu_\tau$ interactions; being at high energy it can select unambiguously NC and CC events: the disappearance method is here the comparison at two positions along the beam of the ratio NC/CC. This ratio is in first approximation independent of the detector sizes, and of the beam spectra.

4.2 Advantages of high energy

At high energy it is easy to identify $\mu$, one can then select NC and CC
and use the method described previously which has small systematic errors. Also the background from cosmic rays is easier to reject.

At high energy rates are higher because of increasing cross-sections. This explains the improvement over low-energy experiments in the region of small mixing angles.

Last but not least $\nu_\tau$ is no longer sterile. This fact amplifies the effect of oscillations into $\nu_\tau'$, and if oscillations are found, this could be the way of studying $\nu_\tau$ interactions. But the probability of oscillations varies like $(R/\xi)^2$ : High energy means large distances.

4.3 Experimental set-up

Fortunately, as seen in Fig. 5, the SPS beam goes up with a slope of 4%. It reemerges from the Jura mountain at a point ~ 17 km from the present site, in a place actually easily accessible.

The set-up is then composed of: a near detector on the CERN site, and a far detector in the mountain. The two detectors have the same structure, first an electron calorimeter based on the flash-tubes + 3 mm iron layers technique developed at Saclay for a large proton lifetime experiment, followed by a magnetised iron muon spectrometer. The far detector has a fiducial mass of 100 tons.

4.4 Results

Fig. 6 shows a comparison of the CDHS and CHARM experiments at PS energy, with the Jura experiment, searching for the disappearance of the incoming $\nu_\mu$ beam.

Fig. 7 shows a comparison of the BEBC experiment at PS energy, with the Jura experiment, searching for the appearance of a $\nu_e$ component in the dominantly $\nu_\mu$ beam.

But the Jura experiment uses both methods. These two independent measurements of oscillations are correlated: what has disappeared must have reappeared.
in a new flavor. This correlation is shown in Fig. 8, for different hypothesis on the origin of the oscillation.

V. FARTHER AND FARTHER.

If in five year time oscillations are still unfound, and if theorists have not decided that neutrinos are massless after all, one will want to improve further the limits reached by experiments such as the Jura one.

Using still the \((\text{R/E})^2\) law, this can be done by going farther away. To stay in Western Europe there will be at least two very large detectors ideally suited to make neutrino interact : the Frejus and the Gran Sasso detectors. Fortunately the mass scales with the distance : 1000 tons for the Frejus, 10 000 tons for the Gran Sasso, and the number of events, obtained with \(5 \times 10^{18}\) pot and a beam of the SPS type, is not negligible.

Details of possible beams have been studied by B. Pietryck. They do not present unsurmountable difficulties being underground and necessitating only a 300 m tunnel for the decay volume. By scaling the parameters of the Jura experiment, the limits which could be achieved are summarized in the table:

<table>
<thead>
<tr>
<th></th>
<th>Jura</th>
<th>Frejus</th>
<th>Gran Sasso</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass (tons)</td>
<td>100</td>
<td>1000</td>
<td>10 000</td>
</tr>
<tr>
<td>distances (km)</td>
<td>17</td>
<td>135</td>
<td>725</td>
</tr>
<tr>
<td>NC events</td>
<td>5 000</td>
<td>800</td>
<td>275</td>
</tr>
<tr>
<td>limit on sin 2(\theta) (\Delta m^2)</td>
<td>0,15 eV(^2)</td>
<td>0,03 eV(^2)</td>
<td>(5 \times 10^{-3}) eV(^2)</td>
</tr>
</tbody>
</table>

Indeed the limits continue to improve with increased distance, and the last limit reaches the domain up to now considered reserved for atmospheric neutrinos.
VI. CONCLUSIONS

The problem of neutrino masses is essential to our understanding of Nature. There are experimental hints pointing to the existence of massive neutrinos:

- astrophysics puzzles (missing mass, black halo) would like neutrinos of mass $\sim 5$ eV and 30 eV,
- The tritium decay experiment giving the result $m_\nu \sim 30$ eV is still with us,
- in double $B$ decays, experiments and interpretations of the results are very difficult, some analysis give $\nu$ masses of order $\sim 10$ eV.

On the theoretical front, it seems that $SU_5$ is not yet the final theory. All GUT's grander than $SU_5$ give a mass to the neutrinos, although without firm prediction.

For these reasons it would be a pity if CERN were to stop prematurely this kind of search, which is one of the few going beyond the already old physics of the 100 GeV scale.
Fig. 1 - Present experimental situation in the 3 channels
\[ \nu_e \leftrightarrow \nu_{\mu}, \quad \nu_e \leftrightarrow \nu_{\tau}, \quad \nu_{\mu} \leftrightarrow \nu_{\tau}. \]

Fig. 2 - Possible limits in a search for heavy neutrinos via decays into \( e^+ e^- \nu_e \).

Fig. 3 - Schematics of the \( \nu_e \) beam in Proposal 150.

Fig. 4 - Limits in the search \( \nu_e \rightarrow \nu_{\tau} \) in the case of Proposal 150.

Fig. 5 - SPS Neutrino beam profile across the Jura mountain.

Fig. 6 - Result of the Jura and the PS experiments in the disappearance method.

Fig. 7 - Results of the Jura and BEBC experiment in the appearance method.

Fig. 8 - Correlation between appearance and disappearance methods in the Jura experiment.
Fig. 2
Fig. 3

Fig. 4
Fig. 5
$\nu_\mu \rightarrow \nu_e$

$2\sigma$ limits from comparison of $\nu_e, \nu_\mu$ rates

Fig. 6
Fig. 7
Fig. 8
FUTURE POSSIBILITIES FOR MEASUREMENTS OF
SEMILEPTONIC NEUTRAL-CURRENT PROCESSES AT THE SPS

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ABSTRACT
Some possibilities for improvements of measurements of semileptonic neutral-current interactions of neutrinos on nuclei are discussed in the context of the SPS fixed-target programme.

1. INTRODUCTION

In the last decade, the study of semileptonic neutral-current neutrino interactions has been an important testing ground for the electroweak theory. In this report the need for future measurements will be discussed in the context of the SPS fixed-target programme. No attempt will be made to give a complete review of the experimental status of these measurements; the reader is referred to excellent review papers existing in the literature1).

The theory of electroweak interactions can be approached by experimenters in two different ways: one is to assume its validity and to measure the value of its only free parameter, \( \sin^2 \theta \), in different reactions; the other approach is to test the validity of the theory by measuring a combination of quantities for which the theory provides a prediction. The difference between these two approaches will be made more clear in the following sections.

Section 2 of this report deals with possible future improvements of the measurements of the left-handed and right-handed couplings of up and down quarks separately. Section 3 summarizes possibilities of high-precision measurements of \( \sin^2 \theta \). Section 4 is devoted to the coupling of heavier quarks and some other topics in semileptonic neutral-current neutrino interactions.

2. MEASUREMENT OF COUPLING CONSTANTS OF LIGHT QUARKS

By measuring the left- and right-handed coupling constants of the u and d quarks separately (\( u_L \), \( u_R \), \( d_L \), and \( d_R \), respectively), valuable information is obtained, on the basis of which different models may be disproved. It is for this reason that these quantities should be measured with a precision as high as possible. To set a reasonable aim, a comparison could be made with the accuracy reached for the coupling constants of the heavier quarks at LEP. For c and b quarks (and t quarks eventually) a statistical accuracy of a few per cent can be achieved for \( 10^6 \) to \( 10^7 \) \( Z^0 \) decays.

To determine the coupling constants separately it is not sufficient to measure cross-section ratios on isoscalar targets; these measurements provide \( u_L^2 + d_L^2 \) and \( u_R^2 + d_R^2 \) by combining neutrino and antineutrino data. In order to separate the contributions of u and d, two ways are open: one is to start with a different mixture of u and d, by measuring on a proton or neutron target; the other is to separate u and d by tagging the final state with the charge of pions in the current fragmentation region. Of course both methods can be used simultaneously.
At CERN these measurements have been performed with BEBC filled with hydrogen or deuterium. A deuterium filling has the advantage that both protons and neutrons are available simultaneously, where all four coupling constants can be obtained in one experiment, while a hydrogen filling has the advantage that it is a pure proton target. In the following a few measurements obtained with BEBC in the past and a few future possibilities are discussed. In Table 1 both presently available data on the neutral-current to charged-current (NC/CC) cross-section ratio of neutrinos on protons, $R_p^\nu$, and expectations are summarized for the different options.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Beam</th>
<th>Target</th>
<th>$R_p^\nu \pm \sigma$</th>
<th>Cuts</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEBC + EMI</td>
<td>WBB</td>
<td>H$_2$</td>
<td>0.51 ± 0.04</td>
<td>$E_H &gt; 5$ GeV, $p_H &gt; 4$ GeV, $p_H &gt; 1.5$ GeV</td>
<td>$R_n^\nu$ also obtained</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D$_2$</td>
<td>0.48 ± 0.04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BEBC + EMI + TST</td>
<td>WBB</td>
<td>H$_2$</td>
<td>0.49 ± 0.05</td>
<td>Soft, effectively: $E_H &gt; 2$ GeV, $p_H &gt; 1$ GeV</td>
<td></td>
</tr>
<tr>
<td>BEBC + EMI + IPF</td>
<td>WBB</td>
<td>H$_2$</td>
<td>± 0.02</td>
<td>$E_H &gt; 5$ GeV, $p_H &gt; 2.5$ GeV, $p_H &gt; 0.75$ GeV</td>
<td>$R_n^\nu$ also obtained</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D$_2$</td>
<td>± 0.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BEBC + EMI + IPF + e.m. calorimeter</td>
<td>WBB</td>
<td>H$_2$</td>
<td>± 0.005 (stat)</td>
<td>Soft cuts approx. like TST</td>
<td>$R_n^\nu$ also obtained</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D$_2$</td>
<td>± 0.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NBB</td>
<td>D$_2$</td>
<td>± 0.02</td>
<td>$\pi^+/$\pi$^-$ ratios</td>
<td>also obtained</td>
</tr>
</tbody>
</table>

2.1 Present data

2.1.1 Solution I: "bare" BEBC + EMI

In this solution the bubble-chamber was used together with the inner and outer external muon identifier (EMI) planes for the identification of muons$^2$. The major background problems to be solved for this type of measurements are: background induced by neutral hadron interactions in the fiducial volume, electronic inefficiency of the EMI confusing CC events with NC events, and a cut in the muon momentum ($p_H$) of 4 GeV/c, below which the muons cannot be identified any longer with the EMI. In order to obtain a clear sample of NC interactions only events are accepted with a total energy of the hadronic system $E_H$ above 5 GeV. For further purification of the samples the total visible transverse momentum of the event, $p_T$, is required to be larger than 1.5 GeV/c. Only 30% of the events satisfying the $E_H$ cut survive the $p_T$ cut. In Fig. 1 is shown the way in which the background is reduced by several cuts in $p_T$, as well as how many events survive the cuts$^3$. The actual values of the cuts were chosen by balancing systematic and statistical errors. It should be mentioned
that the estimated uncertainties in the various corrections are roughly: 40% of the correction for neutral hadron interactions, 30% for the correction for EMI electronic inefficiency, and 10% for the cut in muon momentum.

2.1.2 Solution II: BEBC + TST + EMI

A track sensitive target (TST) was placed inside BEBC containing liquid hydrogen of \( \sim \frac{1}{8} \) of the total fiducial mass. The TST was surrounded by a heavy mixture of neon and hydrogen.

In return for the loss of a factor of 5 in fiducial mass, energy carried by neutrals (especially photons) is measured with much higher efficiency than in BEBC filled completely with hydrogen or deuterium. The reconstruction of the final state is more complete, allowing a more reliable determination of kinematic quantities such as the total energy, total longitudinal and transverse momentum, etc. Full use of this feature was made by applying a multidimensional analysis (stepwise discriminant analysis) whereby a separation on an event-by-event basis into the classes NC, CC, and neutral hadron-induced background was achieved\(^5\). The quality of the separation is illustrated in Fig. 2. The EMI was only used to initiate the analysis, but not for the final event selection. The efficiencies reach unity for \( E_H \) above 2 GeV and \( p_T \) above 1 GeV/c approximately, thereby making use of essentially all interactions in the fiducial volume.
It is shown in Table 1 that, although the total number of interactions was much smaller, the final sensitivity equals that of the measurements discussed in the previous section.

2.2 Future possibilities

2.2.1 Solution III: BEBC + EMI + IPF

BEBC is presently equipped with the addition of an internal picket fence (IPF) covering almost the complete circumference of the chamber body. This system records the position and timing of hits deposited by charged tracks (entering or leaving the chamber) and of conversion products of neutrals. It is a valuable tool to separate events recorded on film by the timing information provided by tracks leaving the chamber\textsuperscript{6)\textsuperscript{)} (Fig. 3).
Some data have already been taken with the IPF installed. A preliminary analysis of these data indicates that a large reduction of the background induced by neutral hadrons can be achieved\(^7\). The additional timing information will certainly help in reducing problems arising from noise and backgrounds in associating tracks with EMI hits. A large part of the electronic inefficiency of the inner EMI plane can be removed by combining the inner EMI plane and the IPF information. The association of low-energy muons will be more efficient because three, rather than two, points are available to follow these curled tracks.

These improvements can only be made more quantitative once the presently available data are fully analysed. For the moment it is expected that lowering the \(p_T\) cut to half its value is possible, while keeping the systematic error down by a factor of 2. With a \(p_T\) cut of 0.75 GeV/c twice the number of events is used for the same exposure. A more reliable interpretation of the measured cross-section ratios will be possible in terms of the coupling constants since a larger fraction of the structure-function integral is measured. Balancing statistical and systematic uncertainties a net improvement by a factor of 2 compared to the present results seems achievable.

2.2.2 Solution IV: BEBC + EMI + IPF + electromagnetic calorimeter

Some time ago it was proposed to extend the capabilities of BEBC by installing an electromagnetic calorimeter inside the chamber. The advantage of such a device for the type of physics considered can be estimated from the TST results. The determination of the electromagnetic energy is at least equivalent to what was achieved with the TST, and is available for the complete fiducial volume. Results of detailed studies for a deuterium exposure in the narrow-band beam (NBB) of a total of \(6 \times 10^{18}\) protons on target can be found elsewhere\(^8\). Some numbers are summarized in Table 1 and Fig. 4. In this study both

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Fig. 4 Capabilities of BEBC + electromagnetic calorimeter for measurement of coupling constants in the NBB\(^8\)
the cross-section ratios, differentiated into the y variable, and π⁺/π⁻ ratios were combined in order to achieve an improvement of a factor of 5 to 6 in the measurement of the left-handed coupling constants. To measure the pion ratios, the combination of the good definition of the kinematics of the events and the knowledge of the energy spectrum of the beam gives a much better definition of the current fragmentation region, as required for such measurements. Another study was made of a hydrogen exposure in the wide-band beam (WBB). With a neutrino exposure corresponding to \(4 \times 10^{18}\) protons on target a statistical uncertainty of \(\pm 0.005\) in the quantity \(R_p^0\) can be obtained\(^9\). The possibility of a precision determination of \(\sin^2 \theta\) and a discussion on the systematics one has to worry about will be given in another section. For the case of deuterium exposed to the WBB, the information from the electromagnetic calorimeter can provide a valuable improvement in the reduction of problems due to rescattering, which can cause confusion between events originating from proton or neutron interactions. Altogether the conclusion that the installation of an electromagnetic calorimeter inside BEBC will significantly improve semileptonic NC studies seems largely justified.

3. **HIGH-PRECISION MEASUREMENTS OF \(\sin^2 \theta\)**

Before discussing high-precision measurements of \(\sin^2 \theta\) one should first have a feeling as to which precision is desirable.

One way of defining the aim in precision is to consider the influence of higher order corrections to the predictions. The prediction of the mass of the \(Z^0\) from semileptonic neutrino interactions differs whether one uses the lowest order approximation or the second-order one. The difference of the two mass predictions \(\Delta M(Z^0)\) turns out to be 5 GeV for this process\(^1\). Assuming that the \(Z^0\) mass will be measured directly at \(e^+e^-\) machines to a precision better than 100 MeV, the neutrino prediction can then be used to measure the effects of radiative corrections. To be sensitive to the gauge nature of the theory one would like to measure \(\Delta M(Z^0)\) with \(\pm 7\sigma\) significance\(^1\), setting the aim of a precision of \(\pm 0.005\) in \(\sin^2 \theta\). There are other reasons to aim for high precision. One would like to demonstrate unambiguously that the weak NC has a right-handed component, as predicted by the theory, where it is generated by the mixing with the electromagnetic current which is a vector.

The existence of the right-handed component of the quark currents, \(g_R^2 = (u_R^2 + d_R^2)\), has only been demonstrated in a model-independent way to \(3\sigma\) different from zero. Also for this quantity one would prefer to have at least a \(\pm 7\sigma\) determination. At \(e^+e^-\) machines the separation of the left- and right-handed parts of the couplings requires polarized beams.

The parameter \(\rho\), describing the relative strength of the NC and CC, is fixed in the theory to unity to lowest order if the simplest structure of the Higgs fields is assumed. Indeed present measurements indicate that \(\rho\) is close to one. In second order, the effect of radiative corrections on the W-propagator changes the value of \(\rho^2\) by \(\sim 1.5\%\)\(^1\). (The corrections are sensitive to large mass splittings of multiplets.) Therefore a measurement of \(\rho^2\) to better than 1% would be desirable, though hard. At present this can only be achieved by neutrino scattering, since there it involves the measurement of a ratio. The eD asymmetry experiment is insensitive to this number\(^1\). Clearly such a high precision requires a high-statistics experiment with good control over systematic uncertainties. In addition, uncertainties in theoretical interpretation of the measurements need special consideration. Two possible scenarios for reaching high precision will be discussed.
3.1 The CHARM Collaboration detector exposed to a quadrupole-focused beam

With an isoscalar target a measurement of $\sin^2 \theta$ can be obtained by measuring the ratio $R$ of NC to CC events in a neutrino beam (the corresponding antineutrino ratio $\bar{R}$ is insensitive to $\sin^2 \theta$) or by exploiting the Paschos-Wolfenstein (P.W.) relation\(^\text{13}\), using both the neutrino and antineutrino NC/CC ratio.

The CHARM Collaboration has obtained the NC/CC ratio by recognizing NC and CC interactions on an event-by-event basis in a NBB exposure of $1.5 \times 10^{18}$ protons on target\(^\text{14}\). Evaluated in Born approximation, these measurements yielded from the different methods:

\[
R: \quad \sin^2 \theta = 0.220 \pm 0.014 \\
P.W.: \quad \sin^2 \theta = 0.230 \pm 0.023
\]

(only experimental errors quoted). The experimental systematic errors were a factor of about 4 smaller than the statistical ones. Therefore, in order to improve this result, a gain in statistics by a factor of 20 is required.

One solution is to run the NBB about five years longer. A more practical solution is to use a quadrupole-focused beam (QFB). This type of beam [first proposed by Atherton\(^\text{15}\)] provides (anti)neutrino fluxes, which are six times higher, for the same number of protons, than the NBB. It is capable of meeting the other essential requirements, namely:

i) high average neutrino energy;
ii) low backgrounds, measurable with high accuracy;
iii) relative normalization of antineutrino to neutrino exposure is possible to the required precision.

More details will be discussed in Section 3.1.3.

3.1.1 $\sin^2 \theta$ from $R$

An estimation of the capabilities of the CHARM detector exposed to the QFB was made extrapolating from the NBB experience. The most important error sources are listed in Table 2 together with their influence on the measurement of $R$ and $\bar{R}$. The table is compiled for an exposure of $4.5 \times 10^{18}$ protons on target, corresponding to 100,000 neutrino CC events and 50,000 antineutrino CC events. This balances the systematic and statistical error in the case of the NC/CC ratio for neutrinos. A measurement of $R$ to $\pm 0.003$ accuracy provides an estimate of $\sin^2 \theta$ to $\pm 0.005$ (experimental errors only). A two-parameter fit to the data would provide a measurement of $\rho$ with an accuracy of 15. Combining the neutrino and antineutrino data a significance of more than seven standard deviations can be obtained for a non-zero value of the right-handed coupling $u_R^2 + d_R^2$.

<table>
<thead>
<tr>
<th>Error source</th>
<th>$\sigma(\bar{R})$</th>
<th>$\sigma(R)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistics</td>
<td>0.0020</td>
<td>0.0040</td>
</tr>
<tr>
<td>Background from decays</td>
<td>0.0009</td>
<td>0.0020</td>
</tr>
<tr>
<td>before momentum selection</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Muon recognition $CC \rightarrow NC$</td>
<td>0.0010</td>
<td>0.0006</td>
</tr>
<tr>
<td>$\pi$, $K$ decay in showers $NC \rightarrow CC$</td>
<td>0.0007</td>
<td>0.0005</td>
</tr>
<tr>
<td>$\nu_e$ background from $K_{e3}$</td>
<td>0.0015</td>
<td>0.0006</td>
</tr>
<tr>
<td>Knowledge of spectrum</td>
<td>0.0008</td>
<td>0.0008</td>
</tr>
<tr>
<td>Total systematics</td>
<td>0.0023</td>
<td>0.0024</td>
</tr>
<tr>
<td>Total syst. + stat.</td>
<td>0.0030</td>
<td>0.0046</td>
</tr>
</tbody>
</table>
At this point it is worth while to consider the theoretical uncertainties introduced by interpreting $R$ in terms of $\sin^2 \theta$. Following Llewellyn Smith\(^\text{10}\) the NC cross-section is related to the CC neutrino and antineutrino cross-sections by merely an isospin rotation:

\[
\frac{d^2 \sigma_{\text{NC},\nu}}{dxdy} = \left( \frac{1}{2} - \sin^2 \theta + \frac{5}{9} \sin^2 \theta \right) \frac{d^2 \sigma_{\text{CC},\nu}}{dxdy} + \frac{5}{9} \sin^2 \theta \left( \frac{d^2 \sigma_{\text{CC},\bar{\nu}}}{dxdy} + \frac{d^2 \sigma_{\text{CC},\bar{\nu}}}{dxdy} \right),
\]

(1)

where $\varepsilon$ and $\bar{\varepsilon}$ are higher twist corrections. In this analysis it turns out that the higher twist contributions to the uncertainty are certainly smaller than $0.005$.

Another correction arises from the fact that in Eq. (1) only $u$ and $d$ quarks were considered and the Cabibbo angle was set to zero. The uncertainties due to heavy quark contributions are introduced by ignorance of elements of the Kobayashi-Maskawa mixing matrix (for the CC) and by the lack of knowledge of the strange-sea component in the nucleon. The combined effect of the latter uncertainties, with present knowledge, is an uncertainty of roughly $\pm 0.01$ on the value of $\sin^2 \theta$. However, this "theoretical" uncertainty is not irreducible and can be improved in the future\(^\text{15}\). Valuable information can be obtained with holographic bubble chambers capable of tagging charged particles or with a hybrid bubble chamber\(^\text{17}\) identifying all particles in the final state in order to tag strange particles as well. Therefore it seems that there is, in principle, no obstacle to reducing the theoretical uncertainties on $\sin^2 \theta$ to less than $0.005$.

Nevertheless, the large error induced by our present lack of knowledge leads us to consider the use of the P.W. relation for extracting $\sin^2 \theta$ from the data. This relation involves a ratio of the difference of the NC neutrino and antineutrino cross-sections and the corresponding CC cross-sections. Therefore the sea cancels exactly in the case of the NC (effects of the necessarily different neutrino energy spectra only enter through small scaling violations).

In the CC sector there are still uncertainties induced by the mixing angles. With the present knowledge of these, the theoretical uncertainties on $\sin^2 \theta$ are limited to $\pm 0.003$\(^\text{10}\). This error will almost certainly be improved in the near future, since it involves a combination of quantities, which is directly measurable in CC interactions.

3.1.2 $\sin^2 \theta$ from the Paschos-Wolfenstein relation

As for the measurement by the ratio method, the NBB experience of the CHARM Collaboration was applied to examine the uncertainties to be expected from a measurement of $\sin^2 \theta$ using the P.W. relation. In order to match statistical and systematic experimental uncertainties, and to make best use of beam-time, the evaluation is made for an exposure with the QFB corresponding to $8 \times 10^{18}$ protons giving 300,000 CC neutrino events and 80,000 CC antineutrino events. This exposure is significantly larger than the exposure needed for the ratio method, because a subtraction is involved. The corresponding statistical uncertainty in $\sin^2 \theta$ is $\pm 0.003$.

The experimental systematic uncertainty is composed of the same error sources as listed in Table 2, with the addition of the neutrino to antineutrino flux ratio. The need to know
the flux ratio is not a serious problem, since an achievable 4% uncertainty in this ratio does not introduce significant additional errors. The total systematic uncertainty is estimated to be ±0.003 \( \sin^2 \theta \), the major part of it being again the uncertainty in the \( v_e \) background. Combining the experimental uncertainties with the theoretical one (an additional ±0.003) it is seen that a total uncertainty of ±0.005 in \( \sin^2 \theta \) is achievable with this method.

Of course, using one method does not exclude using the other as well, providing a valuable cross-check. Slightly different radiative corrections are involved in the two evaluations\(^{10,18}\).

3.1.3 Quadrupole-focused beam

A design of a beam suitable for the studies of semileptonic NC processes was found, using as focusing elements only quadrupoles. A sign selection is obtained by shifting the first quadrupoles sideways, close to the production target. The extracted proton beam is rotated by 4 mrad with respect to the final beam line (see Fig. 5). In this way the decay region available to wrong-sign particles is limited to 8 m on average, under an angle of 4 mrad. The beam line is tuned to approximately 160 GeV, optimizing the costly antineutrino flux. The total length of the part of the beam line used for focusing is 35 m, leaving almost 400 m decay region (see Fig. 5).

Parent particles with momentum below 80 GeV/c are not transmitted, ensuring a very effective suppression (<< 1%) of the neutrino flux below 10 GeV, required to maintain good pattern recognition in electronic detectors. The background due to decays of wrong-sign parents and to prompt decays in the target and proton dump can be measured by putting a shutter in the beam, 10 m from the target. With this shutter less than 1% of the non-background flux and more than 98% of the conventional background flux is measured in the neutrino detector. The prompt background from the target and the dump are exactly reproduced.

The problem of muons passing the shield can be solved by pointing the proton beam 4 mrad downwards to hit the target. All potentially dangerous muons (momenta > 200 GeV/c) are then dumped into the ground 50 m before the decay tunnel, safely ranging them out up to 450 GeV/c at the detector. The neutrino spectrum is very similar to that of the NBB run at 160 GeV/c; the energy-radius relation is however lost. The event rate is a factor of 6 higher than in the 160 GeV/c NBB, but a factor of 5 lower than in the WBB. Since the event rate is much

![Fig. 5 Schematic set-up of quadrupole-focused beam](image-url)
higher than in the NBB, it is possible to run the beam with a spill in the range of 1 ms. Only the runs with the shutters should be made with a short spill (23-100 μs) in order to keep the cosmic background low. A total time of 10% of those background runs is required. Event-rate estimates for the CHARM detector were made. No dead-time problems are expected in the spills mentioned above, so that the proton beam can be run at $1.5 \times 10^{13}$ protons per pulse if a thick target is used.

In a running period of 110 days, divided into 90% normal running, 10% background running, $\bar{\nu}/\nu$ (time) = 2/1, $1.5 \times 10^{13}$ protons per pulse at 450 GeV/c, with 75% total efficiency, one arrives at 300,000 neutrino CC events and 80,000 antineutrino CC events as required for the P.W. method. This corresponds to an exposure of $8 \times 10^{18}$ protons. The numbers were calculated running the same computer program (with the same particle production) for the NBB and for the QFB. The absolute scale was set by the actual event rates presently obtained in the NBB.

The beam has desirable properties not only for the study of semileptonic NC processes, but also for the study of structure functions, because it combines a high event rate with a relatively flat neutrino-energy spectrum (see Fig. 6).

![Graph](image)

**Fig. 6** "Event-rate" spectra (neutrino flux weighted with energy) in quadrupole-focused beam

### 3.2 BEBC with electromagnetic calorimeter exposed to the wide-band beam

As mentioned in Section 2.2.2, a measurement of $R_{\nu}^{\nu}$ in BEBC equipped with an electromagnetic calorimeter filled with hydrogen can provide a statistical accuracy of $\sigma(R_{\nu}) = 0.005$ in an exposure in the neutrino WBB of $4 \times 10^{18}$ protons on target$^9$. This corresponds to a purely statistical error of $0.005$ on $\sin^2 \theta$. It is expected that the experimental systematic uncertainties due to backgrounds and misidentification can be controlled to an acceptable level, although a detailed study of these is still needed.
The main problem in achieving a reliable estimate of $\sin^2 \theta$ lies in the fact that theoretical uncertainties are of a different nature from those for an isoscalar target. No isospin arguments can be used to demonstrate that the higher twist terms do not induce a large uncertainty (up to 10%), and the extraction of $\sin^2 \theta$ relies to a great extent on model calculations. It is, however, possible to exclude contributions from higher twist terms by making a $Q^2$ cut, if applied to NC and CC in the same way. Uncertainties in the model for sea contributions have to be and can be removed by excluding low-$x$ data from the cross-section ratios.

Even if these cuts are made, the value of $\sin^2 \theta$ relies on a good knowledge of relative contributions of u and d quarks to the proton momentum, integrated over the x region accepted by the cuts. A knowledge of this effective u/d ratio to better than 2% is required to reduce the systematic error due to this source below $0.005$. However, the u/d ratio as a function of x is accessible to this experiment if combined with the corresponding high-statistics antineutrino exposure by comparing the neutrino and antineutrino CC data. A relative normalization of neutrino and antineutrino beams to better than 2% is then required. Alternatively, the u/d ratio can be obtained from a measurement on deuterium, separating the CC events on neutrons and protons. This measurement requires a precision in the separation of n- and p-induced events to better than 1%. In summary, although all these uncertainties can in principle be removed, a more detailed study is needed to determine the practical limitations of this measurement.

The corresponding measurement on a deuterium target with BEBC equipped with an electromagnetic calorimeter should also be considered. Deuterium is an isoscalar target; therefore the knowledge of u/d is not needed and higher twist effects are limited to being necessarily small. A study of the application of the multidimensional analysis for the separation of NC and CC events in deuterium is in progress$^3$.

4. OTHER TOPICS

4.1 Coupling constants of heavy quarks

The aims for the precision to be reached in the determination of the couplings of the strange and charm quarks by neutrino interactions are necessarily more limited than those for the light quarks. The presently existing data on the heavy quark couplings$^{19,28}$ give a first hint that probably nothing is terribly wrong with the standard picture, but nothing more can be said. In future it is expected that $e^+e^-$ interactions with centre-of-mass energies near the $Z^0$ resonance will provide a means of measuring the charm-quark coupling better by an order of magnitude than neutrino experiments will be able to achieve. The strange-quark coupling is probably not directly accessible to such experiments, while in neutrino scattering a 20% accuracy is achievable.

A minimal aim for the precision to be reached by future experiments can be derived by considering the value of the coupling constant (i.e. sum of squares of left- and right-handed couplings, $g_s^2$ and $g_C^2$) as a function of $\sin^2 \theta$, the third component of the weak isospin of the left-handed quark, $I^L$, and the corresponding quantity of the right-handed quark, $I^R$. With some confidence it can be assumed that the left-handed multiplet assignment is correctly given by the standard model (as indicated by measurements in the CC sector to which it is accessible), and that $\sin^2 \theta$ measured on light quarks is also applicable for these
heavier quarks. With these assumptions the value of the sum of the squares of the left- and right-handed couplings has $I_3^R$ as the only free parameter, and a measurement of it can be used to determine $I_3^R$.

In Fig. 7 it is shown how present data\(^{19}\) on $g_s^2$ constrain the value of $I_3^R$ of the strange quark. It turns out that only $+1/2$ is excluded but both $-1/2$ and 0 are allowed. It is also clear from the figure that an improvement of a factor of 2 is desirable. In Table 3 the situation for the strange and the charm quark is summarized. The measurement of $g_s^2$ can be done more accurately in the future owing to an improvement by a factor of 2 of the statistical accuracy in the NC sector in the NBB and to a much larger improvement in the CC sector in the QFB. Hence the aim to determine the right-handed multiplet assignment of the s quark is achievable. A possible improvement in the measurement of $g_c^2$ by a factor of 2 larger statistics is not at all sufficient to reach a separation of the various multiplet assignments.

![Graph showing determination of $I_3^R$ from measurement\(^{19}\) of $g_s^2$, the shaded area shows the ±1σ allowed region.](image)

**Table 3**

Heavy quark couplings

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Measurement</th>
<th>Method</th>
<th>Precision aimed at</th>
<th>Possibilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s_L^2 + s_R^2 = g_s^2$</td>
<td>0.26 ± 0.08</td>
<td>NC, CC $y$ distributions</td>
<td>0.04</td>
<td>Try vN</td>
</tr>
<tr>
<td>$c_L^2 + c_R^2 = g_c^2$</td>
<td>0.30 ± 0.14</td>
<td>$\psi$ production</td>
<td>0.025</td>
<td>Need $e^+e^-$ at $Z^2$</td>
</tr>
</tbody>
</table>
4.2 Study of $x$ and $y$ distributions of neutral-current interactions

The information on the kinematics of NC events is much more difficult to obtain than for CC events, where the muon track provides a large part of the measurements. For the $y$ distributions it is sufficient to combine a measurement of the total energy of the outgoing hadronic system with the knowledge of the neutrino energy spectrum of the NBB. In this beam the neutrino energy is known (up to a twofold ambiguity) if the vertex of the event is sufficiently well measured. The ambiguity of the neutrino energy information prevents the measurement of $y$ on an event-by-event basis for all events if no additional information is available; for example, on the invariant mass of the hadronic system. The CHARM Collaboration has solved this problem by exploiting the beam information on a statistical basis, treating it as a doubly peaked resolution function in an unfolding procedure\(^9\). Of course, the statistical significance of the final result is diluted (by a factor of $\sim 2$) compared to what one would expect by purely counting the events in the sample. The limitations are not serious for the $y$ distributions and significant results were obtained as discussed, for example, in Section 5.1. The $x$ distribution was also obtained in a similar way, with the addition of the measurement of the direction of the energy flow of the hadronic system. In this case the statistical dilution factor is larger. Results were reported recently\(^21\).

In bubble chambers the measurement of $x$ and $y$ distributions has been prevented by the loss of energy in the final state due to unmeasured neutrals. This situation can be improved substantially by the installation of an electromagnetic calorimeter in BEBC. The additional detailed information of the final state enables one to solve the energy ambiguity in the NBB on an event-by-event basis\(^8\). Expected resolutions in this beam are: $\sigma(y) = 0.05$ to 0.10 and $\sigma(x) = 0.05$ to 0.15, both depending on $x$ and $y$. Another possibility is to construct a hybrid system capable of fully identifying all particles in the final state and of measuring their energy\(^17\). In this case the measurement of $x$ and $y$ distributions is possible in a wide-band type of beam.

4.3 Test of $\nu_e$-$\bar{\nu}_e$ universality of neutral-current coupling

The familiar high-energy neutrino beams provided by accelerators contain dominantly muon type neutrinos. Electron neutrinos are only a small impurity in these beams. A few years ago a beam enriched in its contents of electron neutrinos was proposed\(^22\). The technique is to exploit the fact that the decay products of the $K^0_L$ contain more electron neutrinos than muon neutrinos. The optimum $\nu_e$ fraction can be reached with a pure $K^0_L$ beam and is $\nu_e/\nu_\mu = 1.65$. In practice, there are always contaminations in these beams, enlarging mainly the $\nu_\mu$ fraction. The first design of a $K^0_L$ beam aimed at reaching $\nu_e/\nu_\mu = 0.7$. A more advanced design was studied yielding a ratio\(^23\) of $\nu_e/\nu_\mu = 1.1$. A test of the universality of $\nu_e$ and $\nu_\mu$ NC interactions relies on separating the CC events of both neutrino types by identifying the electrons (positrons) and muons in the final state. Neutral-current events of $\nu_e$ and $\nu_\mu$ are expected to look identical and cannot be separated. The number of $\nu_e$ NC events is derived from the total NC sample after subtraction of the $\nu_\mu$ NC events predicted by the measurement of $\nu_\mu$ CC events and the NC/CC ratio for $\nu_\mu$ obtained in different experiments. It is clear that the final sensitivity of the test profits from a low $\nu_\mu$ background. This is shown more quantitatively in Fig. 8. For the situation of the more advanced design and $4 \times 10^{19}$ protons on target a test of NC universality is obtained with 17% sensitivity at a two standard deviation level, corresponding to an 8% measurement of the quantity $R = (\nu_e NC + \bar{\nu}_e NC)/(\nu_\mu NC + \bar{\nu}_\mu NC)$. 
5. CONCLUSIONS

Substantial improvements to the present status of the knowledge on semileptonic neutral currents can be made at the SPS in the coming years. The use of the IPF around BEBC can improve the measurements of the u and d couplings by a factor of 2, while BEBC equipped with an electromagnetic calorimeter can give a gain by an order of magnitude. There is no obstacle, in principle, to measuring $\sin^2 \theta$ with a precision of ±0.005 with two different schemes. One is to use an isoscalar target and an electronic detector; the other is to use a hydrogen filling of BEBC equipped with an electromagnetic calorimeter. For the latter possibility systematic uncertainties in the interpretation of the measurement may be hard to reduce. The right-handed NC coupling may be demonstrated to exist with more than 7σ, and a 1σ measurement of $\rho$ may be achievable. The aims for heavy quark-couplings are necessarily limited, but for the strange quark significant results can be obtained. The universality of the NC interactions of $\nu_e$ and $\nu_\mu$ can be tested to 17% at a 2σ level. A summary of the time required in the different beams for all these measurements is given in Table 4.

Table 4

Approximate number of protons and the time needed to perform experiments discussed in this report.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Protons on target</th>
<th>Beam</th>
<th>Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEBC-He</td>
<td>$10^{15}$</td>
<td>WBB</td>
<td>2-3</td>
</tr>
<tr>
<td>BEBC-D2</td>
<td>$5 \times 10^{18}$</td>
<td>WBB</td>
<td></td>
</tr>
<tr>
<td>CHARM</td>
<td>$8 \times 10^{18}$</td>
<td>QFB</td>
<td>1</td>
</tr>
<tr>
<td>BEBC</td>
<td>$4 \times 10^{18}$</td>
<td>K$^0$ beam</td>
<td>1</td>
</tr>
</tbody>
</table>

Acknowledgements

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Study of NEUtrino induced Purely Leptonic reactions
with an Annular Cherenkov counter (NEUPLACH)

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Ecole Polytechnique, Palaiseau, France

ABSTRACT
A new large detector using Cherenkov light in water is proposed, which gives by measuring the $\nu_\mu e$ scattering an estimation of $\sin^2 \theta_w$ with a precision good enough to test high order calculation of the theory.

INTRODUCTION
The precise measurement of $\sin^2 \theta_w$ in the pure leptonic neutral current reaction $\nu_\mu e \rightarrow \nu_\mu e$ gives by comparison to the expected measurement of the $Z^0$ mass a very good test of the second order calculations in the standard gauge model.

A large water detector, measuring the Cherenkov light emitted by the electromagnetic shower provides a very good angular resolution combined with a large fiducial mass(Ref.1).

Such a detector exposed to the CERN neutrino wide band beam during 2 years allow to determine $\sin^2 \theta$ with an accuracy better than .005.

PHYSICS AIM
The $\nu_\mu e \rightarrow \nu_\mu e$ reaction involves the pure leptonic neutral current which is directly related to the standard model.

The differential cross sections,

$$\frac{d\sigma(\nu_\mu e \rightarrow \nu_\mu e)}{dy} = \frac{2}{\pi} G^2 m_e E_{\nu} \left[ g_L^2 + g_R^2 (1-y)^2 \right]$$

$$\frac{d\sigma(\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e)}{dy} = \frac{2}{\pi} G^2 m_e E_{\nu} \left[ g_L^2 (1-y)^2 + g_R^2 \right]$$

(where $G$ is the Fermi constant, $m_e$ the electron mass, $E_\nu$ the $\nu$ energy and $y = E_\nu/E_{\nu\nu}$ ) depends on the two coupling constants $g_L$ and $g_R$ which are related to $\sin^2 \theta_w$ by :

$$g_L = \frac{1}{2} + \sin^2 \theta_w \quad \quad \quad g_R = \sin^2 \theta_w$$

The measurement of these cross sections provides a value of $\sin^2 \theta_w$ independant of any
hypothesis on the nucleon structure.

The present value of \( \sin^2 \theta_w = 0.227 \pm 0.015 \) obtained from neutral current reactions on nucleons, with a precision limited by systematics, is in agreement with the standard model.

If one assumes that the \( Z^0 \) mass will soon be measured and found to be compatible with the standard model, the next interesting step will be to test the next order calculation of this gauge theory. Such radiative corrections of the \( Z^0 \) mass are of the order of 3 to 5 GeV corresponding to a variation of 0.02 to 0.03 for \( \sin^2 \theta_w \) in the 80 GeV energy range.

The comparison of the high energy value of \( \sin^2 \theta_w \) (at the \( Z^0 \) mass) to the \( Q^2 \sim 0 \) \( \sin^2 \theta_w \) value (from \( e^-e^+ \) scattering) gives a good test of the renormalisability of the theory.

To be significant this measurement must be done with an accuracy of \( \Delta \sin^2 \theta_w = \pm 0.005 \).

STATUS OF THE \( \nu_e \rightarrow \nu_e \) EXPERIMENTS.

The neutrino electron scattering has two main characteristics:

- The cross section is very small (\( \sigma \sim E_{\nu} \times 10^{42} \) cm\(^2\)/GeV, about \( 10^{-4} \) of the nucleon reactions). Therefore a large detector is necessary to get sufficient statistics.

- The typical angle of the scattered electron is very small (\( \theta_e = \frac{2m_e}{E_e} (1-y) \leq \frac{32m_e \text{ rad}}{E_e} \)).

A very good angular resolution is indispensable to separate well the signal from the background and minimize the systematic errors.

The bubble chamber has a good angular resolution but, due to its low mass the statistics are poor (few tens). The counter experiments have a higher mass (typically 80 T.) giving \( \lesssim 100 \) events. The best present value from leptonic neutral currents is (CHARM Collab.) \( \sin^2 \theta_w = 0.21 \pm 0.04 \) (Stat) \( \pm 0.015 \) (Syst.) (Ref. 2). But in the electronic experiments the angular uncertainty is larger than the kinematic limit.

To improve the angular accuracy it is possible to build a finer calorimeter, but independently of the intrinsic limitations of this technique, the cost and calibration problems limit the mass to a few hundred tons. Another approach is to use water as an active target. The \( \nu_e \) interact with the electrons in the water and the Cherenkov light emitted by the secondary electron is detected with a large lever arm which gives very good angular accuracy.

CHERENKOV LIGHT IN WATER.

A \( \beta = 1 \) particle in water gives a Cherenkov cone with a opening angle of 42°. The light of this cone can be detected after some travel in water by photomultipliers. The typical number of photoelectrons is 20 pe/cm this number which includes the effect of the UV absorption of 2m of water, 1 plastic window, and the quantum efficiency of the P.M. has been checked experimentally (ref. 3).

The first idea to use this cone was proposed by J. CRONIN in 1978 (Ref. 4). In his proposal the Cherenkov cone is detected by two tilted opposite windows, in such a way than
for forward particles the two windows are near the orientation for total reflection. A small deviation from the forward direction is measured by comparing the variation of the amount of light in the two windows. This methods gives $\Delta \theta = \frac{2\theta}{\pi}$ (same order as kinematic limits), but is delicate because of problems with calibration and with the energy measurement.

In the NEUPLACH method two independent measurements of the cone are proposed:

1) The forward measurement which also use a tilted window (but with a larger tilt than in the Cronin's proposal) followed by mirror system which gives a very precise measurement of the angle, and a first estimation of the energy.
2) The inner detector as in the Irwin Michigan Brookhaven proton lifetime experiment (Ref.3) mainly gives an energy measurement and some pattern information.

**FORWARD DETECTOR**

A photon cherenkov of direction $\vec{k}$ in water gives a photon direction $\vec{k}'$ in the air (after passing the window) and gives a point $M(x,y)$ in the focal plane of a mirror. There is therefore a unique relation between the detected point position in the focal plane of the mirror and the direction of the photon in water (Fig. 1).
The cone from a straight track has an image in the focal plane which is almost an arc of an ellipse. The detection of this curve allows a precise measurement of the electron direction.

**ELECTRON SHOWER MEASUREMENT IN THE FORWARD DETECTOR.**

For an electron shower the preceding curve is smeared by the multiple scattering. This effect is amplified by the bremsstrahlung + pair creation processes which degrade the electron energy. But in other hand a electron pair originating from the beginning of the shower retains the direction of the primary electron. Taking account of all these effects, a Monte Carlo simulation shows that there is an universal curve (independent of $E_e$) $n(\theta_z)/E_e$ versus $\theta_z$ (fig. 2) where $n(\theta_z)$ is the number of photo-electron emitted by all the charged tracks of the shower at angle $\theta_z$ and $E_e$ is the initial electron energy. Each event will give rise to a distribution of the form shown in Fig.2.

![Diagram of electron shower measurement](image)
Such a distribution, combined with geometrical corrections gives, for each shower informations:
- 0 measurement.
Takig for each event the maximum of $n(\theta)$, one gets a very good angular measurement. Typical errors are (fig. 3)

$$\Delta \theta \sim \frac{4-7}{\sqrt{E}} \text{ mrad} \Rightarrow \Delta \theta_{\text{esp}} = \frac{6-10}{\sqrt{E}} \text{ mrad.}$$

these two extreme numbers correspond to extreme photoelectron numbers which depend on window and mirror photon loss.

- The integral of the curve of the Fig.2 over $\pm 20 \text{ mrad}$ gives a first estimate of the electron energy:

$$\int_{-20}^{+20} n(\theta) d\theta \Rightarrow E_F \quad \Delta E_F/E_F = 25\% \sqrt{E}$$

- the shape of the peak near the maximum gives information very useful in the rejection of background from single muons or hadrons shower.
THE INNER DETECTOR

In addition to the forward detector which has a very narrow acceptance, it is proposed to set photomultipliers, inside water, around the fiducial volume, as in the IMB proton life time experiment (Ref. 5). The inner detector will give the following information:

- Total energy measurement $E_T$. With one to three 5 inches P.M. per square meter it is possible to obtain a 1.5 to 4% coverage. Assuming 2% coverage the number of photoelectrons detected is $200 E_{\text{GeV}}$, which gives an error on electron energy of
  $$\Delta E_T/E_T = 12%/\sqrt{E}$$

- Position measurement
  The forward detector does not give any information on the position measurement. With the above number of P.M. a $\Delta x$ and $\Delta y$ error $\lesssim 10$cm is reasonable.

- Other pattern information such as
  Shower extension, extra track rejection, electron/\gamma separation, $\pi^0$ decay... can be extracted from the inner detector but more work has to be done to be quantitative.

THE NEUTRITON DETECTOR. (Fig. 4)

If one assume that the fiducial volume for the wide band neutrino beam is 4m in diameter, it is necessary to have a 6x6m cross section detector. The length of such a detector is mainly limited by the experimental hall size; 40 meters seems reasonable therefore a 6x6x40m pool gives $\sim 400T$ fiducial mass.

Schematic view of the detector

Fig 4
The two forward detector (θy and θz measurement) use 1000 P.M. (this number can be decreased using light collectors, or additional mirrors). The 2 windows have 480 m² both together and the pressure problem can be solved with rods in tension inside the water. The mirrors have a typical focal length of 30m and a surface of 500m² both together. They can be built by 5 to 10m² pieces.

For the inner detector, with 2% covering, one needs ~ 1500 P.M.

The purification water system has the typical size of classical swimming pool purification and can be found in the industry.

TRIGGER - SELECTION OF EVENTS.

For the standard WB 400 GeV(10^{13}) neutrino beam in 400T fiducial mass there will be ~0.40 νN charged current event per burst, and one νμ e event every 200 bursts.

The basic idea of the trigger uses the comparison of the two energy estimates by the forward and inner detectors $R = E_F/E_\perp$.

For an electron $R = 1$.

For a typical hadron shower $R = 0$ with a tail (5 10^{-3} of the neutrino interaction hadron shower have R >.5) and a forward muon gives $R = 4$. With $R > .5$ at the trigger level, it is possible to kill most of the neutral current and 95% of the charged current events. Therefore it is possible to reduce the acquisition to 1 or 2 events per burst.

Further rough selection criteria can be used off line:
- no forward muon in the event (rejection factor 50)
- more careful analysis of $E_F/E_\perp$ (= 1 ± 2σ) rejection factor 6. Typical numbers for a 20 day run are given in Table 1.

<table>
<thead>
<tr>
<th>Table 1: Typical Event Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^{18} p or 20 day run 400 T</td>
</tr>
<tr>
<td>νμ CC</td>
</tr>
<tr>
<td>4 10^{6}</td>
</tr>
<tr>
<td>$E_F/E_\perp &gt; .5$</td>
</tr>
<tr>
<td>No μ</td>
</tr>
<tr>
<td>$E_F/E_\perp &lt; 1$</td>
</tr>
<tr>
<td>$E_F/E_\perp = 1 ± 2σ$</td>
</tr>
<tr>
<td>7 &lt; E_F &lt; 40</td>
</tr>
</tbody>
</table>
It has to be pointed out that the pattern from the inner detector has not been used at this level.

**TYPICAL EXPERIMENT.**

The more direct way to extract \( \sin^2 \theta_w \) is to measure the total cross sections for neutrino and antineutrino on electrons. The ratio of these cross sections is, as pointed in the CHARM experiment (ref. 2) not too sensitive to most of the systematics.

Assuming the usual time sharing \((1/3 \nu, 2/3 \bar{\nu})\), using \(1.2 \times 10^{19}\) p(i.e. 2 year run) it is possible to get \(1350 \nu_\mu\) and \(1350 \bar{\nu}_\mu (S/B = 8\) to 5\) which gives 4% errors on the cross section ratio and \(\Delta \sin^2 \theta_w = .005\).

The systematics due to relative flux normalisation are reduced by measuring the quasi elastic \( (\nu)\) N events.

One main source of the systematics comes from the coherent production. For this background the resolution of the detector \((1/4 \) of kinematical limit) is capital.

The good angular resolution allows to improve the measurement of \(\sin^2 \theta_w\) by use of the number of events with \(y < .5\) compared to \(y > .5 (y = E_c/E_{\nu})\).

Many other analysis improvements can be envisaged but need more study:
- \(e/\gamma\) separation from the number of photoelectrons at the beginning of the shower.
- \(\gamma/\pi^0\) separation using the good track separation.
- \(\pi^+\) identification by the decay.

In addition, two main improvements can be envisaged:
- decrease the energy threshold (3 GeV) (gain factor 1.5).
- increase the size of the detector (1000T) (gain factor 2.5).

So the \(\Delta \sin^2 \theta_w = .005\) appears to be reached within 2 years run and very probably it is possible to improve the precision.

**OTHER FIELD OF PHYSICS.**

The general properties of NEUPLACH (large mass, good angular accuracy in the forward direction), open other field of search for example:

- neutrino oscillation (using quasi elastic events and \(e/\mu\) identification.

- Beam dump experiment. Search for light particle decay.

- Neutrino decay \(\nu + \nu + \gamma\)

- Super symmetric particle inducing small \(Q^2\) neutrino reactions.
CONCLUSIONS.

The NEUPLACH detector is a new design using old techniques. It uses old techniques like Cherenkov effect in water, windows, mirrors and photomultipliers. But the design gives a large mass (which can be increase until 1000T) with a few milliradian accuracy.

NEUPLACH, can give a measurement of $\sin^2 \theta_w$ with an accuracy better than .005 in a good time scale and consequently makes a very fundamental test of the high order calculations in the non abelian gauge theory.

In addition, many other fields of physics like supersymmetry (goldstino search...),grand unification (neutrino mass) can be studied with such a detector.

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STUDY OF A NEW DETECTOR FOR NEUTRINO-ELECTRON SCATTERING

The CHARM Collaboration
(Presented by K. Winter)

Neutrino-electron scattering was discovered ten years ago by the Gargamelle Collaboration\(^1\). Several measurements of the cross sections for neutrino and antineutrino scattering on electrons have been performed in the meantime. They are summarized in Table 1. Taking

Table 1
Summary of past activities on \(\sigma(\nu\mu e)\)

1) \(\nu\mu\) scattering

<table>
<thead>
<tr>
<th>Experiment</th>
<th>(\nu\mu)</th>
<th>Background</th>
<th>(10^{-42} \sigma) cm(^2)/GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1973 GGM PS</td>
<td>1</td>
<td>0.3 ± 0.1</td>
<td>&lt; 3(90% c.i.)</td>
</tr>
<tr>
<td>Aachen/Pad</td>
<td>11</td>
<td>3</td>
<td>1.1 ± 0.6</td>
</tr>
<tr>
<td>GGM SPS</td>
<td>64K</td>
<td>9</td>
<td>2.4 ± 1.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.5 ± 0.2</td>
<td>0.9</td>
</tr>
<tr>
<td>Col-BNL</td>
<td>15K</td>
<td>8</td>
<td>1.8 ± 0.8</td>
</tr>
<tr>
<td>15' BC</td>
<td>8</td>
<td>0.5 ± 0.5</td>
<td></td>
</tr>
<tr>
<td>LM 0</td>
<td>40</td>
<td>12</td>
<td>1.4 ± 0.3</td>
</tr>
<tr>
<td>CHARM</td>
<td>10(^6)</td>
<td>46 ± 12</td>
<td>2.1 ± 0.55(stat) ± 0.49</td>
</tr>
<tr>
<td>World average</td>
<td></td>
<td>64 ± 10</td>
<td></td>
</tr>
</tbody>
</table>

2) \(\bar{\nu}\mu\) scattering

<table>
<thead>
<tr>
<th>Experiment</th>
<th>(\bar{\nu}\mu)</th>
<th>Background</th>
<th>(10^{-42} \sigma) cm(^2)/GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>GGM PS</td>
<td>3</td>
<td>0.4 ± 0.1</td>
<td>1.0 ± 2.1</td>
</tr>
<tr>
<td>A-P</td>
<td>8</td>
<td>1.7</td>
<td>2.2 ± 1.0</td>
</tr>
<tr>
<td>CHARM SPS</td>
<td>10(^6)</td>
<td>77</td>
<td>1.6 ± 0.35(stat) ± 0.36</td>
</tr>
<tr>
<td>World average</td>
<td></td>
<td></td>
<td>1.58 ± 0.30</td>
</tr>
</tbody>
</table>

all experiments together, about 100 events have been observed in each channel. These results have been important for our understanding of the structure of the weak neutral current. The vector and axial vector coupling constants of the electronic weak neutral current are determined with a four-fold ambiguity, two sign ambiguities and an ambiguity under the exchange of \(g_v\) and \(g_A\). Combining these results with those from \(\nu\mu\) - \(\bar{\nu}\mu\) scattering \(^2\) and from \(e^+e^-\mu^+\mu^-\) at PETRA \(^3\) a unique solution emerges, the one predicted by the standard model of electroweak interactions, with

\[
\frac{g_v^e}{g_A^e} = -0.523 \pm 0.035
\]

and

\[
\sin^2\theta = 0.215 \pm 0.043.
\]
Figure 1 summarizes the present situation. Using the value of $g_A^e$ determined from neutrino-electron scattering one can deduce, from measurements of the angular asymmetry in $e^+e^- + \bar{f}^+\bar{f}^-$, which is proportional to the product $g_A^e \cdot g_A^f$, the axial vector coupling of the other leptonic neutral currents. Table 2 summarizes these results.

Table 2

<table>
<thead>
<tr>
<th>Current</th>
<th>Process</th>
<th>$\xi_{EA}$</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>ee</td>
<td>ee</td>
<td>$-0.523 \pm 0.035$</td>
<td>$0.02 \pm 0.03$</td>
</tr>
<tr>
<td>$\mu\mu$</td>
<td>ee + $\bar{\mu}\bar{\mu}$</td>
<td>$-0.50 \pm 0.08$</td>
<td>$0.01 \pm 0.08$</td>
</tr>
<tr>
<td>$\tau\tau$</td>
<td>ee + $\bar{\tau}\bar{\tau}$</td>
<td>$-0.39 \pm 0.12$</td>
<td>$-0.11 \pm 0.12$</td>
</tr>
</tbody>
</table>

The SU(2) structure is clearly confirmed by these measurements, the left-handed leptons transform as doublets and the right-handed leptons as singlets.

The overall coefficient $\rho^2$, multiplying the theoretical expressions of the cross sections of the neutrino-electron scattering, determines the relative strength of the neutral and of the charged current coupling. In the standard model $\rho = 1$, provided the Higgs fields form an isospin doublet. This simplest version of the theory is already confirmed by the present measurement, giving

$$\rho = 1.12 \pm 0.16$$

At a higher level of accuracy small deviations of $\rho$ from one are expected due to different contributions to the $Z^0$ and $W$ propagators of high mass fermions, for leptons, e.g.

$$\rho = \left| \frac{\sigma(\nu e)}{\sigma(\bar{\nu} e)} \right| = \frac{G_F \nu^2}{\sqrt{2} m^2} w_\nu^2$$

It would therefore be important to determine $|\rho^2-1|$ to $\pm 1\%$.

The most precise determination of the value of $\sin^2\theta$ in the leptonic sector has been obtained by the CHARM Collaboration, making use of the direct relation between the ratio of $\sigma(\nu e)$ and $\sigma(\bar{\nu} e)$ and $\sin^2\theta$,

$$R = \frac{\sigma(\nu e)}{\sigma(\bar{\nu} e)} = \frac{3}{1 - 4 \sin^2\theta + (15/8) \sin^2\theta},$$

In the vicinity of $\sin^2\theta = \frac{1}{2}$ this relation gives $\Delta \sin^2\theta \sim \frac{1}{8} \Delta R$ and, hence, a very precise determination of the mixing angle. The detection efficiency cancels in the ratio and many systematic uncertainties are reduced. Using their upgraded detector, incorporating new measurements of the shower barycentre in two orthogonal projections behind each target plate, the CHARM Collaboration will further improve the accuracy of this result. The plans for further measurements at CERN, FNAL and BNL are summarized in Table 3.
Table 3

Summary of present and future activities on $\nu_\mu$ scattering

<table>
<thead>
<tr>
<th>Group</th>
<th>$\sigma(\Theta)$</th>
<th>S/B</th>
<th>Events</th>
<th>$\Delta\sin^2\Theta$ (stat)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$E = 15$ GeV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flashtube det.</td>
<td>$\sim 8$ mrad</td>
<td>1/1</td>
<td>$\sim 10$ $\nu_\mu$</td>
<td></td>
</tr>
<tr>
<td>FNAL 200 tons</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CHARM 1982</td>
<td>$\sim 12$ mrad</td>
<td>1/2</td>
<td>77 $\nu_\mu$ e, 46 $\nu_\mu$</td>
<td>$\pm 0.04$ Total $\nu$</td>
</tr>
<tr>
<td>70 tons</td>
<td></td>
<td></td>
<td></td>
<td>$\pm 0.02$</td>
</tr>
<tr>
<td>CHARM 1983</td>
<td>$\sim 8$ mrad</td>
<td>1/1</td>
<td>$\sim 60$ $\nu_\mu$</td>
<td>$\pm 0.02$</td>
</tr>
<tr>
<td>BNL 1982</td>
<td>$\frac{12 mrad}{\sqrt{E}}$</td>
<td>1/0.25</td>
<td>80 $\nu_\mu$, 25 $\nu_\mu$</td>
<td>$\pm 0.017$ Total $\nu$</td>
</tr>
<tr>
<td>BNL 1982+1983</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>80 tons</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Are further, improved measurements of neutrino-electron scattering required? The electroweak theory predicts the Born term ($Q^2 \sim 0$) of the mass of the $Z^0$ as a function of $\sin^2\Theta$

$$M_{Z^0} = \frac{37.4}{\sin^2\Theta \cos\Theta} \text{ GeV}$$

Second order electroweak radiative corrections shift $M_{Z^0}$ by $\sim 5$ GeV\(^5\), e.g. for $\sin^2\Theta = 0.220 \pm 0.015$, as determined by the CHARM Collaboration from semileptonic neutral current interactions\(^6\), Wheater and Llewellyn-Smith\(^5\) predict

$$M_{Z^0} \text{ (Born)} = 90 \pm 2.3 \text{ GeV}$$

$$M_{Z^0} \text{ (physical)} = 94.6 \pm 2.3 \text{ GeV}$$

and hence a shift of $\sim 5$ GeV. A precise experimental determination of this shift would constitute a decisive test of the underlying electroweak gauge theory. A significant test could be claimed if the present error on $\Delta M$ would be reduced to 0.7 GeV corresponding to an error on $\sin^2\Theta$ of $\pm 0.005$\(^7\).

Can this accuracy be achieved in experiments? At this workshop Llewellyn-Smith\(^8\) discussed the theoretical uncertainties of the quark model picture of the nucleon and its effects on attempts to measure $\sin^2\Theta$ in semileptonic neutral current interactions. These uncertainties do not exist in the leptonic reaction of neutrino-electron scattering. Here only the experimental problems have to be solved, namely:

1) event rate requiring a large fiducial tonnage and high selection efficiency over a wide window of electron energies;
2) background, dominantly due to quasi-elastic electron-neutrino scattering and to coherent \( \pi^0 \) production has to be reduced by efficient \( e/\pi \) discrimination and precise measurements of the shower direction;

3) monitoring of the relative flux of the different beam components \( \nu_\mu, \bar{\nu}_\mu, \nu_e \) and \( \bar{\nu}_e \) is required to determine the ratio of \( \sigma(\nu_e)/\sigma(\bar{\nu}_\mu) \).

A tentative design of a new dedicated \( (\nu_e) \) detector has been discussed by the CHARM Collaboration. It is based on the principle of a fine-grain target-calorimeter and on the accumulated experience of the CHARM Collaboration with instrumentation of this type. The main concern of this study was the question: can the present technique used for \( \nu_e \) studies be sufficiently improved to match the aim of \( \Delta \sin^2 \theta = 0.005 \) or is a new technique required?

The accuracy of shower direction measurements depends mainly on three contributions

\[
\sigma^2(\theta) \sim (\Delta\theta_N)^2 + (\Delta\theta_V)^2 + (\Delta\theta_{\text{SMEAR}})^2
\]

- on the sampling frequency and on the method used to count the number of shower particles \( N \);
- on the plate thickness and grain size of the calorimeter near the vertex;
- on the lateral shower sampling used to determine the barycentre of the shower.

An optimization is required if limited space is available.

The limiting accuracy is given by the \( Z \) number of the target material,

\[
\sigma(\theta) \sim \frac{Z}{\sqrt{E}} \text{ const.}
\]

The mean \( Z \) of the present marble target is 13, with MgCO\(_3\) (dolomite) a value of \( \sim 8 \) could be achieved. In these light targets with a nucleon absorption length of \( \lambda_{\text{abs}} \sim 4 \) radiation lengths, electromagnetic and hadronic showers have very similar longitudinal profiles\(^9\).

The CHARM Collaboration has developed a new method to discriminate between electromagnetic and hadronic showers in low \( Z \) materials based on the characteristic difference of their lateral profiles (see figure 2). A discrimination by a factor of \( \sim 100 \) has been achieved\(^9\).

Figure 3 shows the resolution in shower direction measurements achieved with the present CHARM detector and with the upgraded version.

The structure of the new, dedicated detector is sketched in figure 4. It consists of 330 modules of 3.5 x 3.5 m\(^2\) surface area, each composed of a 4 cm thick target plate (marble) and of a plane of streamer tubes with 1 cm wire spacing, read out by crossed cathode strips of 2 cm spacing in two orthogonal projections. Using analog electronics the centroid position of a track or a shower can be reconstructed with \( \pm 2 \) mm accuracy. Simulating this structure using Monte Carlo methods (EGS) we find an angular resolution of \( \sigma(\theta) \sim 16 \text{ mrad}/\sqrt{E/\text{GeV}} \) corresponding to \( \sim 4 \text{ mrad} \) at 15 GeV and an energy resolution of \( \sigma(E)/E \sim 20\%/\sqrt{E/\text{GeV}} \). Hence, we expect a reduction of background proportional to \( \sigma^2(\theta) \) by a factor of \( \sim 9 \).

Figure 3 shows this estimate of \( \sigma(\theta) \) compared to the present CHARM I detector. The choices made of analog versus digital readout of strips and of the strip width are illustrated.
in figures 5a and 5b. This configuration has a fiducial target weight of ~320 tons, whereas the CHARM I detector has 70 tons.

Monitoring of the beam composition has been studied in detail for the CHARM I experiments using quasielastic $\nu_\mu \bar{\nu}_\mu$ events. This method can be extended to lower neutrino energies by restricting the value of $Q^2$ to less than 0.01 GeV$^2$ to equalize the cross sections for the neutrino and the antineutrino induced reactions. Figure 6 shows the measurements for quasielastic reactions at low $Q^2$. At $E_\nu > 10.8$ GeV a peak appears at small $Q^2$ because of the inverse $\mu$ decay reaction, $\nu_\mu e^{-} \rightarrow \mu^{-} e^+$. The CHARM II detector will have superior angular resolution for measurement of the muon direction and, combined with a muon spectrometer, will therefore directly monitor the flux ratio $\phi(\nu_\mu)/\phi(\bar{\nu}_\mu)$ to ±2%, required to evaluate the ratio $R$ and the neutrino spectra.

Electron neutrino-electron scattering has a ten times higher cross section than $\nu_\mu \mu$ scattering. The beam contains approximately 2% electron neutrinos and antineutrinos. Aiming at a 5% measurement of $R$ requires a knowledge of the $(\nu_\mu + \bar{\nu}_\mu)$ flux to better than ±10%. We think that this can be achieved by making $dE/dx$ measurements in the plane following the vertex, at angles outside the forward peak. We have also been able to recognize inclusive $\nu_\mu N \rightarrow eX$ events with $y < 0.6$ in the CHARM I calorimeter.

We summarize this feasibility study in Table 4 which gives the selection criteria, the angular resolution, the rate and background for $\bar{\nu}_\mu e$ scattering which would be obtained for $10^{19}$ protons on target.

Table 4

<table>
<thead>
<tr>
<th>Selection</th>
<th>CHARM I</th>
<th>CHARM II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate for $7.5 &lt; E_e &lt; 30$ GeV</td>
<td>$154 \pm 27$</td>
<td>$909 \pm 33$</td>
</tr>
<tr>
<td>$\Sigma_e$ (1 hit)</td>
<td>612</td>
<td>90%</td>
</tr>
<tr>
<td>$\sigma(\theta)$ at $E_e = 15$ GeV</td>
<td>$12$ mrad</td>
<td>$4$ mrad</td>
</tr>
<tr>
<td>Signal/background</td>
<td>$1/2$</td>
<td>$1/0.22$</td>
</tr>
<tr>
<td>Rate for $2.5 &lt; E_e &lt; 30$ GeV</td>
<td>$1364 \pm 40$</td>
<td></td>
</tr>
</tbody>
</table>

The same statistics for $\nu_\mu e$ would be obtained with $5 \cdot 10^{18}$ protons. Hence, we expect to measure

$$R = \frac{N(\nu_\mu e)}{N(\bar{\nu}_\mu e)} \times \frac{1364 \pm 40}{1364 \pm 40} = \frac{1364 \pm 40 (R \pm 2\%)}{1364 \pm 40 (R \pm 2\%)},$$

corresponding to $\Delta \sin^2 \theta = 0.005$. 

An additional physics result may be obtained on the value of $\rho$, derived from a measurement of the ratio of cross sections for $\nu_e \rightarrow \nu_e$ and for $\nu_{\mu} \rightarrow \nu_{\mu}$. The flux monitoring is now internal and, apart from systematic uncertainties due to background subtraction, electron detection efficiency and spectrum determination, the statistical error of $\rho$ would be $\pm 2\%$.

The main conclusion that we draw from this study is that the experiment seems to be feasible using the presently developed fine-grain calorimeter technique. Of course, many details have to be investigated further and it is not the aim of this study to be at the level of a proposal.

REFERENCES


3) See e.g. A. Böhme, DESY 82–084, December 1982, and


7) K. Winter, in Workshop on Weak Interactions, Javea (Spain), September 1982.

8) C. H. Llewellyn-Smith, this Workshop and
   J. Fanman, this Workshop.


Fig. 1 Results of various leptonic reactions determining $g_A^e$ and $g_V^e$.

Fig. 2 Distribution of the width $\Gamma$ of electron and pion induced showers as measured by the lateral energy deposition profile in the scintillator planes of the CHARM I detector.
Fig. 3  Angular resolution of electron shower direction as a function of electron energy. In the CHARM I detector close and far refer to the projection following the target plate in which the event started (close) and the next plate (far). In the upgraded CHARM I detector additional planes of streamer tubes have been installed and the resolution is now the same in both projections.

Fig. 4  Schematic sketch of a new dedicated CHARM II detector
Fig. 5a  Shower profile sampling by detectors with analog and with digital measurements

Fig. 5b  Resolution of the shower direction as a function of the strip width
Fig. 6  Observed $Q^2$ dependence of quasielastic $\nu_\mu (\mu^-)$ and $\bar{\nu}_\mu (\mu^+)$ events
THEORETICAL ISSUES IN NEUTRINO PHYSICS

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ABSTRACT

A brief review is presented of some issues which might be addressed by future neutrino experiments at the SPS.

1. INTRODUCTION

Accelerator neutrino physics is now twenty years old. A decade ago when the SPS programme was being planned at the Tirrenia conference, I examined the nine questions posed by Lee and Yang in their classic 1960 letter and pointed out that only one had then been satisfactorily answered 1):


1) $\nu_\mu = \nu_e$ ?

Experimental answers in 1972

$\nu_\mu \neq \nu_e$

2) Lepton conservation

$\nu \to L^+$ and

$\nu \to L^-$ ?

$$\sqrt{\frac{\sigma(\nu_\mu \to \mu^{-})}{\sigma(\nu_\mu \to \mu^{+})}} \leq 0.068$$

But several different forms of conservation law still allowed

$$\sqrt{\frac{\sigma(\nu_n \to \nu{n}^0) + \sigma(\nu_p \to \nu{p}^0)}{2\sigma(\nu_n \to \nu{p}^0)}} \leq 0.37$$

3) Neutral currents?

4) "Locality" (vector nature of weak interactions)

5) Universality between $\nu_\mu$ and $\nu_e, \mu$ and e?

6) Charge symmetry?

7) CVC; isotriplet current?

8) W ±?

$M_W > 1.8$ GeV

9) What happens at high energy ($E_{\nu} \rightarrow "unitarity limit"$)?

No information

Subsequently the situation has changed dramatically, thanks to the classic Gargamelle PS experiments and numerous experiments at the SPS and FNAL. Not only do we have much better answers to Lee and Yang's question (at least the first seven) but the other main questions which were apparent at the Tirrenia meeting have also been answered:

Are there neutral currents with the properties predicted by gauge theories in $\nu N, \mu N$ and $e^+ e^-$?

Are there heavy leptons - specifically of the type required by many gauge theories?

Is there a fourth quark?

Do quark parton ideas ($\int F_3 dx$, $18/5$ etc. work)?

In addition neutrino experiments have taught us a lot about QCD, which had not been invented
in 1972.

Given that the obvious things have been done, extremely well, the question is whether there is anything else to do with neutrinos at the SPS. Very generally, despite widespread belief in SU(2) x U(1), there may still be surprises in the weak interactions. There is at present no evidence for deviations from the local Fermi theory, let alone for the standard W^+ and Z^0, with gauge theory couplings between W's, or Higgs bosons. More specifically, even if the standard framework is broadly correct there is much to be learned from more accurate measurements of the parameters. As far as strong interaction physics is concerned, the recent observation by the EMC of pronounced differences between the structure functions of iron and deuterium 2) shows that surprises are still possible at SPS energies. This effect should clearly be studied with neutrinos. In addition there are various specific questions which can be further elucidated by neutrino experiments.

In this talk I shall first discuss our present knowledge of electro-weak interactions. I shall then turn to some more specific questions which could be addressed by future experiments.

2. The Standard Model and Alternatives

Existing data are all compatible with SU(2) x U(1) except

1) The observation that \( \frac{\nu_e}{\nu_\mu} = 0.6 \pm 0.2 \) in the 1979 beam dump experiments 3).

2) The observation of same sign dimuons 4).

It is clearly important to confirm these results, find experimental clues to their origin and explore possible theoretical explanations 5). However, given the vast amount of data available and the great difficulty of these measurements, the fact that these are the only problems shows that SU(2) x U(1) is in good shape. On the other hand, it reminds us that SU(2) x U(1) can be threatened by a single decisive experiment.

Although SU(2) x U(1) generally works so well, it is far from established. It is possible to produce almost exactly the same low energy results in a non-gauge theory framework as first pointed out by Bjorken 6). If the standard fermionic currents \( j^{\text{std}} \) of SU(2)_L couple to new unspecified "weak quanta" (e.g. heavy fermion antifermion pairs) which are electrically charged, then the diagrams:

\[
\begin{align*}
J^{\text{std}} & \quad \text{Weak quanta} \\
+ & \\
J^{\text{std}} & \quad J^{\text{em}}
\end{align*}
\]

lead to exactly the standard effective weak Lagrangian (with \( \rho = 1 \)) at low energies, except for an extra term

*The situation with respect to the W has of course changed since the SPS Workshop.
\[ \frac{4G_F}{\sqrt{\alpha}} \cdot C \cdot \frac{\langle J^{em} \rangle^2}{F}. \]

In this framework $C$ is automatically of 0 ($\sin^4 \theta_w$) and actually vanishes if the low energy behaviour of the weak spectral function is dominated by a single resonance, so there is no conflict with the PETRA limit \(^7\) of $C < 0.02$.

To realize this general formalism in a composite model (e.g. "weak quanta" = heavy fermion antifermion pairs which bind to vector resonances), a binding scale of $O(1 \text{ TeV})$ is probably needed \(^8\) to obtain $\sin^2 \theta_w \gg \alpha$. The main difficulty is that one would generally expect a substantial isoscalar ("weak $\omega$") as well as an isovector ("weak $\rho$") contribution. This shows the importance of improving the limits on isoscalar neutral couplings. Even if the isoscalar is absent for some reason, this sort of model would differ from the standard model at low energies in second order contributions, to which neutrino experiments are becoming sensitive.

Alternative gauge theories are strongly circumscribed by existing data, in particular by the observation that $\rho = 1$ and $C < 0.02$. ($\rho = 1$, $C = 0$ can only be obtained in non-standard models by tuning parameters to particular values \(^9\)). Nevertheless if, for example, $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ or $SU(2)_L \times U(1)_R \times U(1)_{B-L}$ models are fitted to low energy neutral current data there is still scope for considerable deviations from the standard predictions for the $Z$ mass, the allowed ranges being \(^10\)

1σ: 83 GeV < $M_{Z_1}^+ < 116$ GeV, $M_{Z_2}^- > 205$ GeV
2σ: 79 < $M_{Z_1}^+ < 135$, $M_{Z_2}^- > 175$.

The direct limits on the masses of charged vectors $W_R^+$ coupled to right handed currents, which must exist in models with an $SU(2)_R$ factor, is of 0 (3 $M_{W_L}$) both from $\beta$ decay \(^11\) and from neutrino experiments \(^12\). Recently it has been claimed \(^13\) that the $K_L - K_S$ mass difference gives an indirect limit of 1.6 TeV. However, it turns out \(^14\) that this result is very sensitive to the $t$ quark mass and to the Higgs couplings, which were ignored, and that, for example, with $M_L \sim 20$ GeV, $M_H \sim 100$ GeV, $M_{R} \sim 300$ GeV is allowed - the limit is much less if $M_L$ is very large.

3. Neutral Current Measurements

Any improvements in the knowledge of weak couplings of quarks and leptons will further constrain non-standard gauge theories and non-gauge models. Specifically

1) Given our total ignorance of the origin of the family structure, we cannot take it for granted that $c$ and $s$ are simply copies of $u$ and $d$, although the success of the GIM mechanism strongly suggests it for the left handed states. At the very least we would like to measure their weak $I_3^R$.

2) Writing, in Sakurai's notation,

\[ L_{NC}^\nu = \frac{C}{\sqrt{2}} \bar{\nu}_\mu (1-\gamma_5) \nu_\mu [\alpha + \delta A^I_{\mu} + \gamma V^I_{\mu} + \delta A^I_{\mu}] \]

we would like better knowledge of $\beta$ and $\delta$, which could distinguish different models: \(^15\), \(^16\)
\[ \beta = 1 \text{ standard model} \]
\[ = 1 \text{ Bjorken's non-gauge framework with or without a "weak \( \omega \)} \]
\[ \# 1 \text{ SU}(2)_L \times \text{SU}(2)_R \times \text{U}(1) \]
\[ = 0.94 \pm .06 \text{ expt} \]
\[ \delta = 0 \text{ standard model} \]
\[ \# 0 \text{ Bjorken's framework with "weak \( \omega \"} \]
\[ = \text{SU}(2)_L \times \text{SU}(2)_R \times \text{U}(1) \]
\[ = 0.10 \pm .09 \text{ expt.} \]

In principle the parameters might be measured directly by studying coherent production of \( \Xi \)'s and \( \eta \)'s on \( I = 0 \) nuclei. In practice they are obtained by a global fit to all neutral current data. Clearly considerable improvement is desirable, especially for \( \delta \).

3) Data which test SU(2) x U(1) to second order are needed to establish that it really is a renormalizable theory and to distinguish it from other models with the same leading order low energy predictions e.g. non-gauge theories of the Bjorken type or "supersymmetric SU(2) x U(1)" in which relatively light SUSY particles in virtual loops alter the radiative corrections \(^{17}\) and could change the predicted values of \( M_{W,Z} \) by a few GeV.

In order to test SU(2) x U(1) it must be shown that all experiments (\( \nu, \overline{\nu}, e, \overline{e}, m_{W}, M_{Z} \)) can be described by the same value of \( \sin^{2} \theta_{W} \), if possible to an accuracy which tests the second order corrections. Very accurate measurements of \( \sin^{2} \theta_{W} \) are also needed for comparison with the predictions of grand unified models. As in the case of tests of QED, SU(2) x U(1) should be tested in as many ways as possible since different experiments are sensitive to different higher order contributions and possible breakdowns e.g. from contributions of new particles. For example, suppose that \( \sin^{2} \theta_{W} \) is extracted from \( \overline{\nu}_{e} \rightarrow \nu_{e} \) and also from \( \overline{\nu}_{\mu} \rightarrow \nu_{\mu} \)—assuming \( \Delta M^{2} \) in calculating the radiative corrections. If in fact \( M_{Z} \) is unexpectedly large, the first result would be larger than the second by
\[ 2 \times 10^{-3} \left( \frac{M_{Z}}{M_{W}} \right)^{2} \] (assuming the theory is otherwise correct).

This gives some idea of the accuracy which is desirable. More specifically, note that the average value of \( \overline{\nu}_{e} \rightarrow \nu_{e} \) gives \( \sin^{2} \theta = 0.227 \pm 0.015 \) leading to \( M_{Z} = 89^{+2.2}_{-2.0} \) GeV if the lowest order theory is used. Including all electroweak radiative correction (W and Z propagator corrections, vertex corrections, wave function renormalization, two W exchange, real bremsstrahlung etc.) we find \(^{18}\) \( \sin^{2} \theta_{W}(M_{Z}) = 0.215 \pm 0.015 \), where this is the value in the \( \text{MS} \) scheme with mass scale \( M = M_{W} \), leading to \( M_{Z} = 93.8^{+2.5}_{-2.2} \) GeV, including second order corrections to the mass formula (assuming \( M_{t} < M_{W}, M_{Higgs} < 1 \) TeV and no further quark and lepton doublets). To make a clear cut distinction between the 1st and 2nd order predictions of \( M_{Z} \), it would be desirable to improve the precision on \( \sin^{2} \theta \) by a factor of 3 or more.

Note that the SLAC ed asymmetry experiment gives \( \sin^{2} \theta = .223 \pm .015 \) which becomes \( \sin^{2} \theta_{W}(M_{Z}) = 0.215 \pm .015 \) when electroweak corrections are included. The fact that the agreement with the neutrino result survives radiative conditions, which might have moved the two values in opposite directions, is non-trivial and shows that incisive tests of the theory are in reach (in passing we note that the SU(5) prediction is \( \sin^{2} \theta_{W}(M_{W}) = 0.215 \pm .006 \) for \( \Lambda_{\text{MS}} = 150^{+250}_{-100} \) MeV).
A further idea of the precision which is desirable can be obtained by considering a simultaneous fit to $\frac{NC}{\nu N}$ and $\frac{NC}{\nu N}$ in terms of two parameters $\sin^2 \theta$ and $\rho^2$ using the lowest order theory, where $\rho$ is the usual NC/CC strength parameter. The corrected value is $\sin^2 \theta_{\text{eff}}(M_W) = \sin^2 \theta_{\text{expt}}(M_W) - 0.004$ in this case, independent of $M_W$. The predicted value of $\rho^2$ is $1 - 0.016 + 4 \times 10^{-3} \left(\frac{M_W}{M_W}\right)^2$ (assuming no further quark and lepton doublets and that $M_W < 1 \text{ TeV}$). This suggests that a measurement of $\rho^2$ to 1% or better would be desirable, although very hard, and might constrain supersymmetric and other non-standard models.

If $\sin^2 \theta$ is measured in $\nu_\mu e$ scattering, the problems are purely experimental [19]. In $\nu_\mu$ hadron scattering, however, we must also worry about theoretical uncertainties in extracting $\sin^2 \theta$ from the data. In particular it has been claimed [20] that higher twist corrections to the parton model could produce essentially irreducible errors in $\sin^2 \theta$ as large as 10%, making further experiments pointless. Luckily this conclusion is wrong for isoscalar targets. The largest terms in $\sigma_{NC}$ and $\sigma_{CC}$ can be related by isospin invariance alone. The QCD parton model is only needed for two relatively small terms for which we multiply the parton results by $1 + \epsilon(x, Q^2)$ and $1 + \bar{\epsilon}(x, Q^2)$, where $\epsilon$ behaves as $0(<p_T^2/Q^2)$ and $\bar{\epsilon}$ as $0(m_q^2/Q^2)$ at large $Q^2$, where $m_q$ is the constituent quark mass. The hypothetical cross-sections (\bar{\epsilon}) for the case of only $u, d, \bar{u}, \bar{d}$ quarks with $\theta_{\text{KM}} = 0$, and an $I = 0$ target are then related by [21]

$$\frac{d^2 \sigma_{NC}}{dxdy} = \frac{1}{2} - z + \frac{5\epsilon^2}{9} \frac{d^2 \sigma_{CC}}{dxdy} + \frac{5\epsilon^2}{9} \frac{d^2 \sigma_{CC}}{dxdy}$$

where $z = \sin^2 \theta$.

With, very conservatively, $<\epsilon> \approx 0.1 <\bar{\epsilon}> < 0.05$, the error in $\sin^2 \theta$ due to higher twists is $\pm 0.005$. This can be removed essentially completely by a $Q^2$ cut (using only hadronic information to determine $Q^2$ so that the cut is the same for NC and CC).

Including the contributions of other quarks and taking $\theta_{\text{KM}} \neq 0$, there are further uncertainties which are dominated by ignorance of the element $U_{CS}$ of the Kobayashi-Maskawa matrix and of the strange quark distribution. The full range $0.80 <|U_{CS}| < 0.98$ which is allowed phenomenologically gives [21] an error $\delta \sin^2 \theta_{\text{eff}} = \pm 0.008$. However, if the common assumption that $U_{CS}$ is close to one is accepted the error is much less [21].

For example, assuming $|U_{CS}| > 0.95$ the error from ignorance of the strange quark contribution is only $\pm 0.002$. In this case the largest error is $\pm 0.004$ from ignorance of the $d \to c$ contribution, and hence of $|U_{dc}|$, due to the fact that the mixture of charmed particles produced by neutrinos is poorly known and there are large errors in the leptonic branching ratios, which are needed to extract $\nu d \to \mu c$ from dimuon production. Ideally it would be useful to study charm production directly in a holographic bubble chamber. This might also clear up the same sign dimuon mystery.

In conclusion, it seems that unless $|U_{CS}| < 1$ is unexpectedly large and remains unknown, theoretical uncertainties will not frustrate more accurate measurements of $\sin^2 \theta$ in semileptonic neutrino interactions. In any case, the theoretical uncertainty can be reduced to $\pm 0.003$ (from uncertainties in $|U_{dc}|$) by using the Paschos Wolfenstein relation
\[ \Delta \equiv \frac{\sigma_{NC}}{\sigma_{\nu N}} - \frac{\sigma_{\bar{\nu} N}}{\sigma_{\bar{\nu} N}} = \frac{1}{2} - \sin^2 \theta_W \]

from which the contribution of the sea drops out. However, \( \Delta \) is subject to systematic errors which are hard to control to the level of accuracy required.

4. Properties of Neutrinos

The importance of measuring neutrino masses/mixing angles/oscillations needs no further emphasis \(^{22}\). The recent discussion \(^{23,22,24}\) of the possibility of observing the decay of neutrinos with masses below 70 MeV, where there is an open window \(^{25}\), reminds us of our ignorance of this subject.

An experiment which has been considered for the SPS is a search for the tau neutrino \(^{26}\). It is known that \( \tau \rightarrow \mu \nu e, \mu \nu \mu, \mu \nu \mu \) in a way which is well described by V-A theory. Here \( x \) could be \( \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\mu, \nu_e \) or, if none of these, \( x = \nu_\tau \) by definition. For \( x = \bar{\nu}_e \) or \( \bar{\nu}_\mu \), \( \frac{\tau \rightarrow e}{\tau \rightarrow \mu} \) is predicted to be 2 or 1/2 respectively \(^{27}\) and both are completely excluded. \( x = \nu_\mu \) is also completely excluded by the failure to see \( \nu_\mu \rightarrow \tau \). \( x = \nu_e \) is excluded, but only at the 90% confidence level, by the fact that it would have led to an apparent anomalous NC/CC ratio from \( \nu_\mu \rightarrow \tau \rightarrow \text{hadrons} \) in the beam dump experiment \(^{3}\). Invoking a little theory, \( x = \nu_\mu \) would lead to the expectation that \( \frac{\tau \rightarrow \mu \nu e}{\tau \rightarrow \mu \nu e} \approx \alpha/\pi \) in contrast to the experimental upper limit of \( 0.4 \times 10^{-4} \). Furthermore in a gauge theory, there is no leptonic GIM mechanism if \( \nu_\tau \) does not exist and one or more of decays such as \( \tau \rightarrow e e e, \tau \rightarrow u u \mu, \tau \rightarrow e e e \) would occur \(^{28}\) at a rate far above the limits of a few times \( 10^{-4} \).

Theoretically, it seems essentially impossible to avoid the conclusion that \( \nu_\tau \) exists and its discovery, although very nice, would be no surprise. The question seems to be whether it would be possible to establish the non-existence of \( \nu_\tau \) - which would necessitate some radical new idea e.g. that \( \nu_\tau \) decays with a short lifetime.

5. Hadronic Final States

It is hard to be specific about the interest of studying multiparticle final states because of our almost total theoretical ignorance about quark jet and target fragmentation, beyond the QCD predictions for the evolution of fragmentation functions and the ability to invent classical Monte-Carlo models which incorporate some QCD inspired ideas and can be tailored to the data. Precisely because of this ignorance, however, it is important to obtain more experimental information. Here it would seem that neutrino experiments are in principle in a favourable position because we know the flavour of the produced quark in the majority of cases (this is also true to some extent in muon experiments since \( Q_d^2 = 4Q_u^2 \))\(^{2}\). Furthermore there is a unique opportunity to study \( \omega d \rightarrow \mu c \rightarrow \text{hadrons} \) and \( \omega s \rightarrow \mu c \rightarrow \text{hadrons} \). Well measured events of this sort from a holographic bubble chamber would be very useful in teaching us about the dynamics.

There is also a great deal which can be learned by studying the exclusive production of charmed baryons in wide band neutrino experiments. Two events have been observed \(^{29}\) which have been interpreted as \( \nu p \rightarrow \mu^- \Sigma^{++}, \Sigma^{++} \rightarrow \Lambda_c^+ \pi^+ \) (\( \Sigma^{++} \) is the \( J = 1/2 \) uuc state). The interpretation is based on the fact that the \( (\Lambda_c^+ - \Lambda_c^-) \) mass difference agrees with the theoretical prediction \(^{30}\) for \( \Sigma^{++} - \Lambda_c^+ \). It would be nice to have more events to
substantiate this interpretation and measure the cross-section which contains very interesting information. It would be even nicer to observe \( \nu p \rightarrow \mu^- \Sigma^{++}_c \) (\( \Sigma^{++}_c \) is the \( J = 3/2 \) uuc state which has not yet been discovered), for which the cross-section is predicted \(^{31}\) to be larger than for \( \Sigma^{++}_c \). This would provide a valuable new strong hyperfine mass splitting and the cross-section would also be most interesting.

6. **Nuclear Effects**

The recent observation by the EMC of substantial differences between the structure functions of iron and deuterium \(^2\) has two important implications for the SPS programme. First, assuming that the effect is confirmed, it becomes important to improve our knowledge of the structure functions of hydrogen and deuterium (assuming that nuclear effects turn out to be relatively small in deuterium!); precision measurements of quark and gluon distributions in neutrons and protons are needed a) because we may hope eventually to calculate them accurately from first principles, e.g. from lattice QCD, whereas presumably accurate calculations for iron will be impossible, and b) as input for other calculations e.g. of cross-sections at the pp collider. Second, further SPS experiments may be needed to understand the origin of the EMC effect.

Assuming that it is not due to a subasymptotic effect ("higher twist"), which would be totally unexpected theoretically and seems somewhat disfavoured experimentally, the EMC data show that, relative to deuterium, in iron \(^{32}\)a) the valence quarks are "softer" b) there is (roughly 50%) more sea c) the gluons are slightly softer. Regardless of any theory, we clearly need confirmation of these effects on a variety of targets and to observe them with neutrinos. More specifically we can ask questions such as:

1) Is the effect due to iron or deuterium? This can be answered with neutrinos by studying

\[
\frac{F^{\nu p}}{F^{\bar{\nu} p}}\frac{F^{\bar{\nu} p}}{F^{\nu p}} = \frac{F^{\nu p}}{F^{\bar{\nu} p}}\]

More generally

\[
\frac{Z F^{\nu p}}{F} + \frac{N F^{\bar{\nu} p}}{F} \frac{F^{\nu p}}{F^{\bar{\nu} p}} = \frac{F^{\nu p}}{F^{\bar{\nu} p}}
\]

is obviously of interest.

2) Does a careful comparison of \( pp \rightarrow \mu^+ \mu^- \) with \( pA+\mu^+ \mu^- \) reveal a large sea in the latter case (this may be complicated by a slower approach to scaling for a nuclear target due to initial state absorption effects at low \( Q^2 \))?

3) If the size of the sea in iron and deuterium are different, is this true for all flavours?

In retrospect the EMC effect is not all that surprising. After all, nuclei are rather dense. At the central nuclear density of 0.17 nucleons \( fm^{-3} \) the average spacing between the centre of neighbouring nucleons is 1.8 \( fm \)-not much more than twice radius of the proton, which is 0.8 \( fm \). Even in deuterium with \( <r> = 4.2 \ fm \), a Hulthen wave function gives a 5% probability that \( r < .5 \ fm \) and the view that there is actually a 0(5%) probability that the six quarks sit in one bag has some advocates \(^{33}\).

It is becoming increasingly evident \(^{34}\) that it is impossible to describe nuclei accurately in terms of \( N, A, \pi \) etc. without reference to the colour degree of freedom and it would seem that a proper discussion of the EMC effect must start from QCD. Nevertheless,
if we start with the idea that the nuclear environment mainly changes the outside of the nucleon we can imagine that it might be possible to describe the effect very approximately in terms of a modification of the pion field. If we suppose that iron contains extra pions relative to deuterium it is clear that they will increase the structure function at small $x$ ($x_{\text{max}} = M_\pi^2 / M_N^2$ for a stationary pion) and decrease it at large $x$ by removing momentum from the nucleons in the infinite momentum frame.

Phenomenologically the data can be explained in this way if, relative to deuterium, iron contains about 8 extra pions which carry about 5% of the momentum. Theoretically we require one pion exchange diagrams

![Diagram: pion exchange](image)

to be about twice as big in nuclei as in deuterium. When corrections to the impulse approximation are included, a considerable enhancement is expected due to a modification of the pion propagator in nuclear matter or, equivalently, initial state correlations and a resonant coherent final state response due to the attractive $\pi N$ force. Such enhancements have long been predicted by nuclear physicists but no way of observing them clearly has been found; they are of considerable interest, being directly connected with the physics of the phase transition known as "pion condensation" expected to take place for $\rho > 0.35$ nucleons fm$^{-3}$ which is important for neutron stars. It seems that with acceptable nuclear parameters the EMC effect can probably be explained by this enhancement but, alas, the parameters are extremely uncertain.

The pion model is speculative but it provides a first example of the sort of guidance which theory should provide for experiment. It predicts the character of the excess events at small $x$ in which the $\gamma^* \pi$ invariant mass is relatively small. It predicts that the percentage of $\bar{\sigma}$ in the sea is less in iron than in deuterium, as the extra pions are mainly non-strange. In principle it can guide us to the most interesting nuclei to study but relevant calculations with finite nuclei are not available. In particular it is not yet clear whether the effect would be fully developed in $^{4}\text{He}$—large density but all surface.

It must be stressed that the EMC effect has no influence on QCD scaling violation tests in nuclei, which do not depend on the assumption that nuclei are made of protons and neutrons.

7) Conclusions

In addition to the specific topics which I have discussed there are many which I have omitted either because they have been covered by other speakers (e.g. scaling violations) or because of lack of time (e.g. study of the evolution of jets in nuclei).

Much has been learned from the very thorough neutrino experiments at the SPS. Nevertheless these experiments may still reveal surprises. Even if orthodoxy prevails, there is
still much which could be learned from high precision experiments both about the electro-
weak and the strong interactions.

Acknowledgement

This talk was prepared while I was visiting CERN. I am grateful for the hospitality
of the Theory Division.

* * *

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37) This was pointed out by K. Winter.
CHARM PHYSICS AT THE SPS; NOW UNTIL © 1990

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ABSTRACT
A review is given of the existing charm programme at the SPS and some future options are discussed. The SPS programme is put into the context of the existing knowledge on charm properties and the associated mysteries.

1. INTRODUCTION

In this report we give a brief outline of the SPS charm programme planned to cover the next few years. To put as yet uncompleted experiments into some perspective we also discuss the present status of the understanding of charm properties. In sect. 2 we give our experimentalist view of what the theorists would like us to investigate; this section is deliberately superficial and incomplete to force readers to study the paper of Fritzsch which they will find elsewhere in this volume. In sect. 3 we present current knowledge on (1) charm decay properties, (2) charm photoproduction and (3) charm hadroproduction. We are mainly concerned with results which have not been reviewed elsewhere [1,2] and thus an exhaustive view of charm knowledge can be best obtained from [1,2] and this report. Finally in sect. 3.4 we give a list of desired measurements whose topics are motivated mainly by experimental curiosity and do not necessarily answer any specific theoretical questions.

Sect. 4 summarises the CERN SPS experiments which are either approved already or have been recently proposed. Sect. 5 discusses future aims and gives the approximate (if optimistic) time scale of approved, proposed and planned experiments. Tevatron plans are also noted in this section. To complete sect. 5 we mention an idealised device which would aim us in the general direction of beauty physics giving charm events as an interesting background.

This report is an attempt to present in a highly concentrated but palatable form the deliberations, discussions and presentations of a small group of physicists who met and worked together at CERN approximately every Friday afternoon between October and December of 1982. The final section serves as an acknowledgement to this working group. Having said that, we must emphasise that any omissions, incorrect statements or errors of interpretation are the sole responsibility of the authors.
2. WHAT THE THEORISTS WANT FROM CHARM PHYSICS

The principle theoretical interest in charm properties lies in differentiating between the dominant QCD diagrams which can contribute to the production and decay of a charm quark.

Thus the study of inclusive charm production characteristics, such as x-Feynman and transverse momentum distributions, and charm pair correlations should give an idea of the relative importance of charm excitation (fig. 2(a)), gluon- (or photon) gluon fusion (fig. 2(b)), quark-antiquark fusion (fig. 2(c)), intrinsic charm (fig. 2(d)), diffraction or even c-valons and fireballs.

These points are discussed, for example, in [3]. Somewhat more speculative, but very interesting also from the experimentalist point of view, is the rôle of the so-called "forgotten diagram" of Halzen [4]. If the Higgs mass is not too high, an important mechanism for producing events with 4 final state charm particles would be via Higgs production and decay described in the "forgotten diagram" (fig. 2(e)). Charm events with a highly characteristic signature would lead us to the Higgs. Highly speculative it may be, but it's what at least one theorist wants from charm physics.

Charm decay properties, in particular charm particle lifetimes, allow one to distinguish between the contributions of the spectator diagram - in which the charm quark decays by the normal weak process while the other quark(s) continue unscathed into the final state particles, the quark-antiquark annihilation diagram which can contribute to $D^+$ decay and the $W$ exchange diagram which can contribute to $B^0$ decay. Decay branching ratios, in particular into Cabibbo suppressed modes and into $F^+$ annihilation modes, which could (and should) contain glueball final states, are also fascinating from the theoretical point-of-view [5].
3. THE PRESENT STATUS OF CHARM PHYSICS

3.1 Decay properties

The review articles of Trilling [1a] and Kalmus [1b] give a complete picture of our current knowledge of charm decay properties. Here we mention two topics only: charm lifetimes, because most of the results are from fixed target experiments; branching ratios, because, in the case of \( D^+ \) and \( \Lambda_c^+ \), we have a curious problem which may best be solved in future fixed target experiments.

D lifetimes are still affected by large statistical uncertainties, but nevertheless a clear picture is beginning to emerge with

\[
\tau(D^0) = (4.0^{+1.4}_{-0.9}) \times 10^{-13} \text{ s} \quad \text{based on 70 decays}
\]

\[
\tau(D^+) = (9.3^{+2.7}_{-1.6}) \times 10^{-13} \text{ s} \quad \text{based on (52 + 98)* decays}
\]

and the ratio

\[
R = \frac{\tau(D^+)}{\tau(D^0)} = 2.2^{+0.9}_{-0.6}.
\]

This situation is presented experiment-by-experiment in figs 3(a), 3(b), 3(c), along with the numbers of decays.

(*) The 52 decays are from pure visual detectors [6,7,8,9,10], the 98 decays (of slightly different quality) from an active silicon target experiment [11].
As given in figs 3(d) and 3(e), the $F^+$ and $\Lambda^+_c$ lifetimes, based on 16 and 20 decays, respectively are

\[ \tau(F^+) = (2.9 \pm 1.8) \times 10^{-13} \text{ s} \]
\[ \tau(\Lambda^+_c) = (2.2 \pm 0.9) \times 10^{-13} \text{ s} \]

The systematic uncertainties on these last two results are large; especially so since a significant proportion of the decays come from experiments without charged particle identification [8,9] and could be highly contaminated.

Based on the decay diagrams mentioned in the previous section, the theorists predict $\tau(D^+) > \tau(F^+) > \tau(D^0) > \tau(\Lambda^+_c)$. The data support this approximately, but more and better data are urgently needed before we can have a clear and convincing picture of the charm particle lifetimes.

Information on branching ratios shows a similar pattern to that of the lifetimes. The $D$ decay channels are reasonably well established with $\approx 70\%$ of the $D^+$ modes and $\approx 80\%$ of the $D^0$ modes understood. At best we can say only that the $F^+$ has been seen with no detailed information on its decay modes and only $\approx 10\%$ of $\Lambda^+_c$ decay modes have been identified.

3.2 Charm photoproduction

In most ways, the information available on charm properties from photoproduction experiments is less abundant than the hadroproduction data. More than anything else, this situation reflects the difficulty of obtaining an adequate photon beam. With the exception of the SLAC backscattered laser beam which gives an almost monochromatic 19.5 GeV photon beam [6] all other real photon results come from experiments with bremsstrahlung beams [7,11,16,17,18]. Other results originate in high energy muon experiments with a pole extrapolation to the real photon [19,20].
3.2.1 Charm signals

Beautiful examples of charm events with clearly visible production and decay vertices are seen in the SLAC high resolution bubble chamber experiment [6] and in the CERN emulsion experiment [7]. As examples, we show in fig. 3(f) an emulsion event and in fig. 3(g) a bubble chamber event. A very important technical step forward in the heavy flavour business was made by the CERN NA1 collaboration [11]. Using an active silicon target they have almost achieved the dream of an "electronic bubble chamber". Fig. 3(h) shows a $D\bar{D}$ event from the NA1 experiment.
Other experiments search for bumps in effective mass plots and fig. 3(i) shows a typical result giving evidence for the F in the CERN experiment WA4 [16].

![Graphs showing events vs. mass](#)

**3.2.2 Cross section versus energy**

Fig. 3(j) contains a compilation of all photoproduced charm cross section data. The curve results from a computation assuming the Photon-Gluon Fusion (PGF) model [21]. Within the large experimental errors the different data points appear to be consistent and compatible with the PGF computation. For the WA4 [16] and CIF [18] data one point shows the D/\bar{D} cross section and a second point the approximate total charm cross section obtained by including an estimate for F and Λc production. If one uses the total charm cross section then a statistically insignificant but suggestive systematic difference appears between real and virtual photon data. Clearly, more and better data are desperately needed.

All data are in agreement that for photon energies above ~70 GeV the total charm cross section is ~1% of the total hadronic cross section.

![Graph showing cross section vs. energy](#)
3.2.3 Production characteristics

Apart from the cross section data noted above, reliable information on charm photoproduction characteristics is almost non-existent. From a total of 28 charm pairs in the CERN emulsion experiment WA58 \cite{7} there are indications that the $\Lambda_c \bar{D}$ cross section is falling with energy and $D\bar{D}$ production begins to take over above $E \gamma \gtrsim 40$ GeV. Many of the decays are not fully reconstructed and so these indications should be treated cautiously; however, such a result would agree with earlier data \cite{2a}. Apart from the EMC data which gives indirect $x$-dependence information \cite{20}, no photoproduction experiment has yet produced any reliable $x$-Feynman distribution to allow, for example, an estimation of the relative amounts of central and diffractive components. Acceptance problems and background problems are the principle culprits denying us a clean $x$ distribution. Preliminary results from the CERN emulsion experiment cited earlier are encouraging and even though acceptance computations have to be completed before an $x$-dependence can be deduced, these data once more emphasise the power of the visual technique whether with bubble chamber or emulsion in obtaining a clean, background-free charm sample.

Again we may conclude that more and better data are needed before we can have any idea of the charm photoproduction characteristics.

3.2.4 The $F$-meson

Photoproduction appears to be a rich source of the $F$-meson. After an initial observation of an excess of $n$ production at a mass corresponding to where the $F$ is expected (using the DASP detector at DORIS \cite{22}), other $e^+e^-$ experiments have failed to see a significant $F$ signal \cite{1,23}. Hadroproduction experiments have similarly been unsuccessful in obtaining clean $F$ samples; the high resolution bubble chamber experiments using LECB and BIBC report a few reconstructed $F$ decays and indicate an $F$ to $D$ hadroproduction ratio $\lesssim 0.1$ \cite{8,9}. These high resolution bubble-chamber results should be taken with caution since neither experiment has charged particle identification. The most compelling experimental evidence for the existence of the $F$ still originates in the emulsion experiment of \cite{10} using a neutrino beam. Photoproduction, however, seems to be the best bet for $F$ physics with an $F$ to $D$ photoproduction ratio of $\lesssim 0.3$; figs 3(i) and 3(k) show the existing $F$ photoproduction evidence from the CERN experiments WA4 \cite{16} and NA1 \cite{11}.
Since charm production with high energy photons appears to consume \( \sim 1\% \) of the hadronic production cross section, photoproduction is potentially a clean source of charm with fewer combinatorial background problems than we find in hadroproduction. Photoproduction experiments have, however, proved difficult and present data does not allow us to deduce much about charm properties. This, plus the indication that F-physics is most feasible with high energy photon beams encourages us to aim for high statistics, clean photoproduction data in the future.

3.3 Charm hadroproduction

3.3.1 Experimental methods, problems and status

This section deals with dynamical aspects of charm hadroproduction. The emphasis is on recent results, older measurements are summarized in [2]. Due to small cross sections and small charm branching ratios the experiments have to face a substantial signal-to-noise problem. So far the following methods have been applied (both on-line and off-line) to suppress non-charm background:

(a) Selection of events with short decay lengths from optical devices, e.g. emulsion [24], high resolution bubble chambers [8,9,25,26] or high pressure streamer chambers. To suppress residual background from strangeness decays one uses generally only events with a pair of decays or single decays with at least 3 decay products. For reliable \( \phi/\Lambda_c^+ \) separation further particle identification is needed (sect. 3.1). Since scanning is tedious high statistics data are not easily
available. On the other hand the data allow for a rather straightforward determination of the cross section (for $x > 0$) which is insensitive to production dynamics and mainly a function of life-time. The acceptance drops to zero for $x < 0$; this is especially a problem for meson beams whereas for proton beams one uses symmetry arguments to obtain the inclusive charm cross sections. From visual devices one expects finally the cleanest measurements of $x_c$ and transverse momentum and rapidity-gap distributions.

A typical event obtained with LEBC is shown in fig. 3(a).

(b) Selection of events with at least one identified particle, i.e.
(i) an identified (strange) hadron from hadronic charm decays [27] or
(ii) an identified electron [28] or $\nu$ [29] from semi-leptonic charm decays.

In the former case one looks for peaks in the effective mass distribution from particle combinations containing the identified hadron, whereas in the latter case one studies effective mass distributions from hadronic decays of charm particles produced in association with the lepton. The proof that eventual signals are due to charm particles comes from the quantum numbers of the particle combination and/or the width of the mass distribution and/or from the correlation with the lepton charge.

From this method one expects relatively unambiguous (in principle) high statistics data on charm production. Combinatorial background is however a problem here; it can be reduced by good identification of

![Diagram](image)

- **360 GeV/c**
- **$pp \rightarrow D\bar{D} + 4$ prong**

**fig. 3**
\( K^0, \ p, \ \bar{p}, \ \Lambda \) and \( \bar{\Lambda} \) from Cabibbo favoured decays and/or by a very good mass resolution and/or by favorable off-line selection criteria. In the latter case a correct estimation of the significance is not trivial.

Since particles are usually identified in a restricted solid angle only, integrated cross sections derived from the data contain substantial model dependence due to extrapolation. Further uncertainties are caused by assumptions on the nature of the lepton parent and on charm-anticharm correlations.

(c) Selection of diffractive event topologies [29]. Cross sections derived from this method represent, of course, only unknown fractions of the inclusive cross section.

(d) Measurement of inclusive single lepton (\( \nu, \ e^+, \ u^+ \) or dilepton (eu) fluxes from semileptonic decays of one or both charm particles. Background sources are either mostly absorbed in a dump (\( \nu \) and \( u \) beam dump experiments [30]) and/or removed by off-line analysis (beam dumps, e: [31], eu: [32]).

This method gives generally significant results. One observes however, only second generation particles without being able to identify their origin. Hence, any extraction of cross sections must be based on a set of assumptions concerning e.g. \( x, p_{\pi^{-}} \), atomic number \( A \) dependence of an unknown mixture \( (D, \ A_{\pi}, F) \) of parent particles, varying branching ratios and lepton spectra in the parent rest frames.

From the discussion above it is obvious that great care must be taken when comparing results from different experiments being subject to different biases and extrapolations [33].

---

![Graph 3m](image_url)

![Graph 3n](image_url)
The present status of experiments searching for peaks in invariant mass distributions is summarized in figs 3(m) and 3(n). Shown are the significances (= signal/(signal+background)) of published results from the ISR and from SPS/FNAL. All ISR data were obtained before 1980. There is no result from a dedicated second generation ISR experiment as yet. Signals from lower energies with significances of more than 4σ are very recent. As examples typical invariant mass distributions are given in fig. 3(o).

As can be concluded from figs 3(m) and 3(n) more convincing results are needed at all energies.
3.3.2 Experimental Results

3.3.2.1 A-dependence

To extrapolate measurements obtained with heavy nuclear targets to free nucleons one has to know the dependence of the inclusive cross section on the atomic number A: $\sigma \sim A^\alpha$. A value $\alpha = 2/3$ was assumed for some time; recent measurements by LEBE (A = 1, [26]) and BIBC (A = 17.1 [9]) favour a linear A dependence which is used throughout this report. This yields also the most consistent results when comparing with beam dump data [30]. It should be pointed out that care (and better measurements) is necessary when studying differential production properties: figs 3(p) and 3(q) show measurements of the exponent $\alpha$ as function of $x$ and $p_T$ for inclusive hadron production [34](*). If these results hold also for charm production, a differential cross section, e.g.

$$\sigma_{\text{invar}}(p\bar{p} + c\bar{c}x) \sim (1-x)^2 e^{-2p_T}$$

would look like

$$\sigma_{\text{invar}}(pF + c\bar{c}x) \sim (1-x)^3 e^{-1.5p_T}$$

when measured on an iron target.

\[\text{fig. 3p}\]

\[\text{fig. 3q}\]

(*) These values of $\alpha$ are used to interpolate between nuclei with $A \neq 1$; an extrapolation to hydrogen is not very reliable [34].
3.3.2.2

**Differential cross section**

(a) $p_T$-dependence: A transverse momentum distribution

$$\frac{d\sigma}{dp_T} \propto -(1.1 \pm 0.3)p_T^3$$

has been measured [25,26] for D production; it corresponds to $\langle p_T(D) \rangle = 0.7$ GeV/c. This result is roughly consistent with all other experiments.

(b) $x$-dependence, baryon beams: In [26] $\frac{d\sigma}{dx} \propto (1-x)^n$, $n = 1.8 \pm 0.8$ was found for both D and $\bar{D}$ production. If confirmed by better statistics this is a surprising result: D-mesons do not share any valence quark with the proton such that one expects a strong $x$-dependence according to counting rule arguments [35]. To illustrate this point, fig. 3(r) shows $\frac{d\sigma}{dx}$ for both D and $\bar{D}$ [26] and $K^0_S$ [36] production at $\sqrt{s} \approx 27$ GeV. Though $K^0_S$ have a d-quark in common with the proton, the $x$-dependence is much stronger for $K^0_S$ than for D production. The $x$-dependence derived from D-production at the ISR [37] is compatible with results from [26]; the same holds for the production of $A^+(=csu)$ which shares only the s-quark with the incident $\pi^-$ [27a]. On the other hand invariant cross sections from beam dump experiments are either consistent with $n \sim 3$ to 4 [30a,b] or even suggest $n \sim 6$ [30c].

---

*fig. 3r*
For $\Lambda_C^+$ production one estimates $d\sigma/dx \sim \text{const.}$ at the ISR [37] or $d\sigma/dx \sim (1-x)^{1.5 \pm 0.4}$ at lower energies [27b].

(c) $x$-dependence, $\pi^-$ beams: The current knowledge on $x$-dependence of D production is summarized in fig. 3(s) [38] where D and $D^*$ cross sections integrated over $x > 0$ are given as function of the exponent $n$, assuming a differential cross section $\sim (1-x)^n$. The LEBC data are compatible with $\sim 70\%$ central and $\sim 30\%$ leading particle ($D^0$, $D^-$) component, a trend supported by data from the u beam dump experiment [30c].

```
Obviously the experimental situation should be clarified before claiming proof or disproof of certain models.
```

3.3.2.3 Cross sections

(a) Baryon beams (see table 1(a)): New $D\bar{D}$ [26,30a,b] and $\Lambda_C^+$ cross sections [24,26,27b,28,30a,30c] are shown in fig. 3(t) as a function of $\sqrt{s}$. It seems that D cross sections at SPS/FNAL energies never differ by more than a factor two; they cluster around 20 $\mu$b. At ISR energies [2,37,39] typical experimental errors are about 50% with systematic uncertainties of a factor 2. Since only little improvement can be expected from the ISR, a more precise determination of s-dependence has to come from measurements at $\sqrt{s} \sim 15$ GeV (and/or from the Tevatron). Present data suggest a very strong increase of cross sections with $\sqrt{s}$. The two upper limits in fig. 3(t) will be discussed in sect. 3.3.2.5.


### TABLE 1

Compilation of recent charm cross sections

#### (a) Baryon beams

<table>
<thead>
<tr>
<th>Beam (GeV/c)</th>
<th>Target</th>
<th>Cross section/Nucleon ($\sigma^{A^1}/\text{ub}$)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>n, $\Xi^-$ 58</td>
<td>C</td>
<td>$\sigma(A^+_{C})$ : 44 ± 16</td>
<td>27b</td>
</tr>
<tr>
<td>$\Xi^-$, 135</td>
<td>Be</td>
<td>B+$\sigma(A^+_{C})$: 4.7 to 12.7</td>
<td>27a</td>
</tr>
<tr>
<td>p, 150</td>
<td>Be</td>
<td>$\sigma(A^+_{C})$: &lt; 24 ± 17</td>
<td>28</td>
</tr>
<tr>
<td>p, 350</td>
<td>Fe</td>
<td>$\sigma(D\bar{D})$: 22 ± 9</td>
<td>30c</td>
</tr>
<tr>
<td>p, 360</td>
<td>p</td>
<td>$\sigma(D^-,\bar{B}^0)$ : 42$^{+23}_{-8}$</td>
<td>26</td>
</tr>
<tr>
<td>p, 360</td>
<td>p</td>
<td>$\sigma(D^+,\bar{D}^0)$ : 14$^{+18}_{-5}$</td>
<td></td>
</tr>
<tr>
<td>p, 360</td>
<td>p</td>
<td>$\sigma(D\bar{D})$: 19$^{+13}_{-5}$</td>
<td></td>
</tr>
<tr>
<td>p, 360</td>
<td>p</td>
<td>$\sigma(A^+<em>{C},\bar{D})$: 18$^{+15}</em>{-10}$</td>
<td></td>
</tr>
<tr>
<td>p, 400</td>
<td>Cu</td>
<td>$\sigma_\text{SL}(A^+_{C})$: 3.9 ± 1</td>
<td>30a</td>
</tr>
<tr>
<td>p, 400</td>
<td>W</td>
<td>$\sigma(D\bar{D})$: 16 ± 3</td>
<td>30b</td>
</tr>
<tr>
<td>p, 400</td>
<td>Em</td>
<td>$\sigma(A^+_{C})$: 106 ± 39</td>
<td>24</td>
</tr>
</tbody>
</table>

#### (b) $\pi^-$ beams

<table>
<thead>
<tr>
<th>Beam (GeV/c)</th>
<th>Target</th>
<th>Cross section/Nucleon ($\sigma^{A^1}/\text{ub}$)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>16/17</td>
<td>p</td>
<td>$\sigma(D^*)$ : &lt; .13 ± .03</td>
<td>27d</td>
</tr>
<tr>
<td>120</td>
<td>Be</td>
<td>&lt; $\sigma(D^*)$ &gt;: 3.8 ± 1.3</td>
<td>28</td>
</tr>
<tr>
<td>175/200</td>
<td>Be</td>
<td>&lt; $\sigma(D^*)$ &gt;: 8.5 ± 1.5</td>
<td>28</td>
</tr>
<tr>
<td>200</td>
<td>Be</td>
<td>$\sigma(D\bar{D})$: 34 ± 8</td>
<td>32</td>
</tr>
<tr>
<td>217</td>
<td>Be</td>
<td>$\sigma(D\bar{D})$ : diff. : 20 to 50</td>
<td>29</td>
</tr>
<tr>
<td>278</td>
<td>Fe</td>
<td>$\sigma(D)$ : 8.2 ± .9, $\sigma(\bar{D})$: 9.5 ± .7</td>
<td>30c</td>
</tr>
<tr>
<td>280</td>
<td>C, Pt</td>
<td>$\sigma(D\bar{D})$: &lt; 35 ± 11</td>
<td>41</td>
</tr>
<tr>
<td>340</td>
<td>ClF6</td>
<td>$\sigma(D\bar{D})$: 28 ± 11</td>
<td>9</td>
</tr>
<tr>
<td>360</td>
<td>p</td>
<td>$\sigma(D^0,D^-)$ : 31$^{+14}_{-7}$</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\sigma(\bar{D}^0,D^+)$ : 9$^{+7}_{-5}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\sigma(A^+_{C})$: 20</td>
<td></td>
</tr>
</tbody>
</table>
The data on $\Lambda_c^+$ production do not give a coherent picture; at $\sqrt{s} = 27$ GeV one finds cross sections of about 3 nb (using $\Lambda_c^{2/3}$) for diffractive production [30c] up to about 100 nb for inclusive production [24].

Finally a large cross section for $\Lambda^+$ production by a 135 GeV/c $\pi^-$ beam should be mentioned: $\sigma(x > 0) \simeq 5$ to 13 ub [27a].

(b) $\pi^-$ beams (see table 1(b)): Recent $D^+$ [27c, 28] and $D^0$ cross sections [9, 25, 27d, 28, 29, 30c, 32] as well as one estimate of $\Lambda_c^+$ production [25] are shown in fig. 3(u). Also given is an earlier result [40] and an upper limit for $D\bar{D}$ production from a Drell-Yan experiment [41]. In [28] the first reliable measurement of the $s$-dependence is reported:

$$\frac{\sigma(\sqrt{s} \leq 15 \text{ GeV})}{\sigma(\sqrt{s} \leq 19 \text{ GeV})} = 0.41 \pm 0.15$$

indicating again a substantial increase with energy.
Generally it seems that π⁻ induced charm cross sections are of the same order of magnitude as cross sections from proton beams. If both processes were dominated by fusion processes one would expect much larger charm cross sections from π⁻ beams due to a large q̅q annihilation component.

3.3.2.4 Single leptons

The charm cross sections derived from measurements of single lepton fluxes - due to semileptonic decays - are subject to many assumptions. A compilation [37] of the measured quantities, i.e. of "lepton/pion ratios", is shown in fig. 3(v) for p beams. The measurements were done at x < 0.1 and p_T < 0.4 to 0.8 GeV/c, a kinematic region expected to be mainly populated by leptons from charm decay. For p_T > 1 GeV/c contributions from ψ, τ and Drell-Yan pairs are dominating. As an example of the most recent measurement the e/τ ratio is shown as function of p_T at √s = 63 GeV [31,37] in fig. 3(w). For fig. 3(v) a linear A dependence for leptons (from charm) and σ ∝ A^{2/3} for pions was assumed; contributions from known single lepton and lepton pair sources were
\[
\frac{\text{lepton}}{\text{pion}} \sim [B_{\text{eff}}(c + t x) \frac{d\sigma}{d\Omega}(c, \sqrt{s})/ \frac{d\sigma}{d\Omega}(\pi, \sqrt{s})] \times \% 0
\]

it reflects the \( s \)-dependence of the charm cross section if the effective semi-leptonic branching ratio \( B_{\text{eff}}(c + t x) \) of an unknown D-F-A \( c \) mixture is independent of \( \sqrt{s} \). The lepton/pion ratio increases by an order of magnitude between \( \sqrt{s} = 27 \text{ GeV} \) and \( \sqrt{s} = 63 \text{ GeV} \) matching roughly the \( s \)-dependence of charm cross sections in fig. 3(t). On the other hand it is not completely ruled out that this "increase" may be nothing but a consequence of low mass (< 400 MeV) dilepton production directly measured at lower energies [42]: \( \nu \) from this source would be suppressed by a factor of about 10 compared to electrons due to a much lower \( Q \) value [42]. This could also give rise to an increase of \( e/\mu \) at very low \( p_\perp \) (\( \lesssim 0.4 \text{ GeV/c} \)). To rule out contributions from this source either \( e/\mu \) and \( u/\mu \) or lepton/pion as function of \( \sqrt{s} \) should be determined by a single experiment. Also a measurement of low mass dilepton production at high energies - while experimentally difficult - seems to be interesting in its own right.

Assuming that prompt neutrinos come from decays of charm particles, one expects identical \( \nu_e \) and \( \nu_u \) fluxes. A recent compilation (fig. 3(x) updated from [43]) of relevant data on forward production (\( p_\nu > 20 \text{ GeV/c} \)) at \( \sqrt{s} = 27 \text{ GeV} \) suggests a systematic trend towards \( \nu_e < \nu_u \) for proton beams; in [30b] \( \nu_e/\nu_u = 0.79 \pm 0.19 \) was found. If the trend is confirmed by more accurate data a new phenomenon is awaiting explanation.
The antilepton/lepton ratio reflects the relative charm and anticharm production rate. With one exception [30a] all measured ratios are consistent with unity [2a] for proton beams. From a \( \pi^- \) experiment at 278 GeV/c \( u^-/u^+ = 2.23 \pm 0.29 \) was obtained for \( p_T > 20 \) GeV/c [30c], yielding some evidence for leading \( D^- \) as also suggested by [25].

3.3.2.5 Correlations

Clean correlations between charm particles were measured for the first time by the LEBC \( \pi^- \) experiment [25]. At this point it is interesting to note that no good measurement of strangeness correlations exists in the SPS/FNAL energy range.

(a) Correlations in azimuth

A distribution of \( \Delta \phi \), the difference of the azimuthal angles of a reconstructed \( D^-\bar{D} \) pair shows a rather narrow clustering near \( \Delta \phi = 135° \); naively one would expect some structure at \( \sim 180° \). The current interpretation of this feature is based upon a rather large (\( \sim 700 \) MeV/c) intrinsic transverse momentum of the gluons involved in the fusion process \( gg \rightarrow c\bar{c} \) [44].

(b) Rapidity gap distributions

The average rapidity gap is measured to be \( \langle \Delta y \rangle = 0.5 \pm 0.1 \) [44] for the LEBC \( \pi^- \) experiment in good agreement with a calculation of the fusion process [45]. For proton beams \( \langle \Delta y \rangle = 1.5 \pm 1.0 \) was found [44].

Effective mass distributions of heavy quark pairs have been calculated in the framework of \( gg \) fusion for pp collisions [46]. Fig 3(y) shows the dependence of the width (hwhm) of these mass distributions relative to the threshold mass \( m^{thr} \) as a function of \( m^{thr}/s \) for strangeness, charm and beauty production. Since the width is related to
the average rapidity gap of heavy flavour meson pairs, fig. 3(y) predicts an s-dependence of $<\Delta y>$ which could be verified experimentally. For a given $<\Delta y>$, i.e. a mass distribution of given width for the parent quark pairs, one can easily calculate the dilepton yield from semileptonic decays of both D-mesons. A comparison [46] of the dilepton spectrum calculated for $<\Delta y> = 0.5$ with dilepton cross sections measured in Drell-Yan experiments yields upper limits of 6 $\mu$b and 25 $\mu$b for $D\bar{D}$ production in pp collisions at $\sqrt{s} = 27$ GeV and $\sqrt{s} = 63$ GeV. These
upper limits saturate the measured dilepton cross section (fig. 3(z)) and
decrease with increasing $<\Lambda\gamma>$. From uncorrelated production of D$\bar{D}$ systems
("flavour excitation"), however, which is predicted to dominate D$\bar{D}$
production in pp collisions [47], both larger upper limits (7 ub and
75 ub) and $<\Lambda\gamma> \approx 1.4$ are obtained [46]. This is possible since
leptons from decays of uncorrelated charm pairs populate mainly regions of
phase space not covered by the experiments. The latter upper limits are
shown in fig. 3(t), they are about a factor of 3 lower than the cross
sections determined by charm experiments. Note also, that $\Lambda_c^+$
production is neglected in the calculations. No problem of this type is
anticipated for charm production by $\pi^-$ beams, since the measured
dilepton yields are much larger than for proton experiments [48].

A resolution of this puzzle is badly needed, it may require
substantial efforts from both charm and Drell-Yan experiments.

3.4 What the curious experimentalist wants from charm

After the mass of information reviewed in the previous sections we
offer this section by way of a summary. It contains a list of items that
any self-respecting charm programme should aim to understand. It reviews
all the puzzles, oddities and inconsistencies that we have mentioned.
Most of the points can best be studied in fixed-target experiments:

- Total cross section, $\sqrt{s}$ dependence: new energy points badly needed,
especially low energy pp.

- Channel cross sections: some anomalous high values.

- $x$ dependence: large inconsistencies; is everyone measuring the same
  quantity?

- A dependence: crucial to allow comparison of different experiments; also
  important for $x$ and $p_T$ dependence.

- Single lepton production: $e/\pi$ anomaly at very low $p_T$; $\nu_e/\nu_\mu$
puzzle.

- Charm pair correlations: rapidity gap distributions lead to
  inconsistencies in pp data.

- Dynamics of photoproduction.
- D lifetimes: still some doubts with errors > 25%.
- F, \( \Lambda_C \) lifetimes: even more so than D.
- What are the missing \( \Lambda_C \) decay modes, what does the F decay into?
- Charm hyperon production and decay properties.

With more than six years of research behind us we have only just begun to come to grips with charm physics. There are still many mysteries at the basic level. When these are all understood, we can hope to investigate more detailed properties of charm particles, such as:

- \( \Lambda_C \) polarisation versus \( p_T \) in hadroproduction.
- \( D^0 - \bar{D}^0 \) mixing parameters.
- \( \Lambda_C \) magnetic moment.

4. PRESENT EXPERIMENTAL PLANS

A summary of all approved (and not yet approved) charm experiments is given in table 2. Interestingly, there are four experiments using a bremsstrahlung photon beam, three with hadron beams (of which one has beauty as its main focus) and one with a wideband neutrino beam.

4.1 Photons

The NAL1 experiment (spokesman L. Foà) continues an already successful charm photoproduction programme [49]. With an active silicon target and the FRAMM spectrometer a relatively large sample of \( D^+ \) decays has already been accumulated and given a lifetime measurement; a few F candidates have been reconstructed [11]. The active silicon target has now been replaced by a monolithic germanium target coupled with a low density silicon telescope which improves spatial resolution in the vertex region by a factor \( \sim 3 \) allowing a study of the shorter lived charm particles (\( D^0, F, \) etc.). Data taking is expected to be completed by the end of 1983.

The proposed NAL4 extension into charm physics (spokesman D. Treille) also relies on solid state detectors [50]. The NAL4 apparatus has already collected data in a high flux high energy photon environment; for the charm extension the vertex region will consist of an active silicon target plus a system of \( u \)-strip detectors. As in NAL1, data readout is
### TABLE 2

(a) PHOTON EXPERIMENTS

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<tr>
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<tbody>
<tr>
<td>1.</td>
<td>NAL1</td>
<td>NA14</td>
<td>P182</td>
</tr>
<tr>
<td></td>
<td>FRAMM + active Ge target</td>
<td>Spectr. + active target + u strip</td>
<td>EHS + HOLEBC</td>
</tr>
<tr>
<td>2.</td>
<td>70 &lt; Eν &lt; 175 GeV</td>
<td>100 &lt; Eν &lt; 200 GeV</td>
<td>100 &lt; Eν &lt; 200 GeV</td>
</tr>
<tr>
<td></td>
<td>n ch increase in Ge.</td>
<td>n ch increase in Si.</td>
<td>Impact parameter by u strip</td>
</tr>
<tr>
<td>4.</td>
<td>~ 10^3 reconstructed D and F</td>
<td>~ few x 10^3 reconstructed D, F and Λ_c</td>
<td>~ 10^3 high quality reconstructed D and F</td>
</tr>
<tr>
<td>6.</td>
<td>Continuation of NAL programme (τ(D^±), few F, ...)</td>
<td>Semi-leptonic decays.</td>
<td>Production characteristics.</td>
</tr>
<tr>
<td></td>
<td>F, Λ properties</td>
<td>Production characteristics.</td>
<td>F properties.</td>
</tr>
</tbody>
</table>

(b) HADRON + υ EXPERIMENTS

<p>| | | | |</p>
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<thead>
<tr>
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<tbody>
<tr>
<td>1.</td>
<td>NAL1</td>
<td>NA27</td>
<td>WA71</td>
</tr>
<tr>
<td></td>
<td>&quot;ACCMOR&quot; + active target + u strip</td>
<td>EHS + HOLEBC</td>
<td>Ω + emulsion + u strip</td>
</tr>
<tr>
<td>2.</td>
<td>200 GeV/c π^-</td>
<td>360 GeV/c p</td>
<td>350 GeV/c π^-</td>
</tr>
<tr>
<td>3.</td>
<td>Charm trigger</td>
<td>Event trigger</td>
<td>Charm trigger</td>
</tr>
<tr>
<td></td>
<td>(n_ch increase in Si)</td>
<td>(n_ch increase)</td>
<td>(n_ch increase)</td>
</tr>
<tr>
<td></td>
<td>scanning</td>
<td>emission scanning</td>
<td>emission scanning</td>
</tr>
<tr>
<td>4.</td>
<td>~ 10^3 reconstructed (3c)</td>
<td>~ 500 D</td>
<td>~ 500 D</td>
</tr>
<tr>
<td></td>
<td>D by 1985</td>
<td>few B events</td>
<td>in ~ 10^3 charm</td>
</tr>
<tr>
<td></td>
<td>~ 50 F, Λ_c</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Key: 1 = Experiment code name and apparatus. 4 = Anticipated charm yield. 2 = Beam characteristics. 5 = Anticipated data taking period. 3 = Trigger characteristics (on-line and off-line). 6 = Physics aims or other comment.
triggered by the detection of a hadronic event. Charm candidates will be selected off-line by a combination of active target multiplicity jumps ('à la NA1') and non-zero track impact parameters detected by the v-strip system. The experiment is aiming for $\sim 10^5$ reconstructed charm decays which, by virtue of good acceptance characteristics, should yield high quality information on charm photoproduction properties. In addition the large statistics should allow a study of individual decay modes - such as semi-leptonic decay modes. Data taking is intended to start in 1984 and the experiment should be completed by 1986. This experiment, proposed in an addendum to NA14 [50] has yet to be approved by the SPSC.

The EHS experiment P182 (spokesman S. Reucroft) uses the successful NA16 technique involving the high resolution hydrogen bubble chamber HOLEBC as vertex detector [51]. A hadronic event triggers the bubble chamber flash and electronics readout and charm candidates are selected by scanning the bubble chamber film. The aim of the experiment is a clean, fully reconstructed sample of 100 F decays. The experiment will also yield approximately $10^3$ reconstructed charm decays in total which will give very clean background free data for the study of charm production characteristics. EHS was not designed for high sensitivity experiments and only the testing phase of P182 has been approved to date in order to prove that EHS can accept a high enough beam intensity to complete the experiment in a reasonable amount of SPS time ($< 2500$ hours). In particular, it has to be demonstrated that HOLEBC and the pictorial drift chamber ISIS can withstand the high photon flux before approval will be given for the main data taking. Subject to this caveat, data taking is expected during 1984 and 1985.

The fourth photoproduction experiment is WA69 (spokesman E. Paul) and it uses the $\Omega^+$ spectrometer with nothing trickier in the vertex region than a simple liquid hydrogen target [52]. In a sense it represents a continuation, to higher photon energies and with technical improvements, of WA4 and WA57 - both of which were referred to in sect. 3. Again the trigger is a hadronic event and the data taking, planned for 1983 and 1984, is aiming at a sensitivity of 200 evt./nb. Critical for clean charm physics is charged particle identification and it is provided in an elegant way for this experiment by the Ring-Image Cerenkov (RIC) specially built for $\Omega^+$.

4.2 Hadrons

The NA11 collaboration (spokesman R. Klanner) with long experience in the charm domain has also turned to solid state detectors for the vertex region [53]. With a 200 GeV/c $\pi^-$ beam and downstream
spectrometer (still known by the collaborations original - and no longer valid acronym ACCMOR) the active target is used at the on-line trigger level to identify multiplicity jump multivertex candidates. High-resolution u-strip detectors will allow off-line analysis of the vertex positions. Data taking is planned to continue until 1986 with an ultimate charm yield of \( \sim 10^4 \) fully fitted charm decays. These statistics should allow a precision determination (± few %) of charm particle lifetimes and give information on hadroproduction characteristics and the spectroscopy of charm particles, including decay modes of the basic states.

The EHS experiment NA27 (spokesman L. Montanet) which is in a certain sense a continuation (with major improvements) of NA16 [8,25,26] is in many ways complementary to NA11 [54]. The high-resolution hydrogen bubble chamber HOLEBC is exposed to beams of 360 GeV/c \( \pi^- \) and 360 GeV/c protons and an interaction in the bubble chamber triggers the readout of the downstream EHS electronics. Charm candidates are detected by scanning the bubble chamber photographs and experience has shown that the technique produces very reliable, clean data. The physics aims of the experiment are those stated in the previous paragraph. The \( \pi^- \) data is already taken and the proton runs are in 1983 with possible (as yet unapproved) extensions into 1984.

Another HOLEBC-EHS proposal which contains an idea worth pursuing is described in P183 (spokesman N. Kurtz). Using a high energy antiproton beam and an annihilation trigger the experiment would investigate the size of the charm component in the antiproton-proton annihilation process [55]. In its original form P183 was not recommended for approval by the SPSC and is not included in Table 1. This experiment will be mentioned again in the next section.

The previous two experiments (NA11 and NA27) are dedicated to charm physics. The WA71 experiment (spokesman G. Diambrini-Palazzi) is actually aiming at a small sample of reconstructed B decays, but the technique is such that a sizeable charm sample should be accumulated as a background [56]. Using the \( \Omega' \) spectrometer for downstream analysis an emulsion stack is exposed to a 350 GeV/c \( \pi^- \) beam. Solid-state detectors are envisaged as on-line charm decay detectors (via multiplicity jumps) and the beauty candidates are sought during emulsion scanning. Since many of the charm triggers will give simply another charm decay in the emulsion, the experiment could give \( \sim 10^3 \) reconstructed charm decays. Data taking should be completed by the end of 1984.
4.3 Neutrinos

The only neutrino experiment with an emphasised interest in charm physics is WA21 (spokesman G. Myatt). The large hydrogen bubble chamber BEEC will be exposed to the wideband $\nu$ beam and photographed holographically in order to achieve high-resolution over a large bubble chamber volume [57]. Data taking is anticipated to be completed by the end of 1984 and could, depending on the achieved optical resolution, give several hundred observed and reconstructed charm decays. The experiment is unique in that it can give high-precision charm particle mass determinations along with neutrino-production characteristics. This has not yet been approved by the SPSC.

5. A GLIMPSE AT FUTURE SPS AIMS AND TEVATRON PLANS

It is evident from the previous section that the present round of approved (and proposed) SPS charm experiments should collect $\sim 10^3$ to $10^4$ identified charm decays by $\sim 1986$. Analyzing the data will take on average $\approx 1$ year per experiment and so we can anticipate having several top quality charm samples under scrutiny before 1987. Since the data will be accumulated under a variety of experimental conditions, this situation is very healthy indeed.

Experimental physicists are by nature careful creatures and it is quite difficult to anticipate the next generation of experiments; future steps depend critically on the experience gained during the present generation. One obvious area of uncertainty involves the performance of the solid-state devices which are at present receiving so much attention. Five years ago nobody could have imagined that the best data available today on charm hadroproduction at the SPS comes from an experiment using a liquid hydrogen bubble chamber.

Nevertheless, based on the most likely outcome of the experiments reviewed in the previous section, several of the existing collaborations have quite well defined plans for the future, notwithstanding the large uncertainty in time-scale.

Both NA11 and NA14 collaborations have plans to attack the problems associated with beauty physics and these thoughts are reviewed elsewhere [58]. The NA1 collaboration is planning a study of diffractive charm baryon production using a high energy proton beam with the active target plus FRAMM spectrometer set-up. Since the NA1 collaboration present experiment is due to finish by 1984, the charm baryon experiment is planned for the years 1984-1986 and is therefore, in a sense, more a contemporary of the experiments of the previous section than a future aim.
The $\gamma'$ photon collaboration WA69 is considering equipping the vertex region with solid state detectors to develop an on-line charm trigger. The eventual aim would be to run with hadron beams to allow a detailed comparison of charm production with a variety of beam particles but under exactly the same experimental conditions. This programme could commence around 1986 and would presumably continue for several years.

The EHS groups are considering several alternatives with the main aim being to escape the image of high quality, low statistics data and proceed towards high statistics experiments. Thus an experiment using a high energy (mean value $\approx 320$ GeV), high flux neutron beam is being planned. The advantage of using a neutral beam is obvious; EHS sensitivity limitations originate in the large number of charged tracks in the beam region. With a high sensitivity option, scanning can no longer be a feasible charm selection procedure and work is continuing on the use of solid state detectors downstream of the bubble chamber to select (off-line) charm candidates. A high energy photon experiment is already amongst the list of current EHS experiments. Experience will tell whether or not this experiment, with its intrinsic factor of 10 gain in charm signal to non-charm background, can become a high sensitivity experiment. One attractive feature of EHS is the large variety of beam particles that can be provided. The interest in using an antiproton beam ($\approx 125$ GeV/c) has already been mentioned and this could lead to a high statistics experiment; another possibility being considered is to use the enriched K$^+$ beam ($\approx 250$ GeV/c) to study F production. The large pictorial drift chamber ISIS is being modified to shield the sense wires in the beam region and HOLEBC flux restrictions will be solved by holographic photography which allows high resolution over the whole bubble chamber volume and therefore gives the bubble chamber a higher flux capability.

Another direction being considered by EHS groups is to simply continue with the successful (from a quality point-of-view) if statistics limited NA16/NA27 technique to study the $\sqrt{s}$ dependence and $A$ dependence of charm production by varying beam energy and bubble chamber liquid. Such a research programme should take several years but would ultimately be a most important contribution to charm physics.

In spite of the recent exciting result on the charm hyperon $A^+$ [27a], at present there are no definite plans for charm hyperon physics and there is no hyperon beam at CERN. Several possibilities are being studied although beam constraints restrict the number of potential locations. EHS offers some advantages, although a more realistic idea seems to be to couple a future high energy hyperon beam to the heavy flavour spectrometer discussed below.
The rather conservative approach at CERN can be compared with the plans for charm physics at the TEVATRON [59]. A first glance indicates the greater ambition of the FNAL groups; a closer inspection uncovers the more adventurous approach to proposal writing but, more importantly, pinpoints the different areas of emphasis in the two laboratories. These differences are discussed in the next paragraphs where, without giving details, we mention the FNAL charm plans.

Experiment E653 (spokesman W. Reay) has grown out of the successful E531 collaboration which played an important rôle in charm lifetime determinations [10]. Instead of the neutrino beam used before, E653 will expose the emulsion stack to a high energy proton beam. This is the only FNAL experiment which closely matches the CERN philosophy with its emphasis on high resolution vertex detection. In general, the focus is on exceptionally high data acquisition rate and this is no more clearly underlined than in the plans of E690 (spokesman B. Knapp). There is nothing particularly unconventional in their apparatus but by virtue of a highly sophisticated on-line data acquisition system they plan to accept $10^6$ interactions per second and reconstruct $10^8$ charm decays per hour. Selecting the charm decays will then be an off-line problem.

Experiment E687 (spokesman J. Butler) which uses the E400 spectrometer has high resolution detectors near the vertex region but again the startling feature is the high proposed data rate. Ultimately there is no concrete reason to expect higher charm yields at FNAL; the production cross section should be higher but the shorter machine cycle time at CERN should compensate for this. CERN experiments tend to quote the final sample size after applying all selection criteria and inefficiencies; FNAL experiments give the number of events one gets with the most loose trigger configuration and the analysis techniques and losses are not discussed. Time scales are such that the FNAL programme is unlikely to be completed before ~ 1986.

Both laboratories can and should benefit from the approach of the other. The time is right for the FNAL collaborations to concentrate on high resolution vertex detection. The CERN groups with much expertise already accumulated in this area can now apply more effort to high-speed data acquisition. In particular, the idea of writing an unbiased, very large sample of events on tape using a minimum bias on-line trigger and using off-line selection to provide charm (and beauty) samples is worth pursuing.

With these points in mind we consider the parameters of an apparatus ideally suited for heavy flavour physics. None of the present CERN set-ups is strong on all requirements and it would be timely to plan now the most appropriate device for the next generation of charm and beauty experiments. Based on all available experience, the set up would have:
- high resolution vertex detection;

- an efficient, high rate multiparticle spectrometer with particle identification capabilities;

- a variety of trigger possibilities.

There is no perfect vertex detector. The hydrogen bubble chamber is strong on every point except data rate. In addition, a variable material vertex detector has to be available to allow A-dependence studies. Potentially, the high resolution solid state detectors satisfy most requirements. Probably the best solution is to have a modular vertex region allowing the use of solid state detectors and/or a bubble chamber and/or an emulsion stack.

The spectrometer has to handle a beam flux up to $10^7$ particles per second with good acceptance for final state charged and neutral particles (to allow charm reconstruction from $x = 1.0$ to $x \sim -0.5$). The effective mass resolution at the D should be $\sim 10$ MeV. Charged particle identification over the full momentum range is an absolute must with good efficiency for neutral particle reconstruction ($K^0, \Lambda, \pi^0, \gamma, n, \bar{n}$). Lepton identification is desirable - at least for $p_T > 0.4$ GeV/c. (An interesting approach is given in [60] with the emphasis on lepton identification). Finally, and most important, there has to be a very fast data acquisition system taking at most a few msec per event with high speed event reconstruction.

There is no known solution to the trigger problem and the fail-safe approach is to accumulate all data and select candidates off-line. On-line multivevertex detection via solid-state detectors gives all indications of being the best solution.

6. CONCLUDING COMMENTS

We have come a long way since the discovery of naked charm, but we have a long way to go. As we have said, the present situation at CERN is healthy and complements well the FNAL programme. However, many of the currently known mysteries and problems and many of the desired measurements will not and cannot be handled from the next round of experiments. In addition, as the old non sequitur goes, we have to expect the unexpected. We are, therefore, guaranteed a far future programme of research if we are ever to understand charm.
Realising the exact status of the world charm programme, digging into
individual experiments in an often highly self-critical manner and brain-
storming the far future was the task of the small group of physicists
mentioned earlier. It was a pleasure working together and we would like
to acknowledge them: Maurice Bourquin, Lorenzo Poà, Bernard French,
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Peter Schmid, Guy Vanderhaeghe, Peter Weilhammer and Peter Wright. In
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* * *

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SEARCH FOR BEAUTY PARTICLES AT THE CERN SPS

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ABSTRACT

The present status of our experimental knowledge on B-hadron decay and production processes is briefly reviewed. Some ideas are presented on how the future research programme on B-particles could evolve at the CERN SPS.

1. INTRODUCTION

This talk will be divided into four parts. I will first make a brief review of what we presently know about the B-hadron decay and production properties from the experimental point of view. After a short presentation of the approved CERN programme of Beauty searches, I will devote most of the time to the discussion of different ideas which were developed during the weeks preceding this Workshop on how this programme could evolve in the next few years. To conclude, I will present some personal impressions.

2. OVERVIEW OF WHAT EXPERIMENTS HAVE ALREADY TOLD US ABOUT THE B-HADRÓN DECAY AND PRODUCTION PROCESSES

2.1. B-hadron decay

Our present knowledge on Beauty hadron decays comes exclusively from experiments carried out at e+e− colliders (CESR, PEP and PETRA). Table I summarizes the main known B-hadron properties and decay characteristics as determined from a mixture of charged and neutral B-hadrons, mostly B-mesons.

It is seen that the B-hadron lifetime is not yet very well constrained experimentally. Should this lifetime be greater than or of the order of 5 x 10^{-14} s, tracks of B-hadrons would be observable by means of various visual detectors such as nuclear emulsion and high resolution bubble chambers as well as in silicon active targets; however, for lifetimes as short as 10^{-14} s only nuclear emulsion would be useful.

From the high mass of the B-hadrons one expects their decays, due to the high Q-value, to exhibit high multiplicities (see Table I) and to lead to secondaries with large transverse momenta. Both these features are useful in designing triggers for experiments looking at B-hadron production. On the other hand, many decay channels being accessible – each with rather small branching fraction – the search for B-particles by hunting for narrow peaks in invariant mass plots will be difficult. Note, in particular, that no exclusive decay mode has been definitely isolated up to now.

From the shape of both the electron and the muon momentum spectra in the semi-leptonic B-hadron decays it has been established that the b-quark

* Talk given at the CERN SPS Fixed Target Workshop (December 1982).
decays predominantly into the c-quark, there being no evidence for a decay transition to the u-quark\textsuperscript{2,3}. This b→c dominance offers the interesting possibility of tagging B\overline{B} pair production in hadron or photon induced reactions either via the detection of their charmed decay products (e.g. increase in particle multiplicity occurring near the production vertex) or by selecting multimuon or multikaon events\textsuperscript{x}). It could also prove to be helpful in reducing the combinatorial background in mass plot studies by introducing additional constraints. At variance, it will probably make the detection of semi-leptonic B-hadron decays somewhat difficult in high resolution visual detectors. Indeed, the average charged multiplicity in D, D* meson decays being 2.5 ± 0.1\textsuperscript{5), these semi-leptonic modes will usually be of low charge multiplicity, i.e. one or two prong events:

\[
B \rightarrow l^\pm + \nu + (D, D^*) + n\pi^\pm (n = 0.55 \pm 0.35 \pm 0.2)
\]

with the D-meson decaying a few millimetres away from the B-hadron decay point.

It has been suggested by Fritsch\textsuperscript{6)} that the decay mode B → ψ X which he and others\textsuperscript{7)} have estimated to occur at the level of 2 to 3 % could constitute a clean signature for identifying B-mesons via the observation of the distinctive two body modes \(\psi \rightarrow e^+ e^-\) or \(\psi \rightarrow \mu^+ \mu^-\). Until now, however, no such decay has been observed and the present experimental 90 % C.L. limit for its branching ratio is 1.4\textsuperscript{2,8)}.

Finally, the data are consistent with the standard six-quark electroweak model.

2.2 B-hadron production

a. Hadroproduction

The present experimental situation concerning the production of B-particles in hadronic interactions at the CERN SPS and FNAL energies is summarized in Table II. No positive signal for Beauty has been found yet and the 90 % C.L. limits on the production cross sections range from about 100 nb to a few nanobarns. Several comments have to be made:

i) only one of the quoted experiments, namely WA\textsuperscript{17)} is of the "peak hunting" type; B-mesons have been searched for in different final states containing a ψ meson and a kaon. The branching fractions of these final states being unknown, only limits on \(\sigma \times Bf\) can be quoted (see Table III)

ii) NA\textsuperscript{19,13} is an emulsion-counter hybrid experiment looking for B → C → X

\textsuperscript{x}) The inclusive production of neutral and charged kaons has been studied on and around the \(Υ(4S)\) resonance by the CLEO Collaboration\textsuperscript{2,4). From this analysis it is inferred that the average number of kaons per B-hadron decay is about 1.5
cascade decays tagged by the presence of 3 or 4 muons. Should the B-hadron lifetime be shorter than $10^{-14}$ s, or much longer than $10^{-12}$ s the sensitivity of this experiment would be almost zero.

iii) the acceptance of most of the experiments is very low (a few %). Cross section estimates are therefore strongly model-dependent. Central or nearly central production is generally assumed as well as a linear A dependence for the cross section. This is not the case for the CCFRS experiment\textsuperscript{15} which is only sensitive to forward produced B-hadrons because it triggers on energetic muons.

iv) If the small values of the cross sections reported by the NA3 Collaboration\textsuperscript{12} are confirmed, B-hadron studies at SPS energies would appear as a difficult experimental challenge. Note that for diffractively produced $B\bar{B}$ pairs their quoted cross sections would be a factor five larger.

These results are shown in fig. 1 together with the estimated cross section corresponding to the observation of a Beauty baryon at the CERN ISR by the BCF Collaboration\textsuperscript{16} \textsuperscript{*}. The curve, taken from F. Halzen's report at the Paris Conference\textsuperscript{18}, represents the prediction for B-hadron production based on perturbative QCD including quark-quark and gluon-gluon diagrams as well as quark excitation contributions. Omitting these last contributions would significantly lower the curve and give fair agreement with the latest results of Badier et al\textsuperscript{12}.

b. Muon- and Photo-production

The only available data on the photo-production of B-hadrons come from two high energy muon experiments.

i) The Berkeley-Fermilab-Princeton Collaboration at FNAL\textsuperscript{19}

The experimental characteristics of dimuon final states from 209 GeV muon interactions in a magnetized iron calorimeter have been compared with the predictions of a Monte Carlo simulation of $B\bar{B}$ production based on the photon-gluon fusion model. From this comparison a 90 % confidence level upper limit of $17 \times 10^{-36}$ cm$^2$ has been set on the cross section of the process $\mu^- + Fe \to \mu^- + B + \bar{B} + X$.

ii) The European Muon Collaboration at CERN\textsuperscript{20}

Three wrong sign trimuon events ($2\mu^+ \mu^- \mu^+$ and $1 \mu^+ \mu^- \mu^-$) have been observed in 250 GeV positive muon interactions in an iron target which could be attributed to the reaction $\mu^+ + Fe \to \mu^+ + B + \bar{B} + X$ followed by the muonic decays of the $B(\bar{B})$ and the $D(D)$ from the associated $\bar{B}(B)$ decay. Assuming one event to be due to background and a mean semi-leptonic branching ratio for both charm and beauty decays of 10 %, the signal corresponds to a $B\bar{B}$ production cross section of $(5 \pm 5) \times 10^{-36}$ cm$^2$.

\textsuperscript{*} It should be mentioned that no Beauty signal was found by the ACDHPW Collaboration\textsuperscript{17} working at the ISR under similar although not identical conditions.
Both these results, expressed in terms of $B\bar{B}$ photoproduction cross sections, are shown in fig. 2 and compared with the predictions of the photon-gluon fusion model in the leading order which is seen to reproduce very well the open charm photoproduction data obtained by the European Muon Collaboration\(^{21}\).

c. Neutrino production

$B$-hadrons can be produced by (anti)neutrinos via processes of the type $\bar{\nu} + u$ (or $c$) $\rightarrow \mu^+ + b$ and $\nu + c \rightarrow \mu^- + \bar{b}$ which are expected to lead to multilepton events. The experimental situation can briefly be summarized as follows

i) opposite sign dileptons are well accounted for by charm production\(^{22-24}\). It may be worth mentioning the suggestion made by N. Armenise et al\(^{25}\) that an excess of events observed around 6 GeV/c\(^2\) in the invariant mass of the hadronic system associated to dimuon events induced by antineutrinos could at least partly be attributed to the quasi elastic production of $B$-baryons.

ii) trimuons are mainly due to muon pair production in the hadronic shower or of electromagnetic origin. Less than 10% of the signal, which is at the level of about $10^{-5}$ times the charged current interaction rate, could be due to beauty hadron production\(^{26}\).

iii) like sign dilepton events remain difficult to interpret. The general characteristics of the events are quite similar to those of opposite sign dimuons but the observed rate is 5 to 10 times bigger than what one would expect for associated charm production and beauty production\(^{23,24}\).

2.3. Conclusion

To conclude, I will say that however one searches for $B$-particles at the SPS, one will have to overcome two major difficulties: small production cross sections and small signal to noise ratios.

3. THE PRESENTLY APPROVED SPS PROGRAM FOR BEAUTY SEARCH.

Two experiments – WA71\(^{27}\) and WA75\(^{28}\) – are now being installed in the upgraded CERN West Area and will be run in the second half of 1983 and during 1984 to search for Beauty hadrons in high energy $\pi^-$ meson interactions. Both experiments have been designed for estimating the $B$-hadron lifetime and will make use of large volumes of photographic emulsion as target and vertex detector. Their main characteristics are summarized in Table IV. They mainly differ in the procedure used to select and detect the $B$-hadron production and decay chain. In the WA71 experiment, which will benefit from the full particle identification power provided by the $D$'spectrometer, the $B$-hadron selection is made via the identification of secondary charmed particle decays, detected by observing jumps in particle multiplicities in a silicon
counter telescope immediately downstream of a thin (1.2 mm) emulsion layer. A sketch of the target and telescope set-up is given in fig. 3. In the WA75 experiment, a rather thick (2 to 4 cm) emulsion target is located in front of a tungsten-iron dump followed by a muon analyzer consisting of a superconducting magnet and a system of scintillator hodoscopes and drift and multwireproportional chambers separated by iron walls. This set-up is illustrated in fig. 4. Single high transverse momentum muons and multimuons will be used to tag the interesting events. B\bar{B} production will be almost unambiguously identified by observing both B(\bar{B}) \to C(\bar{C}) \to hadrons decay cascades in the emulsion. The sensitivity of these experiments is \sim 0.3 event/nb for WA71 and \sim 1.5 events/nb for WA75. The possibility of increasing the sensitivity of the WA71 experiment to \sim 1 event/nb by implementing a high p_T electron trigger is under study. It is to be remarked that this experiment will also accumulate a few hundreds of charmed particles.

4. PROSPECTS FOR BEAUTY PARTICLE PHYSICS AT THE CERN SPS

I will now present various ideas and proposals about how to proceed further with B-particle physics at the CERN SPS. All these projects were discussed during the weeks preceding the Workshop and some of them were presented during the parallel sessions. The comparison of their relative merits should be made, however, with caution because they have not all reached the same level of maturity. It should be emphasized also that if the hadroproduction cross section of B\bar{B} pairs happened to be at the level of a few nanobarns, as claimed by Badier et al.\textsuperscript{12)}, the feasibility of many of the proposed experiments should be reconsidered.

I will discuss in turn the different projects based on the use of visual detectors and active targets, and two target-calorimeter projects.

4.1. Projects based on visual detectors and active targets

a. A reappraisal of a proposal submitted one year ago to the SPS Committee by a Bologna-Firenze Collaboration\textsuperscript{29}) has been made by the authors\textsuperscript{30}). This proposal is quite similar to the approved WA71 experiment\textsuperscript{27}) as it aims to estimate the lifetime of B-particles produced by energetic \pi^- mesons in a nuclear emulsion target located in the \Upsilon magnet. It differs, however, on two points:

i) use is made of a telescope consisting of planes of solid state area image sensors (Charged Coupled Devices) as high resolution vertex detector; it will allow a vertex in the emulsion to be located with an accuracy of 10 \mu m across and 100 \mu m along the beam as well as a two vertex separation of about 500 \mu m

ii) the trigger exploits the b-c dominance in the B-particle decay by requiring three charged kaons in the final state. In the momentum range
from 5 to 70 GeV/c the kaons are identified by the Ring Imaging Cerenkov counter of the φ' spectrometer. It has been estimated by Monte Carlo simulation that such a trigger will select 15% of the kaons from \( B \bar{B} \) events (assuming central production) and \( 1.8 \times 10^{-3} \) of those from background origins. Requiring, in addition, a two-vertex configuration as identified by the CCD telescope will reduce these figures to 10% and \( 3 \times 10^{-4} \) respectively. The sensitivity of the experiment is claimed to be about 3 \( B \bar{B} \) events/nb.

b. **The EHS prospects**

The very nice results on charmed particle lifetimes recently obtained by the NA16 Collaboration \(^{31}\) have proven that, even in an incomplete version, the European Hybrid Spectrometer is an efficient detector for studying these short-lived particles. There is no doubt, after what we heard from S. Reucroft at this meeting \(^{32}\), that in its complete configuration EHS will remain a basic instrument for charm physics at CERN for at least a couple of years.

It is natural to investigate the feasibility of Beauty searches in this detector. In evaluating more quantitatively these prospects, the following assumptions have been made:

i) the vertex detector HOLEBC is equipped with holographic optics and runs at a repetition rate of 30 Hz, a camera repetition rate of 15 Hz and with a 500 µs sensitive gate.

ii) the tolerable number of beam tracks per hologram is 200. In the case of an incident photon beam, the flux limitation is mainly due to the electron pairs background.

iii) a "charm" selecting \(^{x}\) trigger is installed which allows an improvement by about a factor 5 in the charmed to non charmed event ratio, the efficiency for selecting charged events being kept at a level of 30%.

Table V gives the expected numbers of \( B \bar{B} \) pairs produced in a 50 days EHS run with incident charged hadrons, neutrons and photons assuming an overall SPS-EHS efficiency of 50% \(^{33}\). With the anticipated spatial resolution of 10 µm, the detection efficiency is estimated to be 0.3 if the \( B \)-particle lifetime is \( 5 \times 10^{-14} \) s. A further reduction factor must be applied if one requires the decay to be fully reconstructed in the spectrometer.

The conclusion of this exercise is that the sensitivity is much too low to perform a Beauty experiment in the present EHS set-up.

c. The rapid development of Silicon microstrip detectors has provided a new way to study short-lived particles. Two of the groups working at CERN with this technique have looked into its possible use for \( B \)-particles searches.

\(^{x}\) A multivertex trigger is presently under study.
P. Weilhammer has discussed two approaches for studying the hadroproduction of $B\bar{B}$ pairs. The first one can be viewed as an extension of the recently approved NA32 experiment aiming at accumulating large statistics of charmed particles. It is suggested to install a segmented active target made of fine grained silicon counters in front of the existing spectrometer of the ACCMOR Collaboration (fig. 5.a). This device will measure the longitudinal development of the charged particle multiplicity in order to determine the position of the primary vertex and to detect short-lived particle decays by comparing the charged particle multiplicities at the vertex and at about 30 mm downstream. The target is followed by successive doublets of Si counters to reconstruct primary and secondary tracks and to achieve the track matching between the target and the forward spectrometer. It is expected to augment the event rate by a factor of about 50 with respect to the NA32 experiment if allowance is made for reasonable technical developments of the Si counter technology (better spatial accuracy, more efficient read-cut electronics, bigger detectors ...) and for the higher incident energy (350 GeV instead of 200 GeV). One can thus foresee to reconstruct about one thousand charm decays per day. Under the (optimistic) assumption that 0.5% of charmed particles come from B-hadron decays, Weilhammer estimates that some 500 events containing a $B\bar{B}$ pair, where one decay charmed particle has been reconstructed, can be obtained in 100 days of running. However, the problem remains of separating these events from the 100,000 directly produced charmed particles. The only efficient procedure seems to be the study of the impact parameter distribution for all fully reconstructed charmed hadrons decaying into charged particles in order to identify cascade decay processes ($B \rightarrow C + X$). For a B-hadron lifetime of $5 \times 10^{-14}$ s and assuming an accuracy of 5 μm on the impact parameter, a final signal of 50 $B\bar{B}$ pairs over a background of 150 $C\bar{C}$ events is obtained.

A more promising approach could consist in identifying B-particles via measuring muon impact parameters. A 20 mm beryllium target followed by Si microstrip counters for impact parameter measurement is located in front of an instrumented muon identifier (fig. 5.b). For a beam intensity of $\sim 10^7 \pi^-$ mesons of 350 GeV/c momentum per burst, and a $B\bar{B}$ pair cross section of 10 nb, one can expect to collect a few tens of muonic B-hadron decays per day, however depending on the trigger conditions (minimum energy of the accepted muons) about 10 to 100 times more muonic charmed particle decay will be recorded. The separation of both contributions could be achieved by imposing additional cuts on the muon transverse momenta, and by looking at like sign dimuons and multimuons. It should be noted that the association of the trigger particles with tracks in the Si microstrip counters is not trivial ($\Delta \theta_{\text{Coul}} \sim 2.5$ mrad per metre of iron for 50 GeV muons) but could be done by adding multiwire-proportional chambers of 0.5 to 1 mm pitch between the Si counters and the muon.
filter.

ii) The use of semi-leptonic (electronic) decays to tag photoproduced $B \bar{B}$ pairs has been advocated by P. Roudeau\textsuperscript{36}). The proposed set-up is sketched in fig. 6.a. The vertex detector, located in a magnet in front of the NA14 spectrometer\textsuperscript{37}), consists of an emulsion-polystyrene sandwiched target of 0.13 radiation length, followed by sets of Si microstrip counters to predict the vertex position in the target and to measure the impact parameter of "prompt" electrons. An energetic high intensity photon beam ($1.2 \times 10^6$ photons above 100 GeV per pulse) is obtained from bremsstrahlung radiation of a wide momentum $e^-$ beam resulting from the dump of $3 \times 10^{12}$ protons per pulse on a target\textsuperscript{x}). As seen in Section 2.2.b., not much is known about the photoproduction of $B$-particles. Different calculations based on photon-gluon fusion and vector meson dominance models predict, in the considered energy domain, cross sections ranging from less than 1 nb to a few tens of nanobarns\textsuperscript{38}). In his presentation, Roudeau has estimated that for $2 \times 10^5$ pulses in the considered beam, the number of $B \bar{B}$ produced could range from 100 (for $\sigma = 1$ nb) to 840. Requiring electrons of transverse momentum greater than 1.2 GeV/c will almost totally kill the normal hadronic background, leaving a signal of 10 ($\sigma = 1$ nb) to 80 $B \bar{B}$ pairs over 1000 $C \bar{C}$ pairs. Further reduction of the charm background will be achieved e.g. by selecting high multiplicity events, events with high transverse momentum hadrons, ... or by studying invariant mass distributions. It is worth mentioning that the use of an emulsion target makes it possible to identify unambiguously $B \bar{B}$ pairs by the direct observation of the $B \rightarrow C \rightarrow X$ decay chain. At variance, working with emulsion in an intense electromagnetic background, even if it is concentrated at low energy, is an experimental challenge. The use of an emulsion/polystyrene sandwiched target will probably make easier the tracing back of energetic particles as schematically described in fig. 6.b.

d. It has been suggested by R. Meunier and F. Rorhbach\textsuperscript{39}) that a detector made up of a nuclear emulsion target, an avalanche chamber and a spot focusing Cerenkov counter - all install in front of a good forward spectrometer (EHS, $\pi'$, ...) - would constitute a powerful device to study short-lived particles (see fig. 7). Nuclear emulsion has the best spatial resolution of all visual detectors; the flux intensity which can be tolerated is limited only by the availability of large emulsion volumes. An avalanche chamber, close to the target and placed in a magnetic field, will make it possible over a large angular acceptance, to measure the momenta of charged particles coming from the primary vertex in the emulsion, to identify $V^*$ particles and to detect kinks only a few millimeters from the vertex. It is a detector with almost no material, ensuring thus the conservation of the primary par-

\textsuperscript{x}) Methods based on coherent bremsstrahlung could lead to enhancement factors of 2 to 3 in the flux of high energy photons for the same number of electrons.
ticle multiplicity from the target to the spot focusing Cerenkov counter*) which is placed behind the chamber. This counter working above the Cerenkov threshold is insensitive to low energy particles, recoiling protons, soft γ rays, ... and will be used to provide a true multiplicity trigger. From the on-line pulse height scan of the phototube matrix collecting the Cerenkov light, the presence of all particles within a given γ range can be detected. The position of the spot on the matrix gives the emission angle of the particle. Combining this information with momentum measurements could prove to be extremely useful in designing selective on-line triggers to tag short-lived particles.

4.2. Target-calorimeter projects

Should the lifetime of the B-particles be shorter than 10^{-14} s the only remaining way to study them would be by performing either beam-dump or target-calorimeter experiments. Two suggestions along the latter line have been put forward by some members of the European Muon Collaboration^41) and by part of the laboratories involved in the WA75 experiment^42). In both cases the B-particles will be tagged via the detection of multimuon final states. By combining the measurement of the muon transverse momenta with the missing energy carried away by the neutrinos, as estimated in the target calorimeter, it will be possible to reduce strongly the τ and K meson decay background which is known to concentrate at small missing energy and very small transverse momentum values.

a. The EMC proposes to increase by a factor 500 the luminosity of the NA2 experiment in which three wrong sign trimuons have been observed^20). It is therefore suggested

i) to replace the iron Sampling Total Absorption Calorimeter located in front of the NA2 forward spectrometer by a uranium STAC of 0.8 cm sampling providing a mean density of material of about 10 g/cm.

ii) to run for about 40 days at an intensity of 10^8 muons per pulse with a spill length of 2 seconds as compared to the 4 day-run of NA2 with a mean intensity of 1.5 \times 10^7 muons per pulse and a 800 ms spill.

Such beam conditions require some modifications to the NA2 spectrometer allowing for a clean pattern recognition in high electromagnetic background and improving the tracking efficiency in the region close to the beam.

Using the γ-γ fusion model to describe the B̅B̅ photo-production process, the expected numbers of events are about 1000 wrong sign trimuons and about 50 tetra muons. Such trimuon event statistics will allow an investigation of the $Q^2$, $\nu$, $Z$ and $p_T$ dependences of the B̅B̅ production cross sections.

*) The spot focusing Cerenkov counter* can be seen as a ring imaging Cerenkov counter in which a subtraction of a fixed angle $\theta$ is performed optically to the Cerenkov angle $\theta$. For a particular value $\gamma_\theta$ of the Lorentz factor, $\theta = \theta_\gamma$ and the Cerenkov light is focused on a spot.
in the threshold region. In addition, it is anticipated that the experiment will be sensitive to $D^0\bar{D}^0$ mixing effects at the level of $\sim 0.1\%$. Fig. 8 shows, indeed, that the muons from B and D decays have quite different $p_T^2$ dependences and that B-decays dominate at large $p_T^2$. The limit on $D^0\bar{D}^0$ mixing will be obtained by assuming that all the signal at large $p_T^2$ values is from $BB$ production and then parameterising the lower $p_T^2$ region.

b. The other calorimetry experiment\textsuperscript{42}) aims at a high sensitivity measurement of the processes

\[ \pi^- + N \rightarrow \mu^\pm + \mu^\pm + X \]

\[ \pi^- + N \rightarrow 3(\text{or } 4) \mu^\mp + X \]

at 350 GeV beam energy. It is proposed to install a uranium STAC (1.5 cm sampling; $\Delta p/E \sim 0.1/\sqrt{E}$) in front of the muon analyzer of the WA75 experiment\textsuperscript{28}) and to run the experiment at an intensity of $\sim 1.5 \times 10^7$ pions/burst. Several technical problems, not yet fully resolved, related to the use of the calorimeter at such a beam intensity have been discussed by M. de Vincenzini\textsuperscript{42}) (radiation damage, photomultiplier problems, pile-up effects, ...). Demanding two muons at the end of the muon analyzer ($\mu^\mu > 10$ GeV) will lead to the excessive trigger rate of 1500 events/burst which is expected, however, to be reduced to $\sim 100$ events/burst, without rejecting too many $BB$ events, by introducing, on line, cuts on variables such as the muon emission angle, the pulse height in the calorimeter, ...

Event rates have been estimated by Monte Carlo simulation assuming either a central production of $BB$ pairs with the following differential cross section

\[ E \left( \frac{\Delta q^3}{dp^2} \right) \sim (1 - |X|)^{3-2p_T} \]

or a production mechanism "à la Brodsky"\textsuperscript{43}) from an intrinsic beauty component. Describing the $B$-particle decay by the standard 6 quark electroweak model, the results of the simulation are given in Table VI in the case of like sign dimuon events for a total irradiation of $2 \times 10^{12}$ $\pi^-$ mesons of 350 GeV/c momentum and a $BB$ production cross section of 5 nb with a linear $A$ dependence\textsuperscript{49}). Two main sources of background have been considered

\[ \pi^- + N \rightarrow \mu^+ + \mu^- + X \] \hspace{1cm} (1)

\[ \pi^- + N \rightarrow D + \bar{D} + X \]

\[ \rightarrow \mu^+ + \mu^- \] \hspace{1cm} (2)

\* This assumption is not well justified for the Brodsky production mechanism.
where one of the "prompt" muons is associated with a muon from \( \pi \) or K meson decay. \( \tau \), K and D meson production and decay were simulated by Monte Carlo calculations whilst experimental data were used to estimate the contribution of the Drell-Yan process to the background. It is seen from Table VI that applying correlated cuts on the muon transverse momenta and the missing energy will greatly improve the selection of \( B\bar{B} \) pairs.

5. **CONCLUDING REMARKS**

My conclusions will consist in a few personal remarks rather than in a premature attempt to define the guide lines of a long term programme for Beauty study at the CERN SPS.

i) The present constraints on the B-particle lifetime are still very weak; hopefully, the forthcoming experiments (WA71 and WA75) will provide us with the needed information.

ii) Whilst almost nothing is known about the B-particle photo- and leptoproduction, scarce data exist on their hadro-production; however, the quoted limits on the cross sections differ quite substantially and are highly model-dependent. The situation is somehow remaining of what we knew some ten years ago about the production of charmed particles. There is little doubt, however, that a confirmation of the tight limits obtained by the NA3 Collaboration would preclude an intense research programme on the hadro-production of B-particles at the CERN SPS energies.

iii) Since a few years a quite large effort has been devoted at CERN to the development of new techniques for short-lived particle studies. A lot of progress has been made on the technology of silicon microstrips counters and active targets, and first convincing physics results have been produced on charmed particles. Less impressive, but worthwhile of further encouragement, is the development of the holographic bubble chambers. Most of the groups working along these lines are presently planning or already involved in high statistics charmed particle studies.

iv) Some interesting proposals have been presented at this Workshop about the possible application of these techniques to Beauty searches. The realism of such a future programme is, of course, strongly dependent on the values of both the lifetime and the production cross sections of the B-particles.

v) If this lifetime is less than a few times \( 10^{-14} \) s, the only useful visual detector will be the nuclear emulsion. It is now widely known that the automatic scanning and measuring of emulsion pellicles is feasible. From the experience gained by our Japanese colleagues, one can be confident that scanning and measuring a few events per hour is realistic. Several European laboratories are now getting equipped with similar automatic devices.
Much shorter lifetimes would leave this field of research only open
to beam dump and/or calorimetry experiments.

vi) It does not appear very likely that the CERN SPS will become a very ef-
ficient B-particle factory, as it is for charmed particles. I am never-
theless convinced that if the production cross sections are of the order
of or greater than 10 nb and if selective, fast on-line triggers can be
implemented a Beauty physics programme will be developed at CERN, which
will favourably complement the more ambitious projects of those working
at the FNAL Tevatron. Let me remind you that a good knowledge of the
behaviour of the cross sections near threshold and of their variation as
a function of √s is of great importance in testing production mechanisms.

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32) S. Recroft, Charm Physics at the SPS - contribution to be plenary sessions of this Workshop.
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42) M. de Vincenzi, Search for Beauty in a beam dump exposition looking at multimuon events; contribution to the parallel sessions of this Workshop - see also CERN SPSC 82-61.

### Table I

Some B-hadron properties and decay characteristics

<table>
<thead>
<tr>
<th>Mass</th>
<th>( m )</th>
<th>( 5256 \pm 7 ) GeV/c^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lifetime</td>
<td>( \tau )</td>
<td>( \lesssim 10^{-12} ) s</td>
</tr>
<tr>
<td>Charged particle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multiplicity***)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- in semi-leptonic</td>
<td>( \langle n_{\text{ch}} \rangle_{\text{S.L.}} )</td>
<td>( 4.1 \pm 0.3 \pm 0.2 )</td>
</tr>
<tr>
<td>decay</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- in hadronic decay</td>
<td>( \langle n_{\text{ch}} \rangle_{\text{H.}} )</td>
<td>( 6.3 \pm 0.2 \pm 0.2 )</td>
</tr>
<tr>
<td>Semi-Leptonic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Branching fraction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- into electrons</td>
<td>( B \to e^+ + \nu + X )</td>
<td>0.126 \pm 0.014</td>
</tr>
<tr>
<td></td>
<td>( B \to \text{all} )</td>
<td></td>
</tr>
<tr>
<td>- into muons</td>
<td>( B \to \mu^+ + \nu + X )</td>
<td>0.116 \pm 0.022</td>
</tr>
<tr>
<td></td>
<td>( B \to \text{all} )</td>
<td></td>
</tr>
</tbody>
</table>

no evidence for exotic decay modes

***) All figures are taken from ref. 1.

***) \( K^0_S \to \pi^+ + \pi^- \) decays are included.
<table>
<thead>
<tr>
<th>Collaboration and references</th>
<th>Reaction</th>
<th>Beam energy (GeV)</th>
<th>Channel</th>
<th>Technique and Comments</th>
<th>$\sigma$(nb)$^*$</th>
<th>90% C.L. limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>WA1&lt;sup&gt;9&lt;/sup&gt;</td>
<td>$\pi^- \text{Be}$</td>
<td>190</td>
<td>$\psi \mu \mu K (n \tau)$</td>
<td>open spectrometer; invariant mass distributions</td>
<td>see Table III</td>
<td></td>
</tr>
<tr>
<td>CIP&lt;sup&gt;10&lt;/sup&gt;</td>
<td>$\pi^- \text{C, Cu, W}$</td>
<td>225</td>
<td>$\psi \mu \mu$, $\mu \mu \mu$, $\mu \mu \mu$</td>
<td>beam dump</td>
<td>34</td>
<td></td>
</tr>
<tr>
<td>NA3&lt;sup&gt;11&lt;/sup&gt;</td>
<td>$\pi^- \text{Pt}$</td>
<td>280</td>
<td>$\mu \mu \mu$, $\psi \mu \mu$, $\mu \mu \mu$</td>
<td>beam dump</td>
<td>50 - 100</td>
<td></td>
</tr>
<tr>
<td>NA3&lt;sup&gt;12&lt;/sup&gt;</td>
<td>$\pi^- \text{Pt}$</td>
<td>280</td>
<td>$\mu \mu \mu$, $\psi \mu \mu$, $\mu \mu \mu$</td>
<td>beam dump</td>
<td>25 - 80</td>
<td></td>
</tr>
<tr>
<td>NA9&lt;sup&gt;13&lt;/sup&gt;</td>
<td>$\pi^- \text{emulsion}$</td>
<td>350</td>
<td>$\mu \mu \mu$</td>
<td>emulsion as vertex detector in front of muon filter; search for cascade decays</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>SLC-CALTECH&lt;sup&gt;14&lt;/sup&gt;</td>
<td>$p \text{Fe}$</td>
<td>400</td>
<td>$\mu + \mu +$, $\psi \mu \mu$, $\mu \mu \mu$</td>
<td>target calorimeter</td>
<td>42</td>
<td></td>
</tr>
<tr>
<td>CCFRS&lt;sup&gt;15&lt;/sup&gt;</td>
<td>$p \text{Fe}$</td>
<td>350</td>
<td>$\mu + \mu +$, $\psi \mu \mu$, $\mu \mu \mu$</td>
<td>target calorimeter</td>
<td>175</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\mu \text{Fe}$</td>
<td>278</td>
<td>$\mu + \mu +$, $\psi \mu \mu$, $\mu \mu \mu$</td>
<td>diffractive production</td>
<td>40</td>
<td></td>
</tr>
</tbody>
</table>

* Some of these cross sections differ from those quoted in the original paper because they were recalculated using the following values for the different branching fractions: Bf ($B \rightarrow \psi X$) = 1%; Bf ($B \rightarrow \mu X$) = 12%; Bf ($B \rightarrow D$) = 100%; Bf ($D \rightarrow \mu X$) = 8%.
Table III
Some limits on B-meson hadroproduction \(^9\)

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>One standard deviation upper limit of (\sigma \times Bf) (nb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B^\pm \rightarrow \psi K^\pm)</td>
<td>0.21</td>
</tr>
<tr>
<td>(B^0 \rightarrow \psi K^0)</td>
<td>0.17</td>
</tr>
<tr>
<td>(B^\pm \rightarrow \psi K^{*\pm})</td>
<td>0.9</td>
</tr>
<tr>
<td>(B^0 \rightarrow \psi K^{*0})</td>
<td>0.23</td>
</tr>
<tr>
<td>(B^\pm \rightarrow \psi K^0 \pi^\pm)</td>
<td>4.7</td>
</tr>
<tr>
<td>(B^0 \rightarrow \psi K^0 \pi^+)</td>
<td>0.54</td>
</tr>
<tr>
<td>Apparatus</td>
<td>$\Omega'$ spectrometer</td>
</tr>
<tr>
<td>-------------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td>$B$-hadron selection</td>
<td>detection of charmed particle decays by multiplicity jumps in Si counter telescope</td>
</tr>
<tr>
<td>Target</td>
<td>40 l of emulsion (1.2 mm along the beam)</td>
</tr>
<tr>
<td>Beam</td>
<td>360 GeV/c $\pi^-$ mesons</td>
</tr>
<tr>
<td>Beam hodoscope</td>
<td>Si microstrips (100 $\mu$m pitch)</td>
</tr>
<tr>
<td>Vertex detector</td>
<td>Si counters and TPC's</td>
</tr>
<tr>
<td>Number of interactions</td>
<td>$2 \times 10^8$</td>
</tr>
<tr>
<td>i) total</td>
<td>$3 \times 10^4$</td>
</tr>
<tr>
<td>ii) to be scanned</td>
<td>0.3 (+ 1.0)</td>
</tr>
<tr>
<td>Sensitivity (events/nb)</td>
<td></td>
</tr>
<tr>
<td>Beam</td>
<td>Beam intensity no of part. s$^{-1}$</td>
</tr>
<tr>
<td>-----------------------</td>
<td>-------------------------------------</td>
</tr>
<tr>
<td>Charged hadrons</td>
<td>$4 \times 10^5$</td>
</tr>
<tr>
<td>Neutrons</td>
<td>$1.5 \times 10^6$</td>
</tr>
<tr>
<td>Photons$^*$ ($E_{\gamma} &gt; 75$ GeV)</td>
<td>$1.2 \times 10^6$</td>
</tr>
</tbody>
</table>

$^*$ With a fiducial volume trigger.
Table VI
Like Sign Dimuon Event Rates for 350 GeV/c $\pi^-$ mesons in uranium STAC

<table>
<thead>
<tr>
<th>Cut on $p_T^{\max}$ (GeV/c)</th>
<th>No cut on missing energy</th>
<th>Missing energy greater than 50 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B$\bar{B}$</td>
<td>bkg from reaction (1)</td>
</tr>
<tr>
<td></td>
<td>central</td>
<td>intrinsic</td>
</tr>
<tr>
<td>No cut</td>
<td>630</td>
<td>2300</td>
</tr>
<tr>
<td>$&gt; 1.3$</td>
<td>430</td>
<td>1450</td>
</tr>
<tr>
<td>$&gt; 1.5$</td>
<td>350</td>
<td>1020</td>
</tr>
<tr>
<td>$&gt; 1.7$</td>
<td>210</td>
<td>600</td>
</tr>
</tbody>
</table>

$^*$ $p_T^{\max} = \max$ of $p_T^{\mu_1}$ and $p_T^{\mu_2}$

$^{**}$ See text for details; additional assumptions are: muon detection efficiency: 50%; both $p_T^{\mu_1}$ and $p_T^{\mu_2}$ greater than 20 GeV/c and max ($\theta_1^\mu$, $\theta_2^\mu$) $\geq$ 30 mrad.
Cross section of $B\bar{B}$ pair production by hadrons versus $\sqrt{s}$. The curve is taken from F. HALZEN [18].
Cross section of $B\bar{B}$ pair photoproduction versus $\nu$.
Also shown are the data of the EMC for $C\bar{C}$ pairs. The curves represent the prediction of the $\gamma-g$ fusion model (leading order, $m_c = 1.5$ and $m_b = 5$ GeV).
GENERAL LAYOUT

Figure 4
EXTENDED ACTIVE TARGET
[all counters but $\Delta n$ 20$\mu$m pitch]

Target
Short life times
Long life times
$\Delta n$

30 mm

FIGURE 5a

$\mu$ Strip vertex detector
Pitch : 20$\mu$m
Readout : LSI

MWPC'
Pitch : 0.5-1 mm

20 mm Be Target

Inertiated, magnetized iron filter

FIGURE 5b

Two proposed set-ups for $B\bar{B}$ hadronproduction studies $^{34}$
a. General lay-out of an experiment to search for BB photoproduction
b. Emulsion-polystyrène target.
NET-AC-SFD

NET: nuclear emulsion target
AC: avalanche chamber
SFD: spot focusing detector

Experimental set-up proposed by R. MEUNIER and F. ROHRBACH

Figure 7
Comparison of the sum $P_T^2$ distributions for muons coming from $D^0$ and $K$ particle decays

Figure 8
SEARCH FOR MASSIVE NEUTRINOS AXIONS AND SUSY PARTICLES AT CERN SPS ENERGIES

G. Barbiellini, CERN

INTRODUCTION

The contributions to this review of "Exotic" particle physics on the occasion of the SPS Fixed Target Workshop are due to:

J. Aspiazu: Massive neutrinos
G. Batignani: SUSY particles
P. Musset: SUSY particles
V. Khovansky: SUSY particles
C. Santoni: Massive neutrinos

No contributions on axions have been presented to this Workshop. To honour the title of this review, I will give my personal view on the present status of axion searches and on future possibilities for an SPS experiment on axions.

1. MASSIVE NEUTRINOS

Gauge theories successfully describe the known interactions among the fundamental particles but do not give a satisfactory explanation of the source of the particle masses. Our ignorance, both theoretical and experimental, on a fundamental physical quantity such as the mass of the neutrino spans more than order of magnitude. The existing experimental limits on the neutrino masses are\(^1\):

\[
m(\nu_e) \leq 50 \text{ eV} \\
m(\nu_\mu) \leq 30 \text{ KeV} \\
m(\nu_\tau) \leq 250 \text{ MeV}
\]  

(1)

where \(\nu_e\), \(\nu_\mu\), and \(\nu_\tau\) indicate the neutrino emitted in decays with a lepton partner that is the electron, the muon, or the tau, respectively.

The values of the existing experimental limits on the neutrino masses justify the search for neutrinos with a mass in the range of up to a hundred MeV.
Neutrino oscillation experiments also aim at demonstrating the existence of massive neutrinos but their characteristic is to detect mass differences rather than mass values and they are presently sensitive to $\delta m \sim 10^{-2}-10^{-2} \text{eV}$ and to the flavour mixing angle in the range $10^{-1}-10^{-2}$ \cite{1}. 

The measurement of neutrino mass values in the MeV range can be made using two experimental methods, as suggested by R.E. Shrock\cite{2}.

The first experimental possibility is the search for monoenergetic peaks in the region below the value predicted for zero mass neutrino in $\pi$ and $K$ two body decay. If the neutrino masses are larger the the experimental momentum resolution the charged lepton momentum spectrum will look like that of Fig.1\cite{2}. The area of each secondary line is proportional to the mixing angle between the flavour eigenstates and the mass eigenstate

$$v_e = \sum U_{ei} v_i$$  \hspace{1cm} (2)

A second way of measuring neutrino masses and mixing angles is the detection of the decay rate of heavy neutrinos into a given final state. This method, suggested in Ref. 2) has recently been analyzed in detail in a theoretical paper from M. Gronau\cite{3}. A massive neutrino with mass larger than a few MeV and lower than the pion mass will have a decay analogous to the muon decay through the emission of a virtual $W$ boson, as shown in Fig.2.

The $v_i$ decay rate can be scaled by the $\mu$ decay rate, taking into account the two different mass values, and introducing a suppression factor due to the mixing angle of the $v_i$ with the electron $|U_{ei}|^2$.

The two very detailed contributions to this Workshop on massive neutrinos are:

1. Limit on $v_\tau$ mass from the SPS decay beam dump experiment (J. Aspiazu).

2. Search for massive neutrino decay in the Wide Band neutrino Beam (WBB) at the SPS (C. Santoni).
1.1 SEARCH FOR DECAYS OF HEAVY UNSTABLE NEUTRINOS IN THE SPS BEAM DUMP EXPERIMENT (J. Aspiazu)

The production and decay of massive neutrinos in the 400 GeV proton beam dump experiment at CERN was investigated by the CHARM Collaboration, exploring a decay region of 35 m length and of 3x3 m² cross section parallel to the CHARM neutrino detector.

Assuming a production of τ neutrinos by leptonic decays of the F-meson (F → τ ν) the neutrino beam produced by high energy protons interacting in a Cu beam dump would contain a large fraction of such heavy neutrinos. If these neutrinos have a mass larger than a few MeV they can decay into a light neutrino and two electrons.

Considering the expected neutrino flux and taking into account the large volume of the decay set up, a very sensitive test on neutrino decays was possible.

The detector is shown in Fig.3. The decay region is parallel to the neutrino beam line at a mean distance of 5 m, corresponding to an angle of 10 mrad with respect to the incident proton beam, and is defined by a scintillator plane (SC1) with a 6 x 4.8 m² active area as the start of the decay volume.

One module of the CHARM fine-grain calorimeter defined the end of the decay region 40 m downstream of the scintillator plane. This module is 1.2 m long and has an active area of 3x3 m².

The decay volume is divided into three regions using two sets of proportional tubes (P1 and P2). Each set consists of four planes of proportional drift tubes preceded by a lead plant of 1/2 radiation length thickness.

In order to improve the angular resolution of the shower and to better reconstruct the decay point, a low density detector was added in front of the CHARM calorimeter module. This comprised three sets of proportional tubes (P3, P4 and P5) covering an area of 4 x 4 m². In front of these sets a scintillation counter plane (SC2) of the same area was placed, defining the end of the decay region.
Since no event could be identified as a $\tau$ neutrino decay, an upper limit in the electron-tau neutrino mixing angle was set. The limit as a function of the neutrino mass is shown in Fig.4, together with previous results on $|U_{\text{e}1}|^2$.

1.2 SEARCH FOR MASSIVE NEUTRINO DECAYS IN THE WIDE BAND SPS NEUTRINO BEAM (WBB) (C. Santoni)

If neutrinos are massive, according to eq.(2) the weak eigenstates can be a linear combination of the mass eigenstates. Neutrino beams produced at accelerators through $\pi$ and $K$ decays can then contain a fraction of heavy neutrinos. A search for neutrinos decaying into two electrons and a light neutrino (Fig.2) was performed in a sample of $1.3 \times 10^6$ neutrino and $1.4 \times 10^6$ antineutrino interactions collected in the fine-grain CHARM calorimeter. The neutrinos and antineutrinos were produced by $1.4 \times 10^{18}$ and $5.7 \times 10^{18}$ protons on target respectively.

Candidate events are selected as muonless events appearing as showers of narrow width, characteristic of showers initiated by electrons and photons in the CHARM calorimeter\(^7\). The selected events have a shower energy $E$ deposited in the calorimeter between 7.5 GeV and 50 GeV and a value of the variable $E^2 \theta^2$ below 0.54 GeV\(^2\) ($\theta$ is the angle between the shower axis and the direction of the incoming neutrino). A total of 331 neutrino and 769 antineutrino events were selected.

The neutrino events surviving the selection criteria are due to the following known sources:

a) elastic and quasi-elastic charged current events induced by the electron-neutrino contamination of the beam;

b) events induced by the scattering of neutrinos on electrons;

c) neutral-current events with $\gamma$ and/or $\pi^0$ in the final state produced by coherent scattering of muon neutrinos on nuclei\(^8\).
The contribution of these reactions and of the possible neutrino decay events to the selected sample was computed making a study of the event distribution versus the variables $E_f$ and $E^2\theta^2$. $E_f$ is the energy deposited in the first scintillation plane following the shower vertex.

As shown in Fig.5, showers initiated by the decay of massive neutrinos into two electrons or by reaction c) almost always have values of $E_f$ larger than that released by one minimum ionizing particle (6 MeV), whilst a large fraction of the showers due to single electrons induced by reactions a) and b), give an energy deposition corresponding to one minimum ionizing particle\(^5\).

The $E^2\theta^2$ distribution for the events induced by reaction b) and by the decay of heavy neutrinos is expected to peak at $0^\circ$ while for events a) and c) it is almost flat\(^5\).

The results of this analysis are summarized in Table 1; only statistical errors are given. The number of events attributed to heavy neutrino decay is compatible with zero.

Table 1: WBB experiment: results of the background subtraction analysis

<table>
<thead>
<tr>
<th>Event Type</th>
<th>$E_f&lt;8$ MeV</th>
<th>$E_f&gt;8$ MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic and quasi-elastic $v_e$ events</td>
<td>127 ± 36</td>
<td>369 ± 40</td>
</tr>
<tr>
<td>$v_\mu$ e scattering events</td>
<td>41 ± 11</td>
<td>87 ± 24</td>
</tr>
<tr>
<td>Coherent scattering events</td>
<td>3 ± 2</td>
<td>472 ± 50</td>
</tr>
<tr>
<td>Neutrino decay events ( partner: $\mu$ )</td>
<td>0 ± 0.005</td>
<td>0.6 ± 47</td>
</tr>
<tr>
<td>Neutrino decay events ( partner: $e$ )</td>
<td>0 ± 0.005</td>
<td>0.7 ± 58</td>
</tr>
</tbody>
</table>
From this result, taking into account the statistical errors and the uncertainties on the background subtraction and on the normalization, a limit on the product of the mixing angles defined in (2) can be obtained.

The limits at 90% c.l. on $|U_{ei}|^2$ and on $|U_{ei}U_{\mu l}|$ are shown in Figs. 4 and 6. The limits on $|U_{ei}|^2$ and $|U_{ei}U_{\mu l}|$ are obtained assuming that the heavy neutrino is produced in the $\pi$ and $K$ decay together with an electron and a muon, respectively.

In conclusion there is no evidence for the existence of heavy neutrinos in the mass range 10-140 MeV in the limit of the mixing angle shown in Figs. 4 and 6.

2. THE AXION

No contribution has been submitted to this Workshop on possible investigation of the existence of axions at the SPS. Recently many experimental results show that the existence of an axion with the characteristics predicted by the Peccei-Quinn model is incompatible with the present experimental limits. The only positive indication for the existence of a neutral penetrating particle decaying into two photons from the SIN beam dump experiment do not seem to be confirmed by successive experiments. While waiting for a final clarification on the subject, it is not surprising that physicists searching for exotic particles have not for the moment considered axion search at the SPS to be possible. It can, however, be mentioned that the negative search for heavy neutrino decay in the decay beam dump experiment presented by J. Aspiazu at the Workshop, can also be interpreted as absence of axion decay into two photons with a significant low limit.
3. SUPERSYMMETRIC PARTICLES

Supersymmetry relates particle fields with different statistical properties (boson and fermions). For example, left handed and right handed electrons correspond to two scalar particles, $s$ and $t$, with zero spin and the same leptonic number (the selectrons) and so on; for every known particle we expect a supersymmetric partner. SUSY is clearly broken since no evidence of selectrons or squarks has been found by PEP and PETRA experiments looking for $e^+e^-$ annihilation into selectron or squark pairs, as reported in a recent review\(^{12}\). The previous reference is a useful source for experimentalists to get an orientation on the colourful jungle of the supersymmetric particles. The scale of the supersymmetry breaking is not clearly defined but some models of symmetry breaking\(^{13}\) predict the existence of a supersymmetric partner of the known particles with masses lower than the W mass.

The contributions on SUSY presented at this Workshop are:

1. Bounds on SUSY particles from beam dump experiments (V. Khovansky)
2. Search for short-lived R particles (P. Musset)
3. Experimental search for light supersymmetric particles at the CERN SPS (G. Batignani).

3.1 BOUNDS ON SUSY PARTICLES FROM BEAM DUMP EXPERIMENTS (V. Khovansky)

The supersymmetric models predict partners of ordinary quarks, leptons, and bosons at a mass scale of 100 GeV which will become accessible at future generation accelerators. However, these models also predict particles with naturally small masses. These are the supersymmetric partners of gluons and photons - gluinos and photinos.

A chain of three processes leads to a signal in beam-dump experiments. They are:

1. hadroproduction of gluino pairs in proton-nucleus collisions.
2. gluino decay into a photino and hadrons $\tilde{g} \rightarrow \tilde{\chi}_1^0 q\bar{q}$;
3. photino-induced interaction in the beam-dump detector \( \tilde{q} \rightarrow \tilde{g} q \) which is the cross-channel of process (2).

The latter process resembles neutral-current neutrino interactions but with smaller missing energy.

To get an upper limit on the product of the gluino production cross section and the photino interaction cross-section, data collected in the CHARM detector exposed to the neutrino beam produced by the dump of 400 GeV proton in a solid Cu target were used.

In the exposure of \( 6.96 \times 10^{17} \) protons on the full density target (a 2 m long copper block), \( 80.5 \pm 14 \text{(stat)} \pm 6.3 \text{(syst)} \) muonless events of prompt origin with \( E_{\text{vis}} > 20 \text{ GeV} \) have been observed. These events include charged current (CC) and neutral current (NC) interactions of \( \nu_e \) and \( \bar{\nu}_e \) as well as interactions of neutrino-like particles without a muon in the final state. The number of prompt CC events induced by \( \nu_e \) and \( \bar{\nu}_e \) has been estimated to be \( 60.7 \pm 13 \text{(stat)} \pm 5.3 \text{(syst)} \) by direct identification. From this number of CC events the corresponding number of NC events with \( E_{\text{vis}} > 20 \text{ GeV} \) were calculated to be \( 15.8 \pm 3.4 \text{(stat)} \pm 1.5 \text{(syst)} \). Subtracting these \( \nu_e \) and \( \bar{\nu}_e \) events from the observed number of muonless events, \( 4 \pm 21 \) events with \( E_{\text{vis}} > 20 \text{ GeV} \) were found. This events could be attributed to the interaction of other neutrinos or neutrino-like particles. Expected photino rates were calculated by Monte-Carlo simulation.

Results deduced from the observed excess rate, as compared to these expected rates, are plotted in Fig.7. The solid curve is a lower bound at 90\% c.l. The broken lines indicate the gluino lifetime constraints.

The results of this search for supersymmetric particles do not favour the existence of low mass gluinos \(< 2 \text{ GeV}\) and scalar quarks \(< 100 \text{ GeV}\).

The analysis of the 1982 beam dump data of 7.5 times higher statistics is in progress.
3.2 SEARCH FOR SHORT-LIVED R PARTICLES (P. Musset)

The relation boson-fermion built in the supersymmetry theory predicts a
supersymmetric partner of leptons, quarks and gluons. The existing limit on s
quark mass is $M > 15$ GeV from PETRA experiments. The supersymmetric partner
of the colour gauge boson, the gluon ($g$), is a spin one half particle, the
gluino ($\tilde{g}$). The mass of the gluino can be smaller than the squark mass.
Gluinos can form bound states with a normal quark ($q$) and antiquark ($\bar{q}$). The
bound states ($q\tilde{g}$, $qq\bar{q}$) are called R particles.

$q\tilde{g}$ fermionic meson

$R$

$qq\bar{q}$ bosonic baryon

The R particles are produced in hadronic interactions with a rate depending on
the R particle mass and with interaction strength similar to that of the
strong interaction:

$$\sigma_R \sim \sigma_H$$

The R particles decay rapidly and for the mass values which can be
investigated at SPS energies the lifetime predicted is $\tau = 10^{-12}$-$10^{-14}$ sec.

The gluino decays into a hadron and a lighter (if it exists) R particle. The
signature for the production and the decay of an R particle will be given
by finding events with two close vertices at the decay vertex. The light
invisible R particle produces missing energy which, contrary to the known
ccharm decay, is not accompanied by the presence of a charged lepton.

The present experimental limit and search for R particles are:

1. Beam dump experiment giving limits on gluino mass between 1 and 2 GeV

2. The emulsion experiment (WA75)$^{14}$ can put limits on the cross section
   for the reaction

$$\pi N \rightarrow RRN$$

at a level of one microbarn for gluino mass 1-3 GeV

3. The EHS experiment from a sample of 77 charm candidate events
   reconstructs 54 charm decays; the remaining 23 can be used to
   establish an upper limit for R particle production cross section.

The emulsion experiment and the high spatial resolution bubble chamber
experiment can observe different R particle lifetimes ranges $10^{-14}$-$10^{-12}$ sec
and $10^{-13}$-$10^{-11}$ sec, respectively.
The technical limitations and the possible improvements for the experiments searching for R particles are:

a) increase of statistics
b) more refined lepton (electron and muon) identification to separate the charm decays from the R particle decays
c) extension of the lifetime range using solid state detectors.

3.3 EXPERIMENTAL SEARCH FOR LIGHT SUSY PARTICLES IN e⁺e⁻ ANNIHILATION (G. Batignani)

Some supersymmetric models require a minimum extension of the interactions symmetry from SU(3) x SU(2)_L x U(1) to SU(3) x SU(2)_L x U(1) x U(1) with an extra U(1) group\textsuperscript{13).} The extra gauge boson corresponding to the new U(1) symmetry is coupled to the fermion antifermion pairs with coupling g\textsuperscript{11}, as shown in Fig.8.

An analysis of present neutral current phenomenology suggests that new neutral gauge bosons, if they exist at all, can have light mass and small coupling to the fermion pair.

A neutral gauge boson with mass value in the range 10\textsuperscript{1}-10\textsuperscript{2} MeV can be produced in e⁺e⁻ annihilation and detected by its decay into electron or neutrino pairs. No experimental data from e⁺e⁻ storage rings are available below 300 MeV centre of mass energy.

The exploration of e⁺e⁻ annihilation in the energy range \(\sqrt{s} \leq 300\) MeV can be done using the high energy positron beam of the CERN SPS on a germanium target. The NA7 apparatus\textsuperscript{15) already used in e⁺e⁻ annihilation for the study of the pion time-like form factor, can be used to search for the u gauge boson. The signature of the production and decay of the u gauge boson is given by the sequence of signals in the lived target as shown in Fig.9\textsuperscript{16).} The expected production rate of the u particle is quite comfortable for a flux of 10\textsuperscript{6} e⁺/burst; seven u are produced in one hour and the complete search for u particles in the energy interval 30-200 MeV can be done in 80 hours.
4. CONCLUSIONS

From the interesting contributions submitted to this group of the Fixed Target Workshop, my impression is that high luminosity experiments which can be carried out with the fixed target SPS are competitive for the search of new phenomena and small deviations from orthodoxy.

Experience has shown the importance for the development of physics of the discovery and understanding of some small but important effects, such as the Cabbibo angle in the weak interaction, or CP violation in rare K decay.

The source of small deviations from the so-called standard model are expected from products of small mixing angles in the mass-flavour eigenstate and from large value of masses for new gauge bosons that simulate superweak interactions. A recommendation to the physicist willing to search for small effects not predicted by the standard model could be: try to be a little bit heretical (but not too much!).
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FIGURE CAPTIONS

Fig. 1 Schematic charged lepton spectra for \(K \rightarrow \nu e\) decay.

Fig. 2 Diagram for heavy neutrino decay.

Fig. 3 Layout of the decay beam dump experiment. SC1 and SC2 are scintillator planes. SC1 is used as veto counter. P1 to P5 are sets of 4 planes of proportional drift tubes each.

Fig. 4 Limits at 90% c.l. on \(|U_{ei}|^2\) (the square of the coupling strength of mass eigenstate \(i\) to the electron neutrino weak eigenstate) as a function of the neutrino mass: a) limits obtained in the proton beam dump experiment. The mass eigenstate is identified with the \(\tau\) neutrino; b) limits obtained in the wide band neutrino beam experiment; c) limits from solar neutrino measurements; d) limits obtained from the search for monoenergetic peaks in the region below the value predicted for zero mass neutrino in \(\pi \rightarrow \nu e\) decay; e) limits from the measurement of the branching ratio \(\pi \rightarrow \nu e\); f) limits from the measurement of the branching ratio \(K \rightarrow \nu e\).

Fig. 5 Measured distributions of the energy deposition in the first scintillator plane following the shower vertex: (a) showers induced by 15 GeV electrons traversing on average half a marble slab (0.45 radiation lengths). (b) photon-induced showers produced by neutrino and antineutrino beams in an energy-angle range where photon induced showers due to coherent processes dominate. \((7.5 < E < 17.5 \text{ GeV}, E^2 \theta^2 > 0.54 \text{ GeV}^2)\). The contamination due to electron-induced showers is estimated to be 15%.

Fig. 6 Limits at 90% c.l. on \(|U_{ei} U_{\mu i}|\) as a function of the neutrino mass from the WBB experiment. \(U_{ei}\) and \(U_{\mu i}\) are the coupling strengths of a mass eigenstate \(i\) to the electron and muon neutrino weak eigenstate respectively.

Fig. 7 The 90% c.l. lower bound on the gluino mass as a function of the scalar quark mass. The broken lines show the gluino life time constraints.

Fig. 8 Diagram for the production and decay of the \(u\) gauge boson in \(e^+e^-\) annihilation.

Fig. 9 Sequence of signals in the solid state detectors of the NA7 experiment as expected by the reaction \(e^+e^- \rightarrow u \rightarrow e^+e^-\).
Fig. 1

Fig. 2
Fig. 4
Fig. 5
Fig. 6
Fig. 7
CP VIOLATIONS AND RARE KAON DECAYS

A special theory seminar organized in preparation for the SPS Fixed Target Workshop with contributions by

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J. Ellis, CERN, Geneva, Switzerland and SLAC, Stanford, USA.
D.V. Nanopoulos, CERN, Geneva, Switzerland.

The Proceedings of this seminar have been published as CERN report, Ref. TH.3464-CERN, available on request from Theory Division Secretariat, CERN. We reproduce here only the Foreword by M. Jacob.

A Workshop was held at CERN on 6-10 December 1982 to discuss physics to be considered for the long-term fixed target programme at the SPS. It was deemed appropriate to prepare the discussion which took place within some of the specialized working groups, by a detailed consideration of the question of CP violation and more generally of the study of rare decay modes. This was the object of a one-afternoon session in October 1982 and the talks of the three main speakers are collected in this report. One may find here in particular current information about weak quark transitions and expected values for previously inaccessible parameters as they appear in the framework of promising models. Also given are limits which new experiments should attempt to reach in order to provide very useful information. An early document, collecting series of the transparencies used by the main speakers, was circulated before the Workshop. The present paper comes back to these questions in a more readable form, handy for easy reference and which should be very useful to all physicists interested in playing an active role in the further exploration of these very important questions.

The first contribution, by S. Pakvasa, discusses the present approach to weak decays, giving in particular information available about the Kobayashi-Maskawa matrix elements. Known values on upper and lower bounds are given, and the corresponding bounds for the angles, as they appear in the standard definition of the matrix, are presented. Also discussed are the parameters relevant to CP violation proper and a summary of the expected values in the six quark model is presented. Considered next are the values which appear in non-standard models based on right-handed currents and on special Higgs couplings.

The second contribution, by J. Ellis, presents some "possible", and, in any case, rare decay modes of K mesons. This was done from the point of view of the standard model but also in connection with technicolour models and in the framework of supersymmetry. Both the latter two approaches presently appear as interesting possibilities (probably mainly the last one) for trying to understand how Higgs mesons can have a reasonably low mass. What is meant by this is a mass of the order of $10^2$ GeV, namely the electroweak symmetry
breaking scale. After a rapid survey of both the technicolour and the supersymmetry approach, some specific experimental questions are tackled. First come the question of $K_L^0 \rightarrow \mu e$ and $K^+ \rightarrow \pi^+ \mu e$ decays, and then the question of $K^+$ decaying into a $\pi^+$ and "nothing" seen, an event where supersymmetric particles could play an important role. The relevant values at which rates should be looked for in connection with technicolour ($K_L^0 \rightarrow \mu e$ decay) and with supersymmetry (the second mentioned $K^+$ mode) are discussed.

The last contribution, by D.V. Nanopoulos, takes us away from direct experimental questions about $K$ decays to a consideration of the relevance of CP violation in our understanding of matter-antimatter asymmetry in the Universe, as it can be discussed within the framework of the Big Bang Cosmology. The review starts with a general survey of present cosmology (standard model), which is followed by a discussion of matter-antimatter asymmetry in the Universe and of the mechanisms which can be considered in generating a non-zero global baryon number. Next comes a consideration of CP violation in grand unified theories. The role of strong CP violation, as it appears in QCD, is reviewed and compared with the violation introduced through the Kobayashi-Maskawa matrix. The great relevance of the still unknown value of the electric dipole moment of the neutron in determining key parameters is stressed; whether it is of the order of $10^{-36}$ e.cm or of the order of $10^{-26}$ e.cm is indeed of great importance when trying to assess the role of CP violation in the dynamics of the Early Universe.

The overall unity of this wide domain of physics, here discussed along three main different lines should thus be clear. It is my hope that this document will provide a good starting point when considering new experimental attacks on these problems.
WEAK DECAYS OF HEAVY FLAVORS\textsuperscript{+})

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1. INTRODUCTION

The search for and the study of the weak decays of heavy flavors (c, b) will be one of the central issues of the SPS fixed target program during the next years. The purpose of this talk is to summarize the main features and problems of heavy flavor decays to be studied in the future. In general one is dealing with two different classes of problems:

a) The weak decays of heavy flavors are excellent tools to study specific properties of the strong interactions, since the final state of a decay process consists of hadrons and leptons, and not of quarks and leptons; final state interactions are important. Furthermore the weak decay amplitudes depend crucially on strong interaction parameters like wave functions, constituent quark masses etc.

b) Studying the weak decays of heavy flavors, one is able to investigate specific features of flavor dynamics. Especially it will be possible to measure the weak interaction mixing angles and to test the universality of the weak couplings of the heavy quarks, one of the central predictions of the SU(2) × U(1)-gauge theory. Furthermore the weak decays of heavy quarks provide an interesting insight into the interplay between QCD and QFD, which is responsible for the multitude of different effects observed in these decays.

Due to the limitation given by energy the SPS fixed target program is best suited for studying the production and decay properties of c and b flavors. There is no hope to find and study t-flavored particles.

Both the SU(2) × U(1) gauge theory and QCD make rather definite predictions for the c and b decays. It is important to test these predictions in the forthcoming experiments.

2. Parameters of Flavor Dynamics

The important consequences of the standard SU(2) × U(1)-scheme\textsuperscript{1}) for the weak decays of heavy flavors are:

a) Lefthanded leptons and quarks are SU(2) doublets; they exhibit a universal coupling to the W bosons. We emphasize the universality property since it needs to be tested carefully by experiment. Thus far the universality is very well tested only for the (u d), (νe e\textsuperscript{-}) and (νμ μ\textsuperscript{-})-systems. It may well be that the weak couplings of heavy quarks and leptons deviate substantially (say 10% or more) from the values predicted by the universality (deviations from universality are, for example, expected in certain substructure models of leptons and quarks\textsuperscript{2}). The discovery of such large deviations from universality would, of course, constitute a major blow against the standard SU(2) × U(1) gauge theory framework.

\textsuperscript{+}) Invited Talk given at the Workshop on SPS fixed target physics, CERN, Dec. 1982
b) In the absence of masses for the leptons and quarks the weak currents are diagonal, i.e. they connect only fields within the same lepton- quark family. The mechanism of mass generation generates mixing between the various families, described by the weak mixing parameters (Cabibbo angle etc.). In the standard SU(2) x U(1) framework the lepton- and quark- masses as well as the mixing parameters are arbitrary. Presumably this is not the final answer; relations between the mixing parameters and the masses may well exist. In any case, it seems that the mixings between families are small, and the unitary mixing matrix \( U \) defined by

\[
\begin{pmatrix}
  d' \\
  s' \\
  b'
\end{pmatrix} = \begin{pmatrix}
  U \\
  s \\
  b
\end{pmatrix}
\]

\((d', ..., s', ..., b': \text{ eigenstates of weak interactions; } d, ..., s, ..., b: \text{ eigenstates of quark mass matrix})\),

is close to the unit matrix.

Both the \( s \) and the \( b \) quarks are lighter than their weak partners (\( c, t \) respectively), and therefore can decay only via mixing. The \( b \)-quark has two different options to decay: \( b \rightarrow c \) or \( b \rightarrow u \). The first possibility seems to be favored by experiment. For the decay amplitudes one finds:

\[
\frac{|b \rightarrow u|}{|b \rightarrow c|} < 0.3
\]

\(1\)

In the subsequent discussion I shall assume that \( b \rightarrow c \) dominates.

3. **WEAK DECAYS OF CHARMED PARTICLES**

Let us consider a "heavy" quark bound together with one or two "light" quarks to form a hadron. If the mass of the heavy quark is much larger than typical strong interaction mass parameters of the order of 1 GeV, one predicts that the weak decay of the heavy particle can be described by the weak decay of the heavy quark inside the particle, without taking reference to the bound state structure (especially to the other constituent quark). The corresponding decay amplitude can be calculated in first order of \( G_F \) (Fermi constant), including radiative QCD corrections. A direct consequence of this picture is: the lifetimes and the semileptonic branching ratios depend only on the heavy quark. In the case of charm this means:

\[
\begin{align*}
\tau(D^+) &= \tau(D^0) = \tau(F^+) = \tau(\Lambda_c^+) ... \\
B(D^+) &= B(D^0) = B(F^+) = B(\Lambda_c^+) ... 
\end{align*}
\]

\(\tau: \text{ lifetime; } B: \text{ semileptonic branching ratio}\).

Experimentally one finds

\[
\frac{\tau(D^+)}{\tau(D^0)} = 2.2 \pm 0.9 \\
\tau(D^0) = 2.2 \pm 0.6
\]

implying a large deviation from (2).
After several years of uncertainty a consensus has been reached that the large deviation from (2) is due to the fact that $m_c$ is not large in comparison with typical strong interaction masses and that bound state effects are still important for charm particle decays. The most important of these effects are:

i) Quark interaction processes$^{5...8}$

One of the constituent quarks can interact weakly with the heavy quark and that way cause the weak decay of the heavy particle. This process depends on the quark structure and can cause differences in life times between the various particles. For example, inside the $D^0$ the $c$ and the $\bar{u}$ can make a weak transition: $(c\bar{u}) \rightarrow (s\bar{d})$. This process can contribute to the nonleptonic $D^0$ decay, but not to the $D^+$ decay, thus violating relation (2). In the nonleptonic $\Lambda_c$ decay$^9$ the weak transition $(cd) \rightarrow (us)$ can contribute, again violating relation (2).

ii) Interference Effects

In the decay $c \rightarrow s \bar{u} \bar{d}$ a $\bar{d}$-quark is emitted which may interfere with the constituent $\bar{d}$-quark inside the $D^+$. In the standard picture this interference is negative, thus increasing the $D^+$ lifetime$^{10}$. The strength of the interference depends on the corresponding overlap in momentum space. Recently it has been calculated using simple bound state models$^{11}$. One finds that the interference effect cannot influence the $D^+$ decay rate by more than 10%. For this reason we shall ignore interference effects for our subsequent discussion.

The question arises whether a violation of eq. (2) by 200% (see eq. (3)) can be understood as being essentially due to quark interaction processes. In that case the Cabibbo allowed $D^0$ decay should be simply due to $c$-decay (no quark interaction processes can contribute to this decay).

The quark interaction process $(c\bar{u}) \rightarrow (s\bar{d})$ is forbidden in naive bound state models in the chiral limit $m_s = m_d = 0$. However in QCD one expects that the $D^0$ wave functions contains terms of the type $(c \bar{u} g)$ where $g$ denotes a gluon and where the $(c\bar{u})$- system is in an $J = 1$ state ($J$: angular momentum). Such terms are generated by color magnetic transitions of the light quarks: $q \overleftrightarrow{g} \rightarrow q \overleftrightarrow{g} + g \overleftrightarrow{g}$. Below we describe the main consequences which follow if one takes into account the quark interaction processes.

a) $D^0$ Decay

The magnitude of the quark interaction process depends on parameters like wave function at the origin which are not known and can only be guessed in naive bound state models. Typical estimates for the $D^0$ decay are $^5...7$ (see also ref. (12)):

$$\tau(c\bar{u} \rightarrow s\bar{d}) \approx 1 ... 2$$

$$\tau(c \rightarrow s u \bar{d})$$

(4)

This gives:

$$\frac{\tau(D^+)}{\tau(D^0)} = 1.7 ... 2.4,$$

(5)

in good agreement with (3). (In relating eq. (4) and eq. (5) a semileptonic branching ratio $B = 16\%$ has been used.).
b) F-decay

The F meson can decay via the weak annihilation process $c\bar{s} \to u\bar{d}$. Again this process is suppressed naively by helicity factors. However it may proceed via terms in the wave function containing gluons$^5$. This time two gluons are required - one for allowing the $(c\bar{s})$-system to be in a $J = 1$ state, the second one for allowing the $(c\bar{s})$-system to be in a color singlet state. It depends on the relative importance of such terms in the $F$ wave function whether the $F^+$ lifetime is close to the $D^+$ lifetime (quark interaction process is negligible) or whether it is close to the $D^0$ lifetime. Presumably the quark interaction process in the $F$ decay is nearly as important as the one for the $D^0$ decay (see ref. (5)), in which case one has

$$\tau(D^0) \approx \tau(F^+) < \tau(D^+)$$  \hspace{1cm} (6)

The lifetimes reported recently$^3$)

$$\tau(D^+): \quad 9.3 \pm 2.7 \cdot 10^{-13} \text{ s}$$
$$\tau(D^0): \quad 4.0 \pm 1.2 \cdot 10^{-13} \text{ s}$$
$$\tau(F^+): \quad 2.9 \pm 1.8 \cdot 10^{-13} \text{ s}$$
$$\tau(^1C_2): \quad 2.2 \pm 0.9 \cdot 10^{-13} \text{ s}$$

are not in disagreement with this picture. However the errors are large, and one of the most important goals of the charm physics in the future must be to measure the lifetimes of the charmed particles with much better accuracy; errors of the order of a few % should be aimed at.

c) Final states in F Decay

Provided the quark interaction process contributes significantly to the $F$ decay, the study of the final state in the $F$ decay is of special interest. The quark interaction process leads to a final state generated by a $(u\bar{d})$-pair. Thus final states like $3\pi$, $5\pi$... should dominate. On the other hand the c decay process leads to a final state containing $s\bar{s}u\bar{d}$, i.e. one should observe $K\bar{K}n$, $nnm$ etc.

Particularly interesting is the final state in the semileptonic $F$ decay$^5$). The quark interaction processes $c\bar{s} \to v_e e^+$, $v_\mu \mu^+$ lead to final states including a lepton pair and a hadronic state made up of glue. One should be prepared to look for decays like $F^+ \to v_\mu \mu^+ +$ glue mesons. Another consequence is noteworthy. The semileptonic branching ratio of the $F^+$ should be larger than the one for the $D^0$:

$$B(F^+) > B(D^0)$$  \hspace{1cm} (7)

even if $\tau(F^+) \approx \tau(D^0)$, since the quark interaction processes can contribute to the semileptonic $F$ decay, but not to the semileptonic $D^0$ decay.
d) $\Lambda_c^+ - \text{decay}$

Here the quark interaction process $c d \to s u$ will contribute to the decay. No gluons are needed to offset helicity suppression factors; the process proceeds being in amplitude proportional to the quark wavefunction at the origin. Simple nonrelativistic potential models give

$$\frac{\tau(D^+)}{\tau(\Lambda_c^+)} \approx 2 \ldots 3,$$

in good agreement with the yet preliminary experimental data.

e) Exclusive Charm Decays

Here the situation is quite confusing, both on the experimental side and on the theoretical one. Before the data were available, theorists relying on the $c$ decay mechanism predicted a strong suppression of the neutral decay modes of the $D^0$, e.g.

$$\frac{B(D^0 \to K^0 \pi^0)}{B(D^0 \to K^- \pi^+)} = \frac{1}{40}$$

(9)

On the other hand the quark interaction process for the $D^0$ decay leads to a final state generated by a $(s\bar{d})$ pair (isospin 1/2).

Thus one expects:

$$\frac{B(D^0 \to \bar{K}^0 \pi^0)}{B(D^0 \to K^- \pi^+)} = \frac{1}{2}$$

(10)

in good agreement with the experimental value $0.73 \pm 0.39$ for that ratio. However we know meanwhile that the $D^0$ decay proceeds only part time via the quark interaction process. A substantial part of the decay rate is presumably due to the $c$ decay mechanism, and the result (10) needs to be modified. Another problem arises here. The quark interaction process and the $c$ decay process lead to different quark and gluon configurations and no interference is expected. However both configurations add up finally to generate a $K\pi$-system. Via final state interactions an interference between both decay possibilities is quite possible. The consequences of such an interference for the $D^0$ decay are unknown.

We mention this since in the pseudoscalar vector decay modes the data show disturbing features. One finds (see e.g. ref. (12)):

$$B(D^0 \to \bar{K}^0 \rho^0) = 0.1 \pm 0.6$$

$$B(D^0 \to K^0 \pi^0) = 1.4 \pm 2.3$$

$$B(D^0 \to K^- \pi^+) = 7.2 \pm 3\%$$

$$B(D^0 \to K^- \pi^-) = 3.6 \pm 1.3\%.$$  

(11)

Thus the neutral decay modes seem to be absent or strongly suppressed. Does this mean that the quark interaction mechanism does not contribute to weak decays leading to a pseudoscalar and a vector meson? This seems odd. New data are needed to clarify this issue.
f) Cabibbo Suppressed Decays

The same quark interaction process which is supposed to be responsible for the enhancement of the \( F \) decay rate in comparison with the \( \Lambda_c^+ \) decay rate will enhance the Cabibbo suppressed decay modes of the \( \Lambda_c^+ \). Thus the inclusive rate \( \Lambda_c^+ \rightarrow (|S| = 0 \text{ final state}) \) should not be \( \sin^2 \theta_c \cdot r(\Lambda_c^+ \rightarrow \text{all}) \) (i.e. a 5% effect), but about twice or three times as large. The preliminary data (see e.g. ref. (16)) are not in disagreement with this expectation, but much more precise data are required to test the predictions.

g) Decay Pattern for Charmed Baryons

The quark interaction mechanism in the case of charm baryon decays requires the presence of a (cd)-pair in the baryon wave function. Thus the lowest lying charmed and strange baryon (quark content (cucs)) cannot decay via the quark interaction process unlike its isospin partner (cds). As a consequence the lifetime of the (cucs)-baryon should be larger than the \( \Lambda_c^* \)-lifetime, which is expected to be equal to the lifetime of the (cds)-baryon.

4. B-PARTICLES

Finally I would like to make some remarks about the decays of b-flavored particles. Thus far no uncontroversial evidence has been found for the production of b-flavored particles in hadronic collisions. Of course, nobody doubts that these particles are produced hadronically. However even fairly optimistic estimates of the production cross sections are not very encouraging for the SPS fixed target program. Presumably the total cross section for b-flavor production in nucleon- nucleon collisions at 400 GeV is between 10 and 50 nb. Considering the problems people have in finding and studying the charmed particles produced in hadronic collisions, I think there is not much space for optimism with regard to b-flavor physics at the SPS. Presumably it is not very useful to look for peaks in invariant mass plots, due to the large number of combinatorial possibilities and the large number of particles in the final state of a b-particle decay. The only hope is to find clean signals. Several possibilities may be considered:

a) The search for short tracks and weak cascade decays in emulsions (assuming that b-particles have a lifetime of a few x \( 10^{-14} \) s).

b) There is a 5 ... 10% chance a b-quark decays according to b \( \rightarrow c \bar{c} s \), and the final state contains a pair of D-mesons and a K-meson, e.g. \( B^-(b \bar{u}) \rightarrow K^-D^+D^- \). In these decays the final state will be much simpler than in the bulk of the b-particle decays, and one may hope to find a peak in the invariant mass plot.

c) Multilepton signals are useful to be considered as triggers.

d) The chance for a b-quark to decay by J/\( \psi \)-emission\(^{17} \): \( b \rightarrow J/\psi + s \) is expected to be of the order of 1%. Here the final state is fairly simple, e.g. \( B \rightarrow J/\psi \ K \bar{m} \). Despite the reduction of the signal due to the small leptonic branching ratio for the \( J/\psi \) the search for b-particles by investigating \( J/\psi \) signals should be intensified.

The rate for the quark interaction process is proportional to \((F/m^2)\) where \( F \) is the corresponding decay constant (given by the wave function at the origin), and \( m \) is the heavy quark mass. It follows that the relative strength of the quark interaction process in the b-decay is reduced by a factor \((m_c/m_b)^2 \approx 10^{-1}\), compared to the one in c-decay. Thus
the lifetimes of $B^0$ and $B^-$ should be nearly equal: $\tau(B^0) / \tau(B^-) \approx 1.1 \ldots 1.2$. (Note that the $B^0$-particle can decay via the interaction process ($b\bar{d} + (c\bar{u}$), unlike the $B^-$-particle.) At least 80% of all $b$-decays should proceed via the weak decay of the heavy quark, e.g. $b \rightarrow c + X$.

It is interesting to note that the $B$-mesons are able to decay into baryon- antibaryon pairs, e.g. $B \rightarrow c \cdot N$. Although it is not possible to calculate the branching ratio for these decays, naive estimates give $10^9$: $B(B \rightarrow c \cdot \bar{N} + X) \approx 1\%$. However the small branching ratio does not stimulate much enthusiasm to observe such decays in hadronic reactions. The $e^+e^-$-annihilation experiments carried out in the future at CESR and DORIS are better suited for it.

5. **FINAL COMMENTS**

No doubt, the physics of heavy flavors will be one of the central issues of the SPS program in the future. During the recent years it has become clear that the production and weak decays of heavy flavors can be understood within our standard theories: QCD and the SU(2) $\times$ U(1) theory. The future SPS program must be seen in this perspective. There is not much hope to find dramatic new effects, which will shake the basic theoretical foundations; such a task must be left to the hadron colliders, LEP, and HERA. Much has to be learned yet about heavy flavors, and the knowledge gained through a careful and time-consuming study of their production and decay processes will be very useful in understanding the dynamical details of QCD and the SU(2) $\times$ U(1)-theory. Of special interest is the rather peculiar interplay between the weak decays of heavy quarks and QCD, which is sensitive to details of the strong interactions (gluons in the wave function of hadrons etc.).

The weak decays of strange particles are under study for about 25 years. Yet the details of these decays ($|\Delta I|=1/2$ rule etc.) are still not fully understood. I hope that during the next years all dynamical details of the decays of charmed (and eventually $b$-flavored) particles will be cleaned up. What is most needed in this respect are precise data, not just signals or data with errors of 50 ... 100%. I am sure that the results of heavy flavor physics will be a large and perhaps the most interesting part of the harvest brought in by the SPS fixed target program of the future.

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HARD SCATTERING AND JET PHYSICS IN CONNECTION WITH REAL PHOTONS

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ABSTRACT
This report contains a summary of the physics discussed in the working groups on (a) jet physics at the SPS in hadron-hadron collisions, (b) hard scattering with incident real photons and (c) large $p_T$ prompt photons in hadron-hadron collisions.

INTRODUCTION
This report is an attempt to summarize the SPS-workshop discussions on the following topics:

- jet physics at the SPS in hadron-hadron collisions
- hard scattering with incident real photons
- large $p_T$ prompt photons in hadron-hadron collisions.

The physics topics were discussed in the light of QCD mainly because of the lack of other challenging alternatives, and because QCD provides enough motivation to test its predictions with many precise experiments.

Jet physics in hadron-hadron collisions has been explored at the SPS and at Fermilab in previous years. Very new results were also presented from the ISR and the pp-collider at this workshop. However hard scattering processes with real photons is a rather new field of research at the SPS where it is just starting.

This presentation is the result of the work done by the people listed in Ref. 1).

1. JET PHYSICS AT THE SPS IN HADRON-HADRON COLLISIONS

It is believed that particle jets with large transverse momenta $p_T$ reflect the hard scattering of two constituents inside the hadrons\(^2\). In the simplest approximation such process should give rise to final states characterized by 2 large $p_T$ jets and 2 spectator jets along the incident beam direction, arising from the hadronisation of the constituents (Fig. 1). The experimental search for jets in hadron-hadron collisions at SPS energies is complicated by at least two problems:

(a) the large $p_T$ jets are not well separated from the beam and target spectator jets,
(b) the necessary selective jet triggers may introduce biases.

The first observation of jet like event structures in hadron-hadron collisions were reported from ISR experiments\(^3\), which employed high $p_T$ single particle triggers. The high $p_T$ particle was interpreted as one of the fragmentation products of a high
Fig. 1: Two constituent scattering process leading to two particle jets at large $p_T$ and two forward backward spectator jets.

Fig. 2: Schematic layout of a large acceptance calorimeter experiment.
$p_T$ jet. It was suggested that single particles at large $p_T$ may be rare cases of jet fragmentation and further insight into hard scattering processes could be gained by triggering directly on particle jets using segmented calorimeters$^4$.

A series of experiments were carried out at Fermilab$^{5,6,7}$ which employed calorimetric jet triggers with an acceptance of 1-2 sr corresponding to the expected jet size. As expected, the cross-sections measured using these so called "jet triggers" were found to be 2 orders of magnitude higher than those for single particle production at large $p_T$.

However it was difficult in principle to verify the existence of jets using the small acceptance calorimeter trigger since this could lead to a trigger bias selecting events which simulate jets due to statistical fluctuations in non-hard scattering processes.

Large acceptance calorimeter triggers have been introduced recently in order to reduce a possible geometrical jet trigger bias$^{8,9,10}$ due to calorimeter acceptance. The NA-5 experiment started the investigation of hard hadron-hadron collisions using a large acceptance calorimeter trigger.

As shown in Fig. 2, a typical calorimeter acceptance is $45^\circ$ to $135^\circ$ in cms polar angle $\theta^*$ and $2\pi$ in azimuthal angle $\phi$. The calorimeter is segmented into many cells to study the event structure. Jets are expected to manifest themselves as energy clusters detected in the calorimeter. This trigger selects events with a large transverse energy $E_T$. The large acceptance calorimeter trigger introduces no jet trigger bias, however it is sensitive to the spectator jets. This effect has been studied by several authors$^{10,11,12}$ using various models for jet-fragmentation. The amount of transverse energy leakage of spectator jets into the calorimeter depends strongly on the assumptions made in the jet-fragmentation models.

The interpretation of the data at the parton level is therefore strongly model dependent and one should use extreme caution in drawing conclusions since the jet-fragmentation is not well understood.

What have we learned from the NA-5 experiment at SPS energies?

i) The large acceptance $E_T$-trigger selects events with high total charged multiplicity ($<n_{CH}>$) and a small average transverse momentum per particle ($<p_T>$). At $E_T > 14$ GeV, for example, $<n_{CH}> = 25$ and $<p_T> = 0.65$ GeV/c for particles in the calorimeter.

ii) No dominant jet structure has been found. The non-planar event structure dominates up to the highest transverse energies ($E_T^{max} \sim 0.8 \cdot \sqrt{s}$).

iii) The cross-sections do not scale.
iv) The ratio of large $E_T$ cross-sections measured with incident protons to those measured with incident pions decreases with increasing $x_T = E_T/\sqrt{s}$. This may suggest that partons take part in the scattering process since the harder parton momentum spectrum in the pions leads one to expect that large $E_T$ events are more easily produced with incident pions than with incident protons.

Several possible interpretations of the observed results were discussed at the workshop. It was suggested that gluon Bremsstrahlung is a possible mechanism which could account for these rather unexpected results. Fig. 3 shows the NA-5 results compared with the model predictions of Fox, Field and Kelly\(^{13}\). The essential ingredient in their model is the inclusion of non-collinear gluon Bremsstrahlung, treated in the leading logarithm approximations, from the initial and final state partons participating in the scattering process. The model seems to be able to describe the data qualitatively rather well.

---

**Fig. 3:** Comparison of the predictions of the QCD parton-shower Monte-Carlo model of ref. 13) with data from NA-5 for both small and large aperture calorimeter triggers. The solid and dashed curves are the predictions at the hadron and parton level respectively.
The effect of soft multigluon emission was discussed by M. Greco \textsuperscript{14}) at the workshop. He pointed out that the same mechanism may explain the large $E_T$ events (Fig. 4a) as well as the $p_T$ behaviour of the Drell-Yan pairs (Fig. 4b). A detailed investigation of the complete final states (multiplicities, average $<p_T>$ per particle, etc.) in both reactions may help verify this assumption in the future.

In conclusion, it is difficult to learn about jet physics at SPS energies using calorimetric jet triggers. If jets exist at these energies then they are buried under much more copiously produced event structures with high particle multiplicities. These high multiplicity events are interesting by themselves and still await a theoretical explanation.

At higher energies (ISR, $p\bar{p}$-collider), jet like event structures emerge very clearly when triggering with calorimeters on a large transverse energy. Latest results on jet physics at the ISR and the $p\bar{p}$-collider were given at the workshop by M. Albrow (APS), R. Böck (UA-1) and A. Rothenberg (UA-2). Fig. 5a, from Ref. 15), shows the cross sections $d\sigma/dE_T$ measured by the UA-2 group at $\sqrt{s} = 540$ GeV. For $E_T > 50$ GeV, the cross section measured with the large acceptance calorimeter trigger ($30^\circ < \phi < 330^\circ$) deviates from the exponential fit which describes the data well at smaller $E_T$. In the region above $E_T > 50$ GeV, the event structure becomes predominantly jet like, while below it looks similar to the one observed in the NA-5 experiment. Fig. 5b), from Ref. 16), and Fig. 5c), from Ref. 17), show jet cross-sections measured by the UA-1 and AFS groups respectively. The jet cross-sections are in good agreement with QCD-model predictions and several orders of magnitudes larger than the single particle inclusive cross-sections at large $p_T$ as expected.

The clear emergence of jets at high energies is probably a result of both the dynamics of the hard scattering process and the better collimation of the jets at larger $p_T$. The jet size is expected to vary like

$$\delta \propto \left(\frac{A}{p_T}\right)^n$$

with $p_T$ the transverse momentum of the parton, $A$ a constant parameter and $n$ a parameter which depends on acceptance\textsuperscript{18}).
Fig. 5: a) large transverse energy $E_T$ cross-sections from the UA-2 experiment\textsuperscript{15).} 

b) jet cross-sections from the UA-1 experiment\textsuperscript{16) and c) jet and single particle cross-sections at large $p_T$ from the ARS\textsuperscript{17) at the ISR.

Also shown are QCD model predictions.
Fig. 6: The fraction of various parton-parton subprocesses predicted from a QCD model as a function of $x_T = 2p_T/\sqrt{s}$. The kinematic range covered by experiments studying jet physics at the SPS, ISR and pp-collider are shown.

In Fig. 6 the fraction of various parton-parton subprocesses predicted by a QCD model are shown as a function of $x_T = 2p_T/\sqrt{s}$. The regions of $x_T$ covered by SPS, ISR and pp-collider are indicated. It is interesting to note that jets at the pp-collider are predominantly of gluonic origin, while jets at the ISR stem from gluons as well as valence quarks. The results of the ISR and the pp-collider experiments indicate that large acceptance calorimeters provide good jet triggers if jets are abundantly produced.

Returning to SPS physics, no new experiment for jet search was proposed at this workshop. However experiments on jet physics will continue at Fermilab (E557, E609, E672) in 1983 and later at higher energies at the Tevatron.

To learn more about hard hadron-hadron collisions at the SPS, W. Geist advertised at this workshop the use of a single particle trigger à la SFM instead of a calorimetric one. In this case, the trigger jet is clearly biased but the $p_T$ balancing jet is not. QCD processes like $q\bar{q} \rightarrow q\bar{q}$ or $gq \rightarrow gq$ are peripheral in nature. For this and kinematical reasons a large $p_T$ hadron at small (large) $\theta^*$ would originate from a scattered beam (target) parton with large fractional momentum $x$. From the trigger particle ratios ($\pi^+/$,$K^+,$,$K^-/$,$\pi^-$, etc.) as a function of $p_T$ and $\theta^*$ measured with different incident beam particles one would possibly obtain information on the flavour flow in the beam and target parton fragmentation. Experiments of this kind performed with different incident beam particles ($\pi^\pm$, $K^\pm$, $p$, $\bar{p}$) and trigger particles would give interesting information
on charge and flavour flow in hard scattering processes. They could be performed with existing set ups, like NA', NA-3 and NA-14, which have high rate capabilities, particle identification and large acceptance spectrometers.

Higher twist effects\(^{19}\) which would lead to events with no forward spectator jets were also discussed at this workshop. These processes are quite accessible at SPS energies and are certainly interesting and should be looked for. More about higher twist will be discussed later in this report.

By showing Fig. 7, which may or may not represent jet physics in hadron-hadron collisions at the SPS, I would like to wish the audience a Merry Christmas and a successful New Year 1983.

![Diagram](image)

**Fig. 7** Merry Christmas

2. HARD SCATTERING WITH INCIDENT REAL PHOTONS

While hadrons behave like composite particles, photons are believed to behave in some cases like truly elementary particles probing directly the point-like nature of the constituents in the proton. We therefore tend to believe that hard scattering processes become more transparent when studying collisions involving real photons. The physics discussed in the following chapter will be studied by NA-14, WA-63 and future NA' experiments.
As shown in Fig. 8 there are basically only three processes involved. It illustrates that the basic physics in terms of first order QCD and QED is the same for photoproduction (Fig. 8a) and prompt photon physics (Fig. 8b). The background to all of these processes is of common origin due to Bremsstrahlung, the VDM (vector meson dominance) and the anomalous behaviour of the photon.

Because of the elementary (partonic) nature of the photon, primordial $k_T$ smearing effects seem to be smaller than in purely hadronic reactions leading to single high $p_T$ particles. The ratios of the cross-sections with primordial $k_T$ on and off are estimated in Table 1 for $p_T = 3$ GeV/c. The primordial $k_T$ effects decrease with increasing $p_T$.

<table>
<thead>
<tr>
<th></th>
<th>$\gamma p + h x$</th>
<th>$p p + \gamma x$</th>
<th>$p p + \pi^0 x$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T = 3$ GeV/c</td>
<td>on/off $\simeq 1.4$</td>
<td>$\simeq 3-4$</td>
<td>$\simeq 10$</td>
</tr>
</tbody>
</table>

Fig. 8: Basic Feynman diagrams for hard scattering processes involving real photons: a) with incident real photons, b) with incident hadrons.
In this respect photoproduction seem to have some advantage over prompt photon production since in the former there is only one initial state hadron involved in the scattering process. On the other hand primordial $k_T$ effects can be studied from the $p_T$ balance in the QED reaction $hh \rightarrow \gamma + \gamma + x$.

It seems that the photon acts like an object with 3 components (Fig. 9).

(a) "point like" i.e., it acts like a truely elementary particle coupling directly to quarks as mentioned before (Fig. 9a);

(b) "perturbative" i.e., it acts like a composite particle with an anomalous structure function, which is exactly calculable in QCD (Fig. 9b);

(c) "hadronic" i.e. it acts like a vector meson (Fig. 9c).

\[ \begin{array}{c}
\gamma \quad q \quad q \\
\downarrow \quad \downarrow
\end{array} \]  \hspace{1cm} \begin{array}{c}
\gamma \quad q \quad \bar{q} \\
\downarrow \quad \downarrow
\end{array} \hspace{1cm} \begin{array}{c}
\gamma \quad \bar{q} \\
\downarrow
\end{array}

\begin{array}{c}
\gamma \quad p \\
\downarrow
\end{array} + \ldots

Fig. 9: Three ways the photon can interact with hadrons:
a) point like behaviour, b) perturbative behaviour,
c) hadronic behaviour.

First indications for the point like behaviour of real photons come from open charm production. The cross-section for photoproduction of charm $\sigma_c$ is anomalously large and 1% of the total hadronic cross-section $\sigma_{tot}$

$$\frac{\sigma_c}{\sigma_{tot}} \sim \frac{1 \text{ mb}}{100 \text{ mb}}$$

when compared to the charm production in hadron-hadron collisions

$$\frac{\sigma_c}{\sigma_{tot}} \sim \frac{20 \text{ mb}}{25 \text{ mb}}$$

A possible explanation for this is the photon-gluon fusion process. Information on the hard component of the photon is also available from deep inelastic electron-photon scattering experiments at the PETRA $e^+e^-$-ring.$^{20}$
In hard scattering processes with incident real photons we expect event topologies with:

(a) three jets in the final state if the photon coupled point like to the target parton, i.e. two large $p_T$ jets and one target spectator jet.
(b) four jets in the final state if the photon acted perturbative or like a hadron, i.e. two large $p_T$ jets, and two beam/target spectator jets.

As shown in Fig. 10, taken from Ref. 21), the 3-jet cross-sections dominate over the 4-jet cross-sections at large $p_T$. The hadronic component of the photon rapidly loses its importance with increasing $p_T$. QCD calculations\textsuperscript{21} predict that at $\sqrt{s} = 19.4$ and $p_T \approx 6-7$ GeV the jet cross-section in photoproduction exceeds the one in hadron-hadron collisions (Fig. 11). Such an observation would manifest the true point like behaviour of the photon. The comparison of deep inelastic photon-hadron with hadron-hadron collision using incident photon and hadron beams belongs to the future research program of the experiments mentioned above.

Fig. 10: Cross-sections predicted by a QCD-model calculation for the reaction $\gamma p \rightarrow \text{jet} + X$ at $\sqrt{s} = 19.4$ GeV. Taken from Ref. 21).
In the following discussion, the photoproduction reactions will be presented in two separate categories:

(a) inclusive and semi-inclusive experiments to study QCD-Compton scattering and gluon fusion;
(b) exclusive experiments to study QED-Compton scattering.

2.1 QCD-Compton scattering and gluon fusion

Some interesting preliminary results from the WA-57 experiment using the \( \hat{\omega} \)-spectrometer have been reported at the workshop by S. Donnachie. They looked at topologies of events in the reaction \( \gamma p \rightarrow \text{hadrons} \) at incident \( \gamma \) energies 50 GeV < \( E_\gamma \) < 70 GeV. The events were selected with a multiplicity trigger in order to exclude diffractive production of vector mesons. The events were analysed following the steps:

i) find a sphericity axis;

ii) look at \( p_T \) distributions with respect to this axis;

iii) look at energy flow as a function of angle with respect to the beam axis.
In Fig. 12 the obtained energy flow versus angle with respect to the beam axis is plotted for all events (Fig. 12a) and for events which passed a $\sum p_T^2 > 3 \text{ (GeV/c}^2\text{)}$ requirement (Fig. 12b). At first inspection the energy flow distribution looks like what one would expect from 3-jet like topologies with a missing forward beam jet. Because of the preliminary nature of the data the authors did not draw any physics conclusions from the data at the workshop, but they pointed out that 3-jet event structures, if they exist, are well detectable in their apparatus. They also mentioned that a small fraction (few %) of the events shown in Fig. 12b) have a single particle jet, a topology one would expect from a higher twist effect (Fig. 13 a). Theoretical predictions of higher twist effects are given in Ref. 22). The importance of these effects were pointed out by E. Berger at the workshop. It was estimated that about 10% of all 3-jet events could originate from higher twist. These events would have a very clean signature: a one particle jet (for example $\nu$) recoiling against a parton jet. Once the $p_T$ and $p_L$ for the $\nu$ are determined, the kinematics of the recoil jet is fixed. Higher twist effects in prompt photon processes are quite similar to photoproduction as illustrated in Fig. 13b). In this case there will be no forward beam jet and a high $p_T$ photon recoils against a parton jet.

![Energy flow versus angle with respect to the beam axis](image)

**Fig. 12:** The energy flow of hadrons with respect to the incident beam axis is shown for the reaction $\gamma p \rightarrow$ hadrons at incident $\gamma$ energies 50 GeV $< E_\gamma < 70$ GeV, a) for all events b) for events which passed $\sum p_T^2 > 3 \text{ (GeV/c}^2\text{)}$ requirement.
In order to be able to disentangle the QCD-Compton and the gluon fusion processes from the 4-jet events the NA-14 experiment stressed the importance to look for exclusive channels as proposed by D. Shiff and collaborators\textsuperscript{23} at this workshop. Their approach is to look for a charge asymmetry of the leading particles in the two large \( p_T \) jets. As illustrated in Fig. 14 charge asymmetry is expected due to the fact that the photon couples preferentially to the charge \( q_u = 2/3 \) of the u-quark.

![Higher twist](image)

**Fig. 13:** Simplest higher twist diagrams for processes which can be studied a) in photoproduction and b) in prompt photon experiments.

![QCD-Compton & Gluon-Fusion](image)

**Fig. 14:** Diagram to illustrate the expected charge asymmetry of leading particles in the QCD-Compton and gluon-fusion processes.
Here it is assumed that the leading particle in a jet remembers somehow the flavour and the charge of the parton it originated from. It is easy to see that by forming the difference of the inclusive cross-sections

\[ \Delta \sigma^{\pi^+ \pi^-} = \left( \frac{d\sigma}{dy} (\gamma p \rightarrow \pi^+ \pi^-) \right) - \left( \frac{d\sigma}{dy} (\gamma p \rightarrow \pi^+ \pi^-) \right) \]

one can select the QCD-Compton process. As shown in Fig. 15 this method allows to suppress most of the 4-jet background events without cutting too much away from the 3-jet signal.

Fig. 15 QCD-model calculations of the inclusive \( \pi^+ \) cross-section and the difference of the inclusive cross-sections \( \pi^+ \pi^- \) for the reaction \( \gamma p \rightarrow \pi^+ \pi^- \) and \( \gamma p \rightarrow \pi^+ \pi^- \) are shown. The contribution of the point-like behaviour of the photon (Born term) is shown in solid, the anomalous in dashed dotted, the hadronic or VDM in small dashed and higher twist in big dashed lines. See text for explanation.
Even more selective is the difference between the double inclusive cross-sections:

\[ \frac{d\Delta^2}{dp_T^1 dy_1 dp_{T2} dy_2} = \frac{d\sigma (\gamma p \rightarrow \pi^+ h^+ + x)}{dp_T^1 dy_1 dp_{T2} dy_2} - \frac{d\sigma (\gamma p \rightarrow \pi^+ h^+ + x)}{dp_T^1 dy_1 dp_{T2} dy_2} \]

where the hadron \( h \) of momentum \( p_T \) is measured in the hemisphere away from the trigger particle \( \pi^- \) or \( \pi^+ \) (with transverse momentum \( p_T \) and rapidity \( y_T \)).

By forming:

i) \( \Delta^+ - \Delta^- \), one isolates the QCD-Compton process leading to a gluon jet in the final state;

ii) \( \Delta^+ + \Delta^- \), one isolates the gluon fusion process, which allows one to study the gluon structure function for example.

It is worthwhile to point out that the double differential inclusive cross-section is no more influenced by primordial k_T- smearing effects. Perhaps this method may lead to a meaningful test of QCD in photoproduction processes.

2.2 QED-Compton scattering

The cross-section for QED-Compton scattering (QED-C) is by a factor \( a_s/a_c \) smaller than for QCD-Compton scattering (QCD-C) because of the purely electromagnetic nature of the process. The detection of QED-C depends on the availability of intense photon beams (Table 2) and the ability to separate the scattered high \( p_T \) photon from abundantly produced background \( \pi^- \)'s, \( n \)'s, etc. The NA-14 experiment, presently situated in the high intensity area NAHIF, is specially designed to look for QED-C processes. It consists of a large magnetic spectrometer with finely segmented calorimeters (Olga, Ilga, Crown) covering a large phase space region (Fig. 16a). The \( \pi^- \) recognition efficiency is 80%-90% for for \( \pi^- \) momenta below 80 GeV. Compared to prompt photon experiments the \( \gamma/\pi^- \) ratio is estimated\(^{24,25}\) to be more favourable (Fig. 16b).

The expected cross-section for QED-C at \( E_Y = 100 \) GeV is 2 nb. The total sensitivity of the NA-14 experiment is 1 event/pb (or 25 events/nb day).

The expected event structure is similar to prompt photon events, only in QED-C the spectator beam jet is completely missing. One expects an isolated high \( p_T \) photon recoiling against a jet, which allows one to put a powerful kinematical constraint on the event selection.
Fig. 16: a) The phase space acceptance of the NA-14 calorimeters Olga, Ilse and Crown are shown; the heavy solid lines indicate equal momenta of the scattered photons.
b) The heavy solid lines show equal $\gamma/\pi^+$ ratios expected from model calculations\textsuperscript{24}.

Preliminary results have been presented by F. Richard at this workshop. Fig. 17 shows the longitudinal momentum distribution of prompt photons with $p_T > 2$ GeV/c. Also shown in Fig. 17 is the estimated $\pi^+$ and $\pi^-$ contamination and the QED-C predictions (with a normalisation uncertainty of ±30%). Although the signal seems to be consistent with the theoretical predictions, more statistics are needed to establish the detection of QED-Compton scattering. Since this process is purely electromagnetic it should give information on the quark charge. The preliminary results are consistent with a fractional quark charge of $2/3$.

D.W. Duke and J. Owens\textsuperscript{26} have calculated QCD-corrections to deep inelastic Compton scattering including the graphs shown in Fig. 18. It turns out that the next-to-leading-order corrections are very small for $p_T^Y > 4$ GeV/c and rapidity values away from the forward region. The Bremsstrahlung contributions, which are similar in prompt photon production, can effectively be reduced by rejecting events where the large $p_T$ photon is accompanied by hadrons.
Fig. 17: Longitudinal momentum distribution of prompt photons produced in the reaction $\gamma L_1 \to \gamma + x$ at photon energies $E_\gamma > 100$ GeV.

Fig. 18: Feynman graphs for the subprocesses $\gamma q \to \gamma g$ and $\gamma g \to \gamma q\bar{q}$. 
Another QCD-correction to QED-C comes from the Box-diagram shown in Fig. 19. The cross-section ratio $\sigma^{\text{Box}}/\sigma^{\text{QED-C}} \sim a_s^4$ is expected to be small, but it depends strongly on the gluon distribution inside the proton. M. Fontannaz and D. Shiff\cite{27} have calculated $\sigma^{\text{Box}}/\sigma^{\text{QED-C}} \sim 10-30\%$ at a rapidity $y = 1$ using known gluon distributions. The contributions decrease with decreasing rapidity. Experimentally they can possibly be recognized by looking at the charge of the leading particles in the away side jet.

![Box-diagram](image)

Fig. 19: The expected charges of the leading particles in the away side jet are illustrated for a) the Box-diagram and b) the QED-Compton process.

In Table 2 the photon beams at the SPS are compared to those which become available at the Tevatron in late 1985. In this comparison $3 \times 10^{12}$ protons per spill and a radiator thickness of 0.1 radiation length have been assumed. The E-12 wide band beam in the North area (NAHIP) is tagged with a resolution of $\sim 3\%$ and will be the most intense photon beam around until 1985. Also shown in Table 2 is the muon beam delivering virtual photons for open geometry experiments with thin targets. The intensity is comparable to the real photon beam intensities at 0.
### Table 2

**Photon-Beams at the SPS and the Tevatron (FERMILAB)**

**SPS:** assuming $3 \times 10^{12}$ primary protons of 450 GeV/c per spill and a radiator of 0.1 radiation length

<table>
<thead>
<tr>
<th>Exp.</th>
<th>$E_e$ [GeV]</th>
<th>$n_e$</th>
<th>$E_\gamma$ [GeV]</th>
<th>$n_\gamma$</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA-14</td>
<td>&lt; 150</td>
<td>$\sim 10^8$</td>
<td>&gt; 100</td>
<td>$10^7$</td>
<td>available since 1982</td>
</tr>
<tr>
<td>(E-12 beam)</td>
<td></td>
<td></td>
<td>&gt; 150</td>
<td>$10^4$</td>
<td></td>
</tr>
<tr>
<td>Q</td>
<td>150</td>
<td>$1.5 \times 10^7$</td>
<td>&gt; 100</td>
<td>$5 \times 10^4$</td>
<td>available in 1983</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>$5 \times 10^6$</td>
<td>&gt; 150</td>
<td>$8 \times 10^5$</td>
<td>change electron energy</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Exp.</th>
<th>$E_e$ [GeV]</th>
<th>$n_\mu$</th>
<th>$E_\gamma^a$ [GeV]</th>
<th>$n_\gamma^a$</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMC</td>
<td>280</td>
<td>$10^8$</td>
<td>&gt; 100</td>
<td>$4 \times 10^5$</td>
<td>oper geometry</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&gt; 200</td>
<td>$8 \times 10^3$</td>
<td>and thin target</td>
</tr>
</tbody>
</table>

**FERMILAB:** assuming $3 \times 10^{12}$ primary protons of 800 GeV/c per spill and a radiator of 0.1 radiation length

<table>
<thead>
<tr>
<th>Exp.</th>
<th>$E_e$ [GeV]</th>
<th>$n_e$</th>
<th>$E_\gamma$ [GeV]</th>
<th>$n_\gamma$</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>wide band</td>
<td>350</td>
<td>$6 \times 10^6$</td>
<td>&gt; 100</td>
<td>$2.3 \times 10^7$</td>
<td>available late 1985</td>
</tr>
<tr>
<td>E-687</td>
<td></td>
<td></td>
<td>&gt; 200</td>
<td>$10^7$</td>
<td>duty cycle 1/4 of SPS</td>
</tr>
</tbody>
</table>

$E_e, \gamma, \mu$ are the energies of electrons, photons and muons respectively. $n_e, n_\gamma, n_\mu$ are the number of electrons, photons and muons per spill.

3. **HADRON-HADRON COLLISIONS WITH PROMPT PHOTONS IN THE FINAL STATE**

The following experiments will study large $p_T$ prompt photons in hadron-hadron collisions at the SPS: NA-3, NA-24, WA-70, UA-6 and in the future also NA-12.

The observation of a growing $\gamma/\pi^0$ ratio with increasing $p_T(x_\gamma)$ as compared to a constant $\gamma/\pi^0 = a$ expected from a purely VDM behaviour of the photon makes us believe that prompt photons originate from a hard scattering process. Prompt photons are clean probes of point-like interactions. Because of the partonic nature of the photon no fragmentation is involved and therefore the kinematical quantities $p_T$ and $p_L$ of at least one parton in the scattering process can be well determined.
Large $p_T$ prompt photons have been detected at Fermilab\textsuperscript{28,29} and the ISR\textsuperscript{30,31}). Fig. 20 and Fig. 21, taken from Ref. 28 and Ref. 29 respectively, show that the $\gamma/\pi^*$ ratio is growing from a few percent at low $p_T$ ($\lesssim 3$ GeV/c) to about 30% at large $p_T$ ($\simeq 5$ GeV/c). Because of the rather small prompt photon signal compared to the large $\pi^*$, $\eta$...etc. background the new generation experiments at the SPS and Fermilab employ photon-calorimeters with high spatial resolution and $\pi^*$ detection efficiencies larger than 90%.

![Graphs showing $\gamma/\pi^*$ ratio vs $p_T$ and $X_F$.](image)

Fig. 20: FNAL data on $pp + \gamma \chi$ from Ref. 28).

![Graphs showing $\gamma/\pi^*$ ratio vs $p_T$ and $X_F$.](image)

Fig. 21: FNAL data on $p\gamma + \gamma + x$ and $\pi^*C + \gamma + x$ at 200 GeV/c from Ref. 29).
Fig. 22 shows the cross-sections for prompt photon production estimated from a QCD-model calculation. In this calculation a $A = 0.4$ GeV, an average primordial $< k_T > = 0.85$ GeV/c and a parametrization of the structure functions of Owens and Reno$^{32}$ were used. It is interesting to note that the $\pi^-p+\gamma+x$ cross-section at large $p_T$ turns out to be larger than the $pp+\gamma+x$ cross-section in this model. This is because the harder parton momentum distribution in the $\pi^-$ wins over the additional annihilation channels available in $pp$-collisions.

The estimated sensitivity of the experiments using incident p and $\pi^-$ beams is 800 events/nb day, and incident $\pi^+$ beams 80 events/nb day at 300 GeV. The physics with incident antiprotons will be the domain of the UA-6 experiment, as long as stored antiprotons cannot be extracted from the SPS. UA-6 quotes a sensitivity of 40 events/nb day (with a Hydrogen jet target) assuming it is the main user at the SPS-collider. In Table 3 the estimated integrated luminosities of the ISR, SPS and Fermilab experiments are listed for $pp$ and $pp$-collisions. The $pp$ luminosities for NA-3, NA-24 and WA-70 are quoted under the assumption that antiprotons could be extracted from the SPS-collider and equally shared among these three users. The extraction of stored antiprotons has been studied in the past$^{33,34}$. Presently it is not possible to extract them to the West area because the appropriate extraction point is occupied by UA-6.

![Graphs showing cross-sections](image_url)

**Fig. 22:** QCD-model predictions for prompt photon cross-sections in a) $pp$, $pp^-$ and b) $\pi^-p$, $\pi^+p$-collisions at 300 GeV.
Table 3

Estimation of integrated luminosities per day

<table>
<thead>
<tr>
<th></th>
<th>pp</th>
<th>√s (GeV)</th>
<th>−pp</th>
<th>√s (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SPS Experiments</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UA-6</td>
<td>$3.10^{35}$</td>
<td>22.5</td>
<td>$\sim 10^{34}$ a)</td>
<td>22.5</td>
</tr>
<tr>
<td>NA-3 NA-24 WA-70</td>
<td>$8.10^{35}$</td>
<td>24</td>
<td>$\sim 10^{35}$ b)</td>
<td>24</td>
</tr>
<tr>
<td><strong>Fermilab Experiments</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E705</td>
<td>$1.2.10^{35}$</td>
<td>24</td>
<td>$2.10^{34}$ c)</td>
<td>24</td>
</tr>
<tr>
<td>ISR</td>
<td>$2.10^{36}$</td>
<td>63</td>
<td>$2.10^{33}$</td>
<td>63</td>
</tr>
</tbody>
</table>

a) assuming: parasitic (bunched) run length of 12h/day, hydrogen jet density 
$\rho(H_2) = 4.10^{14}$ atoms/cm$^2$, which produces an estimated luminosity loss of 10% for UA-1;

b) assuming: extraction of stored $\bar{p}$ in the SPS, $3.10^{9}$ $\bar{p}$/spill per user, 100sec/spill, 100 spills/day, a flat top energy of 300 GeV, and a 1 m liquid hydrogen target;

c) assuming: 1 spill/60 sec, 20 sec flat top, 1 m deuterium target, $2.10^{12}$ protons on primary target give $4.10^{6}$ $\bar{p}$/spill.
From the calculated cross-sections and the quoted sensitivities of the experiments it can be seen that at the SPS the $x_T$ range up to 0.7 can be well explored with incident $\pi^-$ beams and up to 0.5 with incident $\pi^+$, $p$, and $\bar{p}$ beams. As compared to the ISR the unique feature of the SPS is the availability of high intense $\pi^-$-beams which allow one to explore the valence quark - valence antiquark annihilation channels which dominate over other processes at large $x_T$.

The use of different incident beam particles allows one to separately study QCD-annihilation and Compton processes (Fig. 23). For example, the difference $d\sigma(\pi^-p+\gamma+x) - d\sigma(\pi^+p+\gamma+x)$ isolates the annihilation graph. If isoscalar targets are used then the difference also removes most of the $\pi^+$ background. At large $p_T$ the annihilation channels dominate the cross-section and the ratio

$$R = \frac{d\sigma(\pi^-p+\gamma+x)}{d\sigma(\pi^+p+\gamma+x)}$$

![Feynman diagrams](image)

**Fig. 23** Basic Feynman diagrams for processes leading to large $p_T$

prompt photons in $\pi^-p$- and $\pi^+p$- collisions.
is expected to increase rapidly with \( p_T \) (Fig. 24). For isoscalar targets the ratio should grow to \( R = 4 \) (given by the \( u \) and \( d \) quark charge ratio \( q_u^2/q_d^2 = 4 \)) similar to Drell-Yan processes.

In \( p\bar{p} \) and \( \pi^+p \) collisions a large \( p_T \) prompt photon would therefore provide a good tag for a recoiling gluon jet. This opens the possibility to study gluon fragmentation in a rather clean way.

3.1 Gluon Structure Function

QCD-Compton scattering in \( pp \) and \( \pi^+p \) collisions give in principle access to the gluon structure function in the proton and the pion \(^{34}\). Since the quark structure functions in the proton are already known from Drell-Yan and deep inelastic lepton scattering processes the gluon structure function in the proton is perhaps somewhat easier to extract from the data. \( \pi^+p \) collisions are more complicated due to the presence of annihilation channels. These would have to be well understood before the gluon structure function of the pion could be determined from the data. However, it should be tried. Fig. 25 demonstrates that the cross-sections predicted by QCD are quite sensitive to the assumed gluon distributions.

However, the following complications have to be understood first:

i) Bremsstrahlung

ii) higher order QCD-terms

iii) primordial k\(_T\)-smearing

iv) higher twist effects.

Bremsstrahlung contributions \(^{36}\) have been shown to be small for \( p_T < 10 \text{ GeV/c} \) at the ISR \(^{37}\). However, they may become important at SPS energies at large \( x_T \). As discussed before background from Bremsstrahlung photons (Fig. 26) can be reduced by rejecting events where photons are accompanied by hadrons. Higher order QCD corrections have been calculated in Refs. 38,39. They are found to give a \( \sim 20\% \) contribution to the ratio of the inclusive cross-section \( \gamma/\pi^0 \). By using the double differential inclusive cross-section as described in the previous chapter primordial k\(_T\)-smearing effects can be largely reduced.

As already pointed out the detection of higher twist effects is interesting by itself \(^{40}\). Their contribution is small at \( \theta^* = 90^\circ \) but increases at more forward angles and large \( p_T \) as shown in Fig. 27.
Fig. 24: QCD-model prediction for the cross-section ratio \( R = \frac{\sigma(p^+p \rightarrow \gamma X)}{\sigma(p^+p \rightarrow \gamma X)} \) as a function of the transverse momentum \( p_T \) of the prompt photon.

\[ p + p + \gamma \rightarrow X, \quad \theta_{CM} = 90^\circ \]

- Contogouris et al. with \( G \propto (1-x)^p \)
- * * * * * * * G \propto (1-x)^k
- Halzen et al.
- Queen et al. For the other three, \( G \) tallies with solid line.

Fig. 25: The prompt photon cross-section measured at several energies is compared with QCD-model predictions assuming gluon distributions of \( G \propto (1-x)^x \) (solid line) and \( G \propto (1-x)^k \) (dashed line). Taken from Ref. 35.)
Fig. 26: Bremsstrahlung diagrams for the production of prompt photons in hadron-hadron collisions taken from Ref. 36.

Fig. 27: Transverse momentum dependence of the predicted inclusive prompt photon yield $E \sigma / d^4p$ for $\pi^- p + \gamma \pi$ at $\sqrt{s} = 20$ GeV and at center-of-mass photon angles (a) $\theta^\gamma = 45^\circ$, and (b) $\theta^\gamma = 90^\circ$, measured with respect to the incident pion direction. Shown are the high twist yields for $\pi^- p + \gamma \pi$, obtained from the subprocess $\pi q + \gamma q$, and, for comparison, the leading twist yield in $\pi^- p + \gamma \pi$, only from the subprocesses $\pi^+ \pi^- p + \gamma g$. For $\pi^- p + \gamma \pi$, the leading twist yield from $d \pi^0 p + \gamma g$ is $1/8$ that shown for $\pi^- p + \gamma \pi$. Taken from Ref. 40.
3.2 $\gamma\gamma$ and $e^+e^-$ Final States

Interesting physics can be learned from $\gamma\gamma$ and $e^+e^-$ final states in $\pi^-p$ and $pp$-collisions. After the subtraction of the QED-C terms the annihilation channels as shown in Fig. 28 can be studied.

![Feynman Diagrams]

**Fig. 28:** Basic Feynman diagrams of quark-antiquark annihilation processes leading to $\gamma\gamma$, $\gamma g$ and $e^+e^-$ final states.

For example, the cross-section ratio of the Drell-Yan and the QED-C gives directly information on the quark charge. Complementary to QED-C scattering in photoproduction this measurement would be of fundamental interest. From the cross-sections at the parton level

$$\frac{d\sigma^{\gamma\gamma}}{dQ^2} = \frac{a_1^2 a_2^2}{N_c^2 M^2} \left( \frac{2}{\sin^2 \theta} - 1 \right)$$

$$\frac{d\sigma^{e^+e^-}}{dQ^2} = \frac{a_1^2 a_2^2}{N_c^2 M^2} \left( \frac{1 + \cos^2 \theta}{4} \right),$$

with $q$ the quark charge and $N_c$ the number of colours, one can easily see that at $\hat{\theta} = 90^\circ$ the ratio

$$\frac{\sigma^{\gamma\gamma}}{\sigma^{e^+e^-}} \propto \frac{q^+}{q^-}$$

is proportional to the quark charges. This ratio is expected to be equal (non equal) to one if the quarks have charge one (fractional charge). A first result has been reported by the ISR experiment $80_{-41}^{+41}$ yielding a ratio

$$\frac{\sigma^{\gamma\gamma}}{\sigma^{e^+e^-}} = 1.7 \pm 1$$

for $p_T > 3$ GeV/c and $8$ GeV $< m_{\gamma\gamma} < 11$ GeV.
GLUEBALLS: PRESENT AND FUTURE

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CERN, European Organization for Nuclear Research, Geneva, Switzerland

ABSTRACT
This talk reviews the predicted properties of the glueballs. The glueball candidates are presented and a review of experiments looking for glueballs is given.

1. INTRODUCTION

It was recognised in the early years of QCD that gluons similarly to quarks should give bound states [1]. The existence of such states, called glueballs, is due to the self coupling of gluons, a consequence of the non-abelian structure of the SU(3)_{c} group. They have the vacuum quantum numbers except for \( J^{PC}(Q = 0, I = 0, S = 0, B = 0, \ldots) \), but QCD makes no prediction on their properties, so that one has to use various QCD inspired models to get information on the classification (sect. 2), the masses (sect. 3), the width (sect. 4) and the decay modes (sect. 5).

One can wonder why glueballs have not been seen after about 20 years of spectroscopy. One of the reasons one can think of is that at low energy (privileged place for spectroscopy), the hadronic dynamics is dominated by the valence quarks while gluons play only a little rôle. Therefore, glueballs should be searched in specific reactions where gluons are at work (sect. 6), but they still may be confused with normal quark-antiquark mesons (sect. 7). Experimental work on glueball is recent, but there are already some candidates which I discuss in sect. 8. Some of the points described in the present talk are discussed with more details in reviews to which I refer the reader [2-5].

2. GLUEBALL CLASSIFICATIONS

Similarly to the non relativistic quark model, one can construct the glueballs with \( 1^{-} \) building blocks (gluons) [6]. Taking into account the Bose symmetry, the two-gluon bound states (all with positive \( C \) parity) are

<table>
<thead>
<tr>
<th>( L )</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>..</th>
</tr>
</thead>
<tbody>
<tr>
<td>( J^{PC} )</td>
<td>( 0^{++} )</td>
<td>( 2^{++} )</td>
<td>( 0^{-+} 1^{+-} 2^{-+} )</td>
<td>( 2^{++}; 0^{++} 1^{++} 2^{++} 3^{++} 4^{++} )</td>
<td>( 2^{-+} 3^{-+} 4^{-+} )</td>
</tr>
</tbody>
</table>
It is interesting to note that there appear states which are forbidden as q̄q states: the 1−+, 3−+ series; such states are called oddballs.

With three gluons, one can construct two types of glueballs corresponding to symmetric or antisymmetric colour coupling. In that sector, all JPC combinations can be achieved, the simplest states (with \( L = 0 \)) being 0−+, 1−−, 3−−.

The addition of extra-gluons will obviously not enrich the possible JPC states, but this glueball construction method leads to the following question: as gluons are self coupling objects, how can one say that a glueball contains a given number of gluons? A gauge invariant treatment is to construct all the independent glueball creation operators out of n local fields \( F^a_{\mu\nu} \), or equivalently out of n colour electric or magnetic fields [5, 7-9]. The resulting spectrum is richer than the previous one, since the colour magnetic field is equivalent to a 1++ gluon. In the two-gluon spectrum, the ground level (\( L = 0 \)) contains 7 states

\[
0^{++}, 2^{++}; 0^{-+}, 1^{+-}, 2^{-+}; 0^{++}, 2^{++}
\]

and all JP with \( C = + \) can be achieved. With higher L values. In the three-gluon spectrum, the \( L = 0 \) states are \( 0^{++}, 1^{++}, 2^{++}, 1^{+-}, 2^{-+}, 3^{+-} \) and all JPC are possible using other L values. A similar classification is found within the bag model [10].

Finally, some authors [8, 11, 12] have argued that the gluonic field is transverse and that, from the Landau-Pomeranchuk-Yang theorem [13], 2-gluon states such as 1−+, 3−+, 5−+, ... are forbidden.

Although no general agreement is met on a glueball classification, the main results are:

(a) The lowest lying glueballs should have spin 0++ 0−+, 2++ and possibly 1−+.

(b) There are oddballs i.e. glueballs with spin 0−−, 1−+, 2−+, ... and 0−− which are forbidden for normal q̄q mesons. The lowest lying oddball could be the 1−−.

3. MASSES

There are several approaches to estimate the glueball masses.
3.3 Intrinsic charm in the proton

F. Halsen and D.M. Scott have suggested to look for intrinsic charm in QCD-C processes by using the prompt photon as a signal for large quark charges (u-quark or c-quark). As illustrated in Fig. 31a) one can measure the e/π ratio in the away side jet of a large $p_T$ prompt photon. This ratio may be enhanced due to the semi-leptonic decay of produced charmed particles. For 1% intrinsic charm in the proton they calculate $e/\pi \sim 10^{-4}$ which can be compared to the $e/\pi$ ratio in the jet recoiling against a large $p_T$ (Fig. 31b). For this measurement an apparatus with a good $\pi/e$ rejection is needed. The WA-70 and the UA-6 experiment seem to be good candidates for exploring this physics. Constituent-Bremsstrahlung and gluon fragmentation into charm may be a background one has to watch out for.

It is worth noting that recent results from the EMC experiment seem to indicate that intrinsic charm, if it exists, is smaller than 1%.

![Diagram](image)

**Fig. 31** Schematic illustration of a) the QCD-C process leading to abundant charm production and b) a normal single particle high $p_T$ process.

In Table 4 the approved prompt photon experiments at the SPS and the Tevatron are listed and compared in their main physics goals, their photon and hadron detection systems and their sensitivities. Also shown in Table 4 is the starting year of data taking.
## TABLE 4

List of approved prompt photon experiments at the SPS and at FERMILAB

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Start of data taking</th>
<th>Beam (GeV)</th>
<th>Energy (GeV)</th>
<th>Physics goals stated in Proposal</th>
<th>Photon calorimeter</th>
<th>Photon calorimeter resolution σ(E)/E</th>
<th>Two shower separation ΔX</th>
<th>Hadron measurement</th>
<th>Sensitivity events/nb day</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPS NA-3</td>
<td>82</td>
<td>π⁺, p</td>
<td>200</td>
<td>hh+γX, hh+γγX and g-fragmentation g-structure function</td>
<td>scintillator/lead + shower chamber</td>
<td>&lt; 0.21/√E</td>
<td>&lt; 50 mm</td>
<td>magnet spectrometer, Cerenkov</td>
<td>600</td>
</tr>
<tr>
<td>SPS NA-24</td>
<td>83</td>
<td>π⁺, p</td>
<td>200</td>
<td>&quot;</td>
<td>proportional tube/lead + scintillator/lead</td>
<td>&lt; 0.24/√E</td>
<td>15 mm</td>
<td>segmented hadron calorimeter</td>
<td>800</td>
</tr>
<tr>
<td>SPS WA-70</td>
<td>83</td>
<td>π⁺, p</td>
<td>200</td>
<td>&quot;</td>
<td>liquid scintillator/lead</td>
<td>0.16/√E</td>
<td>15 mm</td>
<td>γ spectrometer, RICH-counter</td>
<td>800</td>
</tr>
<tr>
<td>SPS UA-6</td>
<td>84</td>
<td>π⁻ p</td>
<td>270</td>
<td>hh+γX, π X Drell-Yan e⁺e⁻ pairs and A, A̅ production</td>
<td>proportional tube/lead</td>
<td>?</td>
<td>≥ 15 mm</td>
<td>magnet spectrometer, (main user) dE/dx, transition radiation</td>
<td>40 pp</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FERMILAB</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>E-705</td>
<td>84</td>
<td>p, p, π⁺</td>
<td>300</td>
<td>Charmonium hh+χχ hh+γχ, hh+γγX</td>
<td>scintillating lead-glass</td>
<td>?</td>
<td>50 mm</td>
<td>magnet spectrometer, Cerenkov</td>
<td>~ 120</td>
</tr>
<tr>
<td>E-706</td>
<td>85</td>
<td>π⁺, p</td>
<td>400</td>
<td>hh+γX, hh+γγX Drell-Yan e⁺e⁻ pairs, hh+π⁺γ, π⁺γ, π⁺π⁺X</td>
<td>liquid Argon</td>
<td>0.14</td>
<td>?</td>
<td>magnet spectrometer, calorimeter, RICH-counter, silicon-microstrips</td>
<td>~ 10³</td>
</tr>
</tbody>
</table>
4. CONCLUSIONS

It has been shown that calorimeter triggers at SPS energies select events with complicated topologies, which are interesting by themselves. Hard scattering processes involving jets are difficult to extract from the data. The $p_T$ of the partons involved in the scattering process is unknown. It was suggested to go back to single high $p_T$ particle triggers using an open spectrometer geometry. No new jet physics proposals were put forward at the workshop. This physics however continues to be investigated at Fermilab.

It is believed that hard scattering processes become more transparent when using real photons. High intensity and high energy photon beams are unique to the SPS at present. The competition of Fermilab is expected to start late in 1985.

In prompt photon production the availability of intense $\pi^-$ beams and the stored antiprotons in the collider (UA-6) opens a wide and interesting field of study of quark-antiquark annihilations. Thanks to the closing of the ISR this domain of research will be in the hands of the SPS and Fermilab in the near future. The competition at Fermilab starts in 1984.

Acknowledgements

I would like to thank all my colleagues who have contributed in form of presentations and discussions to this workshop. I am especially grateful to D. Treille, P. Seyboth, F. Costantini, P. Polakos, Th. Schouten, R. Rückl, L. Stodolsky, M. Jacob, D. Shiff, P. Petronzio, M. Fontannaz, E. Berger, S. Donnachie, A. Clegg, E. Paul, M. Martin, M. Kienzle-Focacci and M. Werlen from which I profited in many discussions. My thanks are given to the workshop organizers and the secretaries which typed this manuscript.
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DILEPTONS

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ABSTRACT
First a review of the present status of theory and experiment as discussed at the workshop is given. The need for data from intense \( \pi^+ \) beams is stressed and a possible subtraction procedure of the proton background in the \( \pi^+ \) data is described. The interest in more \( \bar{p} \) and \( p \) induced data is presented together with a comparison of the competition from different accelerators. Finally new projects for the measurement of photons produced in association with lepton pairs are discussed.

1. PREDICTIONS OF THE BASIC MODEL

In 1970 Drell and Yan \(^1\) proposed antiquark-quark annihilation as the mechanism responsible for the hadronic production of lepton pairs.

\[
\begin{align*}
\bar{q}(x_1) & \rightarrow \mu^+(\mu^-) \\
q(x_2) & \rightarrow \mu^-(\mu^+) \\
\end{align*}
\]

In this model an antiquark \( \bar{q} \) with fractional longitudinal momentum \( x_1 \) annihilates with a quark \( q \) with fractional momentum \( x_2 \) producing a massive, virtual photon which materializes as a pair of leptons. From this simple Drell and Yan mechanism one predicts \(^2\):

1 - The cross section \( m^2 \, \frac{d\sigma}{dm} = F(\tau) \) depends only on the scaling variable \( \tau = m^2/s = x_1 \cdot x_2 \).
2 - The magnitude and shape of \( F(\tau) \) are determined by the D.I.S. structure functions.
3 - The structure functions of incident photons, pions, kaons or antiprotons can be determined.
4 - The transverse momentum, \( p_t \), of the lepton pair should be small (\( \lesssim 300 - 500 \) MeV/c). (The model ignores \( p_t \) in its predictions).
5 - In the rest system of the pair, the angular distribution is \( 1 + \lambda \cos^2 \theta \), where \( \theta \) is measured relative to the hadronic collision axis, and \( \lambda = 1 \).
6 - The cross section ratios on isoscalar targets and on hydrogen should reach the limits given by the ratio of the squares of the electric charges of the interacting quarks:

\[
\begin{align*}
\frac{\sigma(\pi^+ p)}{\sigma(\pi^- p)} & \rightarrow 4 \\
\frac{\sigma(\pi^+ C)}{\sigma(\pi^- C)} & \rightarrow 1 \\
\end{align*}
\]

7 - The A dependence of the production cross section should be proportional to \( A^\alpha \) with \( \alpha = 1 \).

Agreement between data and these predictions has been remarkably good, with three major exceptions:

a) there is a K factor, i.e. the observed cross section is approximately twice the expected theoretical cross section using as input structure functions measured in D.I.S.

b) the \( p_t \) of the lepton pair is large and increases with s.
c) there is an experimental controversy about the very high \( x_1 \) region in \( \pi^- \)-nucleus interactions. One experiment has observed an angular distribution with \( \lambda \approx 0 \) for high \( x_1 \).

2. NEW THEORETICAL DEVELOPMENTS

These departures from the basic D.Y. model lead to the inclusion of QCD effects.

The question of anomalies in the angular distributions (point c) was not discussed at this workshop. An extensive discussion can be found in the proceedings of the Workshop of Drell-Yan Processes at Fermilab.\(^3\)

Theoreticians presented calculations concerning point a (K factor) and point b (\( p_t \) dependence).

2.1 K factor and structure function predictions

P. Chiappetta and J.L. Meunier (see appendix 1) presented QCD calculations for the evolution of the K factor and of the \( \pi \) or \( \bar{\pi} \) structure functions in the variables \( Q^2 \) (\( = m^2 \)) and \( y = \frac{1}{2} \ln \left( \frac{x_1}{x_2} \right) \), \( y \) is the rapidity of the lepton pair. Because uncertainties in the gluon structure function have a strong influence on the calculated cross section, they felt it necessary to eliminate the Compton diagram contributions.

Thus, their calculations are presented for the cross section differences \( \sigma \) (anti-particle)-\( \sigma \) (particle). The need to have a "clean" theoretical prediction to test is a strong argument for measuring both anti-particle and particle cross sections. The difference can then be compared with theory.

Soft gluon emission can be calculated in any order of the perturbation theory.

In the leading log approximation the K factor is equal to one. Including the \( \pi^2 \) term in the first order the K factor becomes 1.7. Including soft gluon emission the K factor becomes a function of \( Q^2 \), \( y \) and \( \Lambda \) (the scale parameter in the strong coupling constant).

\[ K = f (Q^2, y, \Lambda) \]

Figure 1 shows the variation of the K factor ratio \( K(y, Q^2, \Lambda) / K(0, Q^2, \Lambda) \) as a function of \( y \) for the \( \bar{p}p \) case (\( \Lambda = 200 \) MeV). The \( Q \) dependence of the K factor is also observed in the S.G.E. predictions for the \( Q^2 \) variation of the Buras-Gaemers parameters \( a, \beta \) of the structure functions.

\[ u(x, Q^2) = A(Q^2) \cdot x^{\alpha(Q^2)} (1-x)^{\beta(Q^2)} \]

Figure 2 displays the variation of \( \Delta \alpha(Q^2) = \alpha(Q^2) - \alpha_0 \) for the \( (\pi^- - \pi^+) \) case.
Figure 3 shows the variation of $\Delta \beta(Q^2) = \beta(Q^2) - \beta_0$ again for $\pi^-\pi^+$. In both cases the S.G.E. model yields a much stronger variation with $Q^2$ than expected from the leading log or first order calculations. Clearly more data are needed to check these predictions.

2.2 $p_T$ predictions

M. Greco $^4$ presented calculations concerning the $p_T$ distributions. The lepton pair $p_T$ distribution can be divided into 3 regions:

1 - The region where $p_T^2$ is of the order of $Q^2$; here the perturbation theory makes sense. But there is as yet little data to compare with. It would be interesting to extrapolate the cross section with its structure functions determined by the data in the low $p_T$ region into the high $p_T$ region and to compare there with the data.

2 - In the region $\Lambda^2 < p_T^2 < Q^2$ the perturbation theory breaks down. QCD in $O(\alpha_s)$ and $O(\alpha_s^2)$ does not reproduce the data in a satisfactory way.

3 - The region with $p_T^2 \simeq \Lambda^2$ is dominated by the primordial transverse momentum of the partons. Here non-perturbative effects are expected to be important.

As discussed in the previous section the comparison between data and theory is much easier for the non-singlet $(\pi^-\pi^+)$ cross sections. On the other hand a measurement of singlet and non-singlet cross sections would allow a separation of the Compton distribution.

M. Greco did the calculation in the so-called Double Leading Logarithmic Approximation (DLLA) for the soft gluon emission and what he called exact kinematics, i.e. transverse momentum conservation is required in the impact parameter space.

The result is compared to $\pi^- N$ data from NA3 $^5$ in Figure 4a, b, c. $<p_T^2>$ intrinsic = .4 GeV$^2$/c$^2$ and $\Lambda = .25$ GeV (or $\Lambda = .15$ GeV for the dashed line) were used as parameters. The low mass region data (Figure 4a) and the $s$-dependence of the mean $p_T^2$ (Figure 4b) are described quite well by the soft gluon mechanism. Figure 4c shows some inconsistencies in the dependence of $<p_T^2>$ as a function of $\sqrt{s}$ and $s$. Clearly more high $p_T$ data are needed at different values of $s$.

3. EXISTING AND FUTURE DILEPTON EXPERIMENTS

Much experimentation has occurred since the pioneering work of L. Ledermann et al. $^6$ at BNL. While experiments searching for new vector mesons used incident protons, experiments studying the continuum structure preferred incident pions or antiprotons where valence-valence interactions dominate.

After the first series of large acceptance experiments using $\pi$-beams at Fermilab (E331 / 444) and the SPS $^5$ (WA11 and NA3) both laboratories installed high intensity beams in order to increase the luminosity by one or two orders of magnitude.

Even after the start up of the Tevatron at the end of 1983, the SPS North Area high intensity facility will compare well with the high intensity area Proton West, Fermilab.

With the Tevatron operating at 1000 GeV/c the PW secondary beams will gain in production cross section but they will also lose with respect to the SPS in the following points:
a loss of a factor 5 due to the longer repetition rate, a factor 2 loss because there will
be less protons available at PW 7 and a loss of a factor 1.5 due to the lower beam accep-
tance. At a momentum of 250 GeV/c the $\pi^-$ flux/min. will be the same for both high intensity
areas, i.e. $10^{10}$ $\pi^-$/min.. At 300 GeV/c (for the moment the maximum secondary momentum in PW)
the flux will be $7.5 \times 10^9$ $\pi^-$/min. in PW against $4 \times 10^9$ $\pi^-$/min. in NAHIF (the SPS operat-
ing at 450 GeV/c). Therefore the SPS $\pi^-$-beam in NAHIF remains very competitive for the
coming years.

In 1982 three experiments (E326, E537, E615) collected data in the high intensity area
at Fermilab. E326 collected 14000 $\mu$-pairs with masses above the $J/\psi$ at a $\pi^-$-momentum of
225 GeV/c. E 537 ran in a tertiary beam with incident antiprotons and piminus at 125 GeV/c,
collecting 416 antiprotons and 1257 piminus induced events with $m > 4$ GeV/c$^2$. E615 instal-
led their apparatus in order to study dimuons in the very forward region and collected
$\sim$5% of their final data sample.

E605, an experiment which has high resolution, was installed in a direct proton beam
in the Meson Lab. at FNAL.

At CERN NA10 was the only fixed target experiment collecting dimuon data in 1982.
L. Kluberg presented these data, which were obtained with 200 GeV/c incident $\pi^+$ on a $W$
target. Although the proton flux on the primary target was lower than requested, the aver-
gage intensity of $(1 - 2) \times 10^9$ $\pi^+$/burst was quite high compared to previous experiments.
When combined with the as proposed performance of the detector, this resulted in a very
large event sample.

A feature of this spectrometer is the high mass resolution, $\frac{\Delta m}{m} = 2.5\% - 3.5\%$, 
obtained for the 2/3 of the events where both muons traverse the air sectors of the toroi-
dal magnet. The remaining 1/3 of the events have medium resolution of $\frac{\Delta m}{m} \equiv 10\%$. Table 1
shows the number of events obtained. Half of the high resolution event sample is displayed
in a $x_1 - x_2$ scatter plot in Figure 5. Also shown in this figure are the hyperbolae
converting to constant mass. The data cover a large kinematical region, and the high
statistics will allow for a differential analysis of the different physics questions. If
for example the mass region between 4.5 GeV/c$^2 \leq m \leq 8.5$ GeV/c$^2$ is divided into 3 mass bins
and a determination of the pion structure function is carried out separately in each bin,
then the statistical error $\Delta a$, $\Delta B$ of the Buras Gaaemers parameters of the pion will vary
between 4% and 8%.

4. DATA FROM INTENSE $\pi^+$ BEAMS

Why do we need $\pi^+$ data? As noted before the theoretical calculations presented in
the previous sections were all done for the particle – antiparticle differences. Only in this
case the Compton diagram contribution cancels. Therefore the subtracted $\pi^+ - \pi^-$ data allow
a better confrontation with theory. Having both $\pi^+$ and $\pi^-$, then allows one to determine
the remaining contributions, e.g., the Compton terms and to study both the pion sea and gluon
terms. Lastly contributions from the double semi-leptonic decay of charm – anticharm or
beauty – antibeauty meson pairs are also eliminated in the difference (see Reference 8 for
more details on the possible importance of such terms).
Until now, high statistics have been obtained only with incident \( \pi^- \). The corresponding number of \( \pi^+ \) induced events is rather small. At present, the highest \( \pi^+ \) statistics have been collected by the NA3 experiment in a tagged positive beam with intensities \( I_{\pi} \leq \text{few } \times 10^7/\text{burst} \). Using a Pt target they found 118 events in the interval 4.1 GeV/c² \( \leq m \leq 8.5 \) GeV/c² (as compared to 21600 \( \pi^- \) induced events). At 200 GeV/c they obtained 1750 \( \pi^+ \) events in the same interval (and 4970 \( \pi^- \) induced events).

In order to reach the level of the \( \pi^- \) statistics the data must be collected with high intensity \( \pi^+ \) beams. Positive beams contain protons, \( \pi^+ \) and a few percent of \( K^- \). Clearly with intensities \( \geq 10^9/\text{sec} \) no tagging is possible. Therefore two questions were discussed:

1. Is it possible to enrich the \( \pi^+ \) content in a positive beam?
2. Is it possible to subtract the background of proton induced events?

H. Atherton studied point 1 for the NAHIF beam. Figure 6 displays the relative \( \pi^+ \) content in this beam as a function of the secondary beam momentum. The \( \pi^+ \) content decreases for momenta of interest from 69% at 100 GeV/c down to a few percent at the maximum positive momentum of 300 GeV/c. Since this ratio depends on the fractional secondary momentum \( \chi^+_{\text{Lab}} / \chi^+_{\text{Primary}} \), one can immediately evaluate the gain in the \( \pi^+/\text{total} \) ratio for the positive beams at the Tevatron. The \( \chi^+ \) ratio of 27% at 200 GeV/c \( \chi^+_{\text{SPS}} = \frac{200}{450} = .44 \) will go up to 69% \( \chi^+_{\text{Tevatron}} = \frac{200}{900} = .22 \).

In contrast, the gain which can be obtained from enriching the \( \pi^+ \) ratio via a low A absorber is rather limited. Decreasing the flux with such an absorber by a factor ten and with a perfect separation of elastic and inelastic secondaries one may get \( \pi^+ / \text{total} = 36\% \) instead of 27% at 200 GeV/c. However the accompanying \( \mu^- \) flux (a source of background for such experiments) remains the same as for the original high intensity beam. Thus the best method of increasing of this ratio is obtained by performing \( \pi^\pm \) experiments at a lower \( \chi^+_{\text{Lab}} \).

Next the question of the subtraction of the proton induced dilepton events must be addressed. With our present knowledge of the structure functions it is possible to predict the cross section \( \frac{d^2}{dm} \) and its error for \( \pi^+ \) and \( p \) induced events.

Figure 7 displays the cross section ratio induced by incident protons divided by the \( \pi^+ \) induced one each multiplied by the relative flux \( F_p, F_{\pi^+} \)

\[
\frac{d^2}{dm} (p) \cdot F_p \quad \frac{d^2}{dm} (\pi^+) \cdot F_{\pi^+}
\]

for each point reflect the uncertainty of the presently known structure functions.

For the normal (27% \( \pi^+ \) content) 200 GeV/c beam the \( p/\pi^+ \) event ratio is rather high for low dilepton masses. The proton background falls below 30% for \( m \geq 9 \) GeV/c² with an uncertainty on this ratio of \( \pm 5\% \). Enriching the beam to 36% (again at 200 GeV/c) the \( p/\pi^+ \) event ratio is shifted slightly to lower dilepton masses. In this case the proton background can be subtracted with a \( \pm 5\% \) error for \( m \geq 8 \) GeV/c². For the normal beam at 120 GeV/c the proton contribution can be subtracted with a \( \pm 5\% \) uncertainty for masses above \( m \geq 4.3 \) GeV/c².
In conclusion, it seems possible to subtract the proton induced background at a momentum of 120 GeV/c in the usual mass interval and to obtain together with $\pi^-$ data taken at the same momentum high statistics for the cross section difference $\sigma(\pi^-) - \sigma(\pi^+)$. 

5. THE INTEREST IN $\bar{p}$ AND p INDUCED DATA

The basic assumptions of the D.Y. model that the magnitude and shape of the cross section is determined by the D.I.S. structure functions can best be verified with anti-protons. The cross section difference $\frac{d\sigma}{dm}(\bar{p}) - \frac{d\sigma}{dm}(p)$ contains only valence-valence contributions. By charge conjugation invariance, the $\bar{p}$ and p structure functions are identical. Thus the number of parameters to be determined is much smaller than for the other Drell-Yan processes and is completely predicted using D.I.S. structure functions. A possible $p_t$ dependence of the nucleon structure function can be studied in the D.Y. reaction while the large (non intrinsic) $p_t$ effects are integrated over in the inclusive D.I.S. experiments.

The $\bar{p}$ world statistics are very small. NA3 obtained 275 events with $m > 4$ GeV/c$^2$ from $\bar{p}$'s at 150 GeV/c and 32 events from p's with equal luminosity. E537 got 416 events from $\bar{p}$'s at 125 GeV/c and no proton data in a rather short data taking period.

How can we increase these statistics?

Four possibilities were studied:

a) $\bar{p}$'s from $\bar{A}$ decays at 120 GeV/c in NAHIF. Here tagging is necessary for both $\bar{p}$ and p induced data.

b) $\bar{p}$'s from the antiproton accumulator (AA) via stochastic SPS extraction at 300-400 GeV/c. Here $\bar{p}$ and p data are easy to get because direct $\bar{p}$'s and p's can be used.

c) $\bar{p}$ interactions with the internal gas jet during $p\bar{p}$ collider operation at 270 GeV/c (UA6 experiment). A p run needs rebuilding of UA6.

d) $\bar{p}$'s from $\bar{A}$ decays of the Tevatron. Since PW will be limited to ≤ 300 GeV/c no corresponding data with direct p's can be taken.

N. Doble compared the luminosities to be expected for the first three possibilities based on the present performance of the $p\bar{p}$ collider. They are shown in Table 2.

According to this estimation the luminosity with the upgraded NAHIF beam at 120 GeV/c on a hydrogen target compares well with the one of the hydrogen gas jet experiment in the collider. The extracted $\bar{p}$ scheme yields a ten times higher luminosity. In addition, the luminosity for experiments on nuclear targets is even more favorable in the case of the extraction scheme. This is especially true since fixed target experiments can run simultaneously on a hydrogen target and a heavy target while according to B. Jeanneret (UA6) an absorber has to be installed in the gas jet experiment when running with a heavy gas.

Table 3 gives some event numbers for 2000 h of running for NA10 or equivalently NA3 $^{10}$ using half of the available $\bar{p}$'s ($5 \times 10^{14}$ $\bar{p}$'s/day). Since the instantaneous fluxes are low and there is no $\bar{\nu}$ halo accompanying the extracted $\bar{p}$ beam the acceptance could be improved. In the case of the extracted $\bar{p}$ scheme the corresponding proton data are obtained very rapidly. For example NA10 did a test run in 1982 with $4 \times 10^{9}$ p's/burst encountering no special problem.

While the extraction scheme can deliver $\bar{p}$'s only to 3 experiments in the North area and one in the West area the gas jet experiment will run parasitically with the collider
experiments. In this mode UA6 will obtain 3100 events for $\mathcal{L} = 10^{31}$ cm$^{-2}$ sec$^{-1}$ and 155 events if $\mathcal{L} = 5 \times 10^{29}$ cm$^{-2}$ sec$^{-1}$ (again in 2000 h and $3.8 \text{ GeV} \leq m \leq 8.5 \text{ GeV}$). If they can use a ten times denser jet for 10% of the time their event numbers may double. In the case of a luminosity of $\mathcal{L} = 5 \times 10^{29}$ cm$^{-2}$ sec$^{-1}$ these event numbers are the same or even smaller than what can be obtained by the ISR dilepton experiments $^1$ in 1983 with pp and much lower than the event rates for fixed target experiments.

How does this compare with the tertiary $\bar{p}$ beam at the Tevatron?

Figure 8 shows the $\bar{p}$ yield for primary protons of 400 GeV/c and 1000 GeV/c in the Fermilab high intensity area PW. Again the large gain in production cross section is reduced by factors mentioned previously: repetition rate, etc... For $2.5 \times 10^{12}$ protons of 1000 GeV/c on target PW gets $1.15 \times 10^4$ $\bar{p}$'s/day. Here both the $\bar{p}$ data as well as the corresponding $p$ data must be obtained in a tagged beam.

Given both the physics interest and the favorable comparison with Fermilab, the CERN dilepton experiments reiterate their interest in extracted $\bar{p}$ beams.

6. ASSOCIATED PRODUCTION OF PHOTONS AND HADRONS WITH LEPTON PAIRS

P. Sonderegger reviewed the associated production of hadrons and photons with lepton pairs. Existing data come from the R209 experiment at the ISR and the WA11 experiment at the SPS.

The main results are that the average charge of the forward hadronic system depends on the charge of the spectator quark in the incident particle. Secondly a large fraction of the $J/\psi$ comes from the decay of $\chi$ states.

\[
\begin{array}{c}
\chi \\
\quad | e^+ \\
\end{array}
\]

Three $\chi$ states with $m_{1,2,3} = 3.415, 3.510$ and $3.555$ GeV have been observed. Their branching ratios into $J/\psi + \gamma$ are:

$\Gamma(\chi_0 + \gamma) : \Gamma(\chi_1 + \gamma) : \Gamma(\chi_2 + \gamma) = 0.03 : 0.31 : 0.15$

Definite predictions $^{12}$ exist for the production mechanism of these $\chi$-states:

$\sigma(gg \rightarrow \chi_0) : \sigma(gg \rightarrow \chi_1) : \sigma(gg \rightarrow \chi_2) = 3 : 0 : 4$

$\sigma(q\bar{q} \rightarrow \chi_0) : \sigma(q\bar{q} \rightarrow \chi_1) : \sigma(q\bar{q} \rightarrow \chi_2) = 0 : 4 : 1$

WA11 observed the $\chi_1$ and $\chi_2$ states via the $\gamma$ conversion in the target with very good resolution but small ($1\%$) acceptance. In order to resolve $\chi_1$ and $\chi_2$ the energy resolution on the $\gamma$ must be $\sigma_E \leq 7\% \sqrt{E}$ and good space and time resolution is also required.

P. Sonderegger proposed to use an electromagnetic calorimeter for the $\gamma$ detection. He showed first promising results from a sandwich of bundled scintillating optical fibers and Pb plates. A resolution of $\sigma_E = 7.3\% \sqrt{E}$ was obtained. Installed in a large acceptance spectrometer like $\Omega$ or NA3 interesting data could be taken.
7. CONCLUSIONS

D.Y. physics remains very competitive at the SPS for $\pi^{-}$ beams up to 300 GeV. Data from intense $\pi^{+}$ beams (hopefully enriched) are possible and needed. $\bar{p}$ and p data allow the best confrontation with theory. The SPS extraction is competitive. Interesting new physics can be obtained with the measurement of $\gamma$'s associated to lepton pairs with high resolution.

ACKNOWLEDGEMENTS

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REFERENCES

7) T. Yamanouchi, invited talk to the SPS Workshop on Fixed Target Physics, CERN, 1982.
9) The following values were used for the structure function (S. Weisz, PhD thesis, Université de Paris-Sud) $\alpha^p = 0.38 \pm 0.04$, $\beta^p = 0.95 \pm 0.05$, $\gamma^p = 8.7 \pm 2.5$, $g_\gamma = 0.49 \pm 0.16$.
   The following values were used for the nucleon structure function (A. Para, private communication) $\alpha_u^p = 0.51 \pm 0.01$, $\beta_u^p = 2.8 \pm 0.052$, $\gamma_p = 8.1 \pm 0.35$, $g_p = 0.52$.
10) NA3 Collaboration, private communication.
11) Private communication by G. Belletini : 300-1000 events are expected at the ISR from the $\bar{p}p$ runs in 1983.
### TABLE 1

**SUMMARY OF NA10 DATA**

<table>
<thead>
<tr>
<th>Target</th>
<th>W 5.6 cm</th>
<th>W 12 cm</th>
<th>W total</th>
</tr>
</thead>
<tbody>
<tr>
<td>J/ψ, total</td>
<td>1.42x10⁶</td>
<td>3.43x10⁶</td>
<td>4.85x10⁶</td>
</tr>
<tr>
<td>J/ψ, high resolution</td>
<td>0.94x10⁶</td>
<td>2.27x10⁶</td>
<td>3.21x10⁶</td>
</tr>
<tr>
<td>m &gt; 40 GeV/c², total</td>
<td>92700</td>
<td>222500</td>
<td>315200</td>
</tr>
<tr>
<td>m &gt; 40 GeV/c², high resolution</td>
<td>61100</td>
<td>146700</td>
<td>207800</td>
</tr>
<tr>
<td>Y, total</td>
<td>1100</td>
<td>2500</td>
<td>3600</td>
</tr>
<tr>
<td>Y, high resolution</td>
<td>700</td>
<td>1800</td>
<td>2500</td>
</tr>
</tbody>
</table>

### TABLE 2

**Possible SPS β facilities (based on present performance)**

<table>
<thead>
<tr>
<th>SPS mode of operation</th>
<th>Proton fixed target (tagged β beams)</th>
<th>Collider</th>
<th>β fixed target</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Secondary flux limited to 2x10¹⁰/pp</td>
<td>Tertiary : A+β/5x10¹²P (450 GeV/c)</td>
<td>pβ</td>
</tr>
<tr>
<td>Lab. momentum of β (GeV/c)</td>
<td>C.M. energy (GeV/c)</td>
<td>n2</td>
<td>H10⁶</td>
</tr>
<tr>
<td>β flux : average/day</td>
<td>β flux/pulse</td>
<td>no. of pulses/day</td>
<td>e⁻ flux/pulse</td>
</tr>
<tr>
<td>1x10⁹</td>
<td>4x10⁹</td>
<td>8x10⁶</td>
<td>2x10⁶</td>
</tr>
<tr>
<td>2x10⁹</td>
<td>5x10⁶</td>
<td>8x10⁶</td>
<td>2x10⁶</td>
</tr>
<tr>
<td>Average luminosity (cm⁻² s⁻¹) on p beam</td>
<td>5x10²⁸</td>
<td>2x10²⁸</td>
<td>8x10²⁹</td>
</tr>
<tr>
<td>- on H tgt (1m Lp )</td>
<td>1x10²⁹</td>
<td>4x10²⁹</td>
<td>1.5x10³¹</td>
</tr>
<tr>
<td>- on Nuclear target</td>
<td>1x10²⁹</td>
<td>4x10²⁹</td>
<td>1.5x10³¹</td>
</tr>
</tbody>
</table>

### TABLE 3

**Target / length [cm] β momentum [GeV/c] Number of events in 3.8 GeV/c² m< 8.6 GeV/c²**

<table>
<thead>
<tr>
<th>Target / length [cm]</th>
<th>β momentum [GeV/c]</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₂ / 100</td>
<td>120</td>
<td>&gt; 220</td>
</tr>
<tr>
<td>Fe / 20</td>
<td>120</td>
<td>&gt; 1370</td>
</tr>
<tr>
<td>O₂ / 100</td>
<td>300 / 400</td>
<td>&gt; 2160 / 2780</td>
</tr>
<tr>
<td>Fe / 20</td>
<td>300 / 400</td>
<td>&gt; 13650 / 17610</td>
</tr>
</tbody>
</table>
Figure 3

Figure 4a
Figure 4b

Figure 4c
Figure 5
Figure 6
The errors bars are due to the present uncertainties in the structure functions.
Figure 8
APPENDIX 1 : THE ROLE OF SOFT GLUONS ON THE K FACTOR IN DILEPTON PRODUCTION *)

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ABSTRACT

We discuss the \( Q \) (lepton pair mass) and \( y \) (rapidity) dependence on the \( K \) factor. Ways to detect soft gluon presence are also given.

More than ten years ago, Drell and Yan \( ^1 \) (D.Y.) proposed a parton model, based on a quark antiquark annihilation into a photon, for the production of a lepton pair of mass \( Q \) at rapidity \( y \). The cross section reads:

\[
\frac{d\sigma_{\text{QM}}}{dq^2dy} = \frac{4\pi \alpha^2}{g q^2 S} \sum_i e_i^2 \left[ q_i^c(x_1) \bar{q}_i^c(x_2) + (q \leftrightarrow \bar{q}) \right]
\]

(1)

where \( S \) is the center of mass squared energy, \( x_1 = \sqrt{t} \ e^y \) (resp. \( x_2 = \sqrt{t} \ e^{-y} \)) are the fractional quark (resp. antiquark) momenta. \( \zeta = q^2/S \) is the scaling variable. The \( q_i^c(x) \) are the quark of type \( i \) distribution functions in the hadron \( H \). to be extracted from deep inelastic scattering measurements. The experiments \( ^2 \) came out with a big surprise: the observed cross section was found roughly two times bigger than expected in the D.Y. model, the ratio being called the \( K \) factor.

Since the work of Politzer and Sachrajda \( ^3 \) it has been possible to reinterpret the D.Y. picture in the framework of perturbative QCD. First calculations were performed for \( d\sigma/dq^2 \) \( ^4 \) and later more detailed calculations for \( d\sigma/dq^2 dx_F \) and \( d\sigma/dq^2 dy \) \( ^5 \). To first order in \( \alpha_s \) two kinds of graphs contribute: quark-antiquark annihilation with real and virtual emission of one gluon and Compton diagrams due to the interaction between an initial gluon and a quark. If \( x_1 \) and \( x_2 \) are the quark fractional momenta just before annihilation (as defined above) and \( t_1 \) and \( t_2 \) the initial quark fractional momenta before emitting a gluon, the cross section can be put into the form:

\[
\frac{d\sigma}{dQ^2dy} = \frac{4\pi \alpha^2}{g q^2 S} \sum_i \left( \frac{d t_1}{t_1} \frac{d t_2}{t_2} \sum_i e_i^2 \left[ q_i^c(t_1) \bar{q}_i^c(t_2) + (q \leftrightarrow \bar{q}) \right] \sigma(t_1, t_2, x_1, x_2) \right)
\]

(2)

where \( \sigma \) is the hard cross section.

The infrared singularities of the annihilation cross section cancel out by the well known Block-Nordsieck mechanism while the mass singularities encountered in the calculations can be absorbed into the bare structure functions via the mass singularities factorization

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*) In collaboration with Y. Gabellini, T. Grandou and M. Le Bellac
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Theorem. Equation (2) reads:

$$\frac{d\sigma}{dq^2dy} = \frac{4\pi\alpha^2}{9q^4s} \left[ \sum_{c} \frac{d\sigma}{dq^2} \prod_{i} \left[ \frac{d\sigma_{H_i}^2}{dq^2} + (q \leftrightarrow \bar{q}) \right] \right]$$

where \( \mu^2 \) is the renormalization mass and the \( M_i^2 \) are the factorization masses. Finally, in the leadinglog framework (\( M_1^2 = M_2^2 = Q^2 \)), one gets:

$$N_L = S(1-z_1) \bar{S}(1-z_2)$$

that is we recover the partonic result with evolved structure functions.

When next to leading first order corrections are included one finds, for \( q\bar{q} \) annihilation:

$$N_{N,L} = S(1-z_1) \bar{S}(1-z_2) \left( 1 + \frac{d\sigma_{CE}}{d\sigma} \right) + 10\% \text{ remaining terms}$$

where \( C_F = 4/3 \) and \( 1/(1-z)_+ \) is the usual principal value distribution. The first order correction is then found roughly as large as the Born term (eq.(1)) with \( \Lambda = 0.5 \text{ GeV} \). Compton graphs give a smaller contribution which must be taken into account for \( pp \) or \( p^+p \) reactions.

This theoretical result appears to be in good qualitative agreement with experiment and is considered as a QCD success. However, since the \( O(d\sigma) \) term is of the same order of magnitude as the Born term, we cannot really trust the first order calculation before we have shown that part of these important first order corrections is understood as the first terms of series which could be resummed and factorized.

This can be done only for annihilation graphs and is therefore valid only for non-singlet cross sections like \( \pi^+K^- \bar{N} \) or \( \pi^-p\bar{N} \). First answers were given for \( d\sigma/dq^2 \) by Parisi \(^7\) and Curci-Greco \(^8\). Their results are the following: the exponentiation modifies the first order result only in the large \( z \)-region. In Figure 1 we have plotted the factor \( K' \) defined as:

$$K' = \frac{(d\sigma/dq^2)_{\text{exponentiated}}}{(d\sigma/dq^2)_{\text{leading order}}}$$

versus \( z \). The important rise predicted for \( z > 0.8 \) cannot unfortunately be experimentally seen, due to the too rapid fall off of the cross section.

If we now consider the differential cross section \( d\sigma/dq^2dy \) (eq.(5)) the situation is more promising as will be shown later.

The first term of eq.(5), called the \( \pi^2 \) term, gives the main part of the contribution in the present experimental range. It originates from the virtual gluon contribution. More precisely it comes from the analytic continuation of the quark form factor \( F_1(q^2) \).
\[ F_1(q^2) = \frac{\alpha_s C_F}{2\pi} \left( -\frac{1}{2} \frac{\ln^2 \frac{q^2}{\Lambda^2}}{\lambda^2} + \ldots \right) \]  
(\Lambda being a mass singularity to be absorbed into the bare structure functions), from spacelike to time like \( q^2 \) values:

\[ 2 \text{Re} \ F_1(q^2) = \frac{\alpha_s C_F}{2\pi} \left( -\frac{\Lambda^2 q^2}{\lambda^2} + \pi^2 \ldots \right) \]  

The computation to all orders of the perturbative expansion of \( F_1(q^2 < 0) \) has been done at leading level\(^9\). The result reads:

\[ F_1(q^2) = \exp \left( -\frac{C_F A_s}{2\pi} \log \left( \log \frac{q^2}{\Lambda^2} \right) \log \frac{q^2}{\lambda^2} \right) \]

So the \( \pi^2 \) term of eq.(5) can be understood as the first order of \( \exp \left( \frac{A_s}{2\pi} C_F \pi^2/2\pi \right) \).

The resummation of the second term of eq.(5), called SGE, has been done by two different ways\(^10\) which lead to the same result up to \( O(d_s^2) \). In the first case the infrared parts of the multigluon ladder graphs have been summed up. This has been carried out using an axial gauge and performing a double Mellin transform. In the second case the exact kinematics of the gluon is taken into account, building a rescaled running coupling constant. Then the factorization masses are chosen in such a way (\( M_1^2 = Q^2, M_2^2 = q^2(1-x_1) \)) that the infrared singularities of the cross section cancel out. Let us now give the phenomenological results. In Figure 2 we have plotted the rapidity dependence of the K factor defined as:

\[ K(y, q^2) = \frac{\frac{d\sigma^{TH}}{dq^2 dy}}{\frac{d\sigma^{PDF}}{dq^2 dy}} \quad (\text{TH = LO, NTL, SGE}) \]

for \( Q = 5 \text{ GeV} \) and \( \Lambda = 100 \text{ MeV} \) in the \( (\pi^- - \pi^0)_{\text{pt}} \) case. The dotted dashed curve represents the full first order prediction (NTL) whereas the full line represents the SGE prediction. So \( K \) is enhanced by roughly 15%. Moreover \( K \) is rather flat giving a strong support to the NA3\(^{11}\) extraction of the pion structure function at \( Q^2 = 25 \text{ GeV}^2 \) where a flat \( K \) factor was assumed. For high lepton masses \( K \) decreases with \( Q \) and is not flat in \( y \), the curvature being increasing with \( Q \). A way independent of absolute normalization to see this is to study the ratio:

\[ R(y, q^2) = K(y, q^2)/K(0, q^2) \]

This has been done in Fig. 3 for the \( \bar{p}p \) reaction choosing three masses with \( \Lambda = 200 \text{ MeV} \). Fig. 3a gives the NTL prediction whereas the SGE case is plotted in Fig. 3b. The curvature of \( R(y, q^2) \) increases with \( Q^2 \) faster in the second case. So a precise experimental determination of the lepton pair mass and rapidity dependence on the K factor is the direct way to detect soft gluon presence to all orders.

An other way to test this mass sensitivity of the K factor shape is to consider the scaling violations of the structure functions extracted from Drell Yan data\(^12\). Let us be more explicit by considering the reaction \( (\pi^- - \pi^+)_{\text{pt}} \). The experimental cross section reads
\[
\frac{d\sigma}{dQ^2 dy} = \frac{4\pi a^2}{3Q^2} K^{\exp} \left[ \frac{4}{9} u_p(x_1, Q^2) + 2 d_p(x_2, Q^2) \right] \tag{11}
\]
where \( u_p(x, Q^2) = A x f(Q^2(1-x)) \beta(Q^2) \) \( \tag{12} \)

\( K^{\text{exp}} \) being assumed flat, the scaling violations can be given in terms of the \( Q^2 \) dependence of \( \alpha \) and \( \beta \) the Buras Gaemers parameters of the pion structure function (eq.(12)), since the proton structure function is assumed known from deep inelastic scattering measurements, and evolved at leading order. If we now take for the left side of eq.(11) the various theoretical frameworks we obtain different predictions for the quantities :

\[
\Delta \alpha = \alpha(Q^2) - \alpha(Q_o^2) \tag{13}
\]
\[
\Delta \beta = \beta(Q^2) - \beta(Q_o^2) \tag{14}
\]

with \( Q_o^2 \approx 20 \text{ GeV}^2 \).

We have plotted in Figure 4 \( \Delta \alpha \). It is clearly predicted to be negative in the leading log and first order cases while SGE predicts an unambiguous positive \( \Delta \alpha \). \( \Delta \beta \) is shown in Figure 5. The presence of soft gluons leads to a faster \( \Delta \beta \) increase with \( Q \) than in the L.O. and NTL cases. So soft gluon presence leads to a faster evolution than in deep inelastic case.

In conclusion, non singlet cross sections (like \( \pi^+ \pi^- \pi^0 \)), in which initial gluons and sea quark effects are avoided, provide a clear quantitative test of QCD. Scaling violations, which have not been clearly observed due to the lack of precise absolute normalization, are also expected. They could be seen either by measuring the rapidity dependence of K factor at several masses or by the determination of the pion structure function. On the other hand singlet cross sections (like \( \pi^+ \pi^- \)) are also needed in order to estimate the Compton graphs which have been computed only at first QCD order and depend on the gluon distribution function.

\[\ast\ast\ast\]

REFERENCES


2) For a review and references to the original publications, see : D. Decamp, talk given at the International Conference on High Energy Physics, Blacksburg, and A. Michelini, talk given at the EPS Lisboa Conference, p. 261.


Fig. 1: The factor $K'$ defined in eq. (6) as a function of the scaling variable $\tau$ for $\pi^-p$ collisions at $\sqrt{s} = 30$ GeV.

Fig. 2: The rapidity dependence of the $K$ factor defined in eq. (9) for $Q = 5$ GeV and $\Lambda = 100$ MeV for $(\pi^- - \pi^-)Pt$ collisions at $p_{lab} = 280$ GeV/c. The full line represents the SOE prediction and the dashed one the NTL prediction.
Fig. 3: The ratio $R$ defined in eq.(10) for the $\bar{p}p$ reaction at $\sqrt{s} = 22.5\text{GeV}$. The full line represents the prediction for $Q = 4 \text{ GeV}$, the dashed one for $Q = 6 \text{ GeV}$ and the dotted dashed for $Q = 8 \text{ GeV}$.

Fig. 3a: NTL prediction – Fig. 3b: SGE prediction.
Fig. 4 : The quantity $\Delta \alpha$ defined in eq.(13) as a function of the lepton mass for $(\pi^- - \pi^0)$ Pt collisions at $P_{lab} = 280$ GeV/C. Full line : SGE prediction with $\Lambda = 200$ MeV. Dashed line : SGE prediction with $\Lambda = 100$ MeV. Crossed-dashed line : leading order prediction with $\Lambda = 200$ MeV. Dotted-dashed line : NTL prediction with $\Lambda = 200$ MeV.

Fig. 5 : The same as Fig. 4 for the quantity $\Delta \beta$ defined in eq.(14).
GLUEBALLS: PRESENT AND FUTURE

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ABSTRACT
This talk reviews the predicted properties of the glueballs. The glueball candidates are presented and a review of experiments looking for glueballs is given.

1. INTRODUCTION

It was recognised in the early years of QCD that gluons similarly to quarks should give bound states [1]. The existence of such states, called glueballs, is due to the self coupling of gluons, a consequence of the non-abelian structure of the SU(3)C group. They have the vacuum quantum numbers except for \( J^{PC}(Q = 0, I = 0, S = 0, B = 0, \ldots) \), but QCD makes no prediction on their properties, so that one has to use various QCD inspired models to get information on the classification (sect. 2), the masses (sect. 3), the width (sect. 4) and the decay modes (sect. 5).

One can wonder why glueballs have not been seen after about 20 years of spectroscopy. One of the reasons one can think of is that at low energy (privileged place for spectroscopy), the hadronic dynamics is dominated by the valence quarks while gluons play only a little rôle. Therefore, glueballs should be searched in specific reactions where gluons are at work (sect. 6), but they still may be confused with normal \( q\bar{q} \) mesons (sect. 7). Experimental work on glueball is recent, but there are already some candidates which I discuss in sect. 8. Some of the points described in the present talk are discussed with more details in reviews to which I refer the reader [2-5].

2. GLUEBALL CLASSIFICATIONS

Similarly to the non relativistic quark model, one can construct the glueballs with \( 1^- \) building blocks (gluons) [6]. Taking into account the Bose symmetry, the two-gluon bound states (all with positive C parity) are

<table>
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<tr>
<th>( J^{PC} )</th>
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<th>( 0^{++} )</th>
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It is interesting to note that there appear states which are forbidden as \(q\bar{q}\) states: the \(1^{-+}, 3^{-+}\) series; such states are called oddballs.

With three gluons, one can construct two types of glueballs corresponding to symmetric or antisymmetric colour coupling. In that sector, all \(J^{PC}\) combinations can be achieved, the simplest states (with \(L = 0\)) being \(0^{-+}, 1^{-}, 3^{-}\).

The addition of extra-gluons will obviously not enrich the possible \(J^{PC}\) states, but this glueball construction method leads to the following question: as gluons are self coupling objects, how can one say that a glueball contains a given number of gluons? A gauge invariant treatment is to construct all the independent glueball creation operators out of \(n\) local fields \(F_{\mu\nu}^a\), or equivalently out of \(n\) colour electric or magnetic fields [5, 7-9]. The resulting spectrum is richer than the previous one, since the colour magnetic field is equivalent to a \(1^{++}\) gluon. In the two-gluon spectrum, the ground level \((L = 0)\) contains 7 states

\[0^{++}, 2^{++}, 0^{-+}, 1^{-+}, 2^{-+}; 0^{++}, 2^{++}\]

and all \(j^P\) with \(C = \pm\) can be achieved. With higher \(L\) values. In the three-gluon spectrum, the \(L = 0\) states are \(0^{++}, 1^{++}, 2^{++}, 1^{-+}, 2^{-+}, 3^{-}\) and all \(J^{PC}\) are possible using other \(L\) values. A similar classification is found within the bag model [10].

Finally, some authors [8, 11, 12] have argued that the gluonic field is transverse and that, from the Landau-Pomeranchuk-Yang theorem [13], 2-gluon states such as \(1^{-+}, 3^{-+}, 5^{-+}, \ldots\) are forbidden.

Although no general agreement is met on a glueball classification, the main results are:

(a) The lowest lying glueballs should have spin \(0^{++}, 0^{-+}, 2^{++}\) and possibly \(1^{-+}\).

(b) There are oddballs i.e. glueballs with spin \(0^{+-}, 1^{-+}, 2^{-+}, \ldots\) and \(0^{--}\) which are forbidden for normal \(q\bar{q}\) mesons. The lowest lying oddball could be the \(1^{++}\).

3. MASSES

There are several approaches to estimate the glueball masses.
3.1 Potential models [7,12,14,15]

If one assumes that constituent gluons are massive \( m \sim 500-800 \text{ MeV} \) [16], the glueball masses can be computed using the Schrödinger equation with an effective potential. Cornwall and Soni [15] have chosen a string potential plus a spin-dependent term and assumed spin \( 1^- \) gluons. With a constituent gluon mass of 500 MeV, they find

\[
m(0^{++}) \sim 1.2 \text{ GeV} \quad m(0^{-+}) \sim 1.4 \text{ GeV} \quad m(1^{-+}) \sim 1.5 \text{ GeV} \\
m(2^{++}) \sim 1.6 \text{ GeV} \quad m(2^{-+}) \sim 1.8 \text{ GeV}
\]

for the simplest 2g states and \( m(0^{++}) \sim 2.4 \text{ GeV} \) for the lowest 3g state.

3.2 Bag model [10,11,17,18]

The modes of a colour field inside a cavity are either Transverse Electric (TE) either Transverse Magnetic (TM) and correspond to respective parities \((-1)^{J+1}\) and \((-1)^J\). The lowest modes are \( 1^+ \), \( 2^- \) (TE or "magnetic" gluons) and \( 1^- \) (TM or "electric" gluons). In the bag model, glueballs are built from 2 or more TE or TM modes filling a cavity and their masses equal the cavity energy when the outwards colour field pressure balances the inwards vacuum pressure. In a spherical bag, Donoghue et al. [11] computed

\[
m(0^{++}) = m(2^{++}) = 0.96 \text{ GeV} \\
m(0^{-+}) = m(2^{-+}) = 1.3 \text{ GeV}
\]

for the 2g states and \( m(0^{++}) = m(1^{-+}) = m(3^{-+}) = 1.45 \text{ GeV} \) for the simplest 3g states. Toroidal bags which are more stable than spherical ones for gluonic modes have been envisaged [19] but no significant difference seems to show up. On the contrary, glue-glue interactions lift the degeneracy between the \( J = 0 \) and \( J = 2 \) states. In particular, the \( 2^{++} \) and \( 2^{-+} \) states could be shifted upwards by \( \sim 500 \text{ MeV} \), whereas the \( 0^{++} \) and \( 0^{-+} \) states would remain almost unchanged [17,18]. Other authors [20,21] have argued that the \( 0^{++} \) state could be shifted toward negative mass and would reappear at an unpredictable mass after mixing with the vacuum condensate.

3.3 Lattice gauge theory

As the estimation of the masses of the normal hadrons from SU(3) lattice calculations has been proved to be reasonable [22], the same type of technique has been used to predict the masses of the glueballs. Except for Seo [23] most of the recent calculations [24-27] quantitatively agree on the mass of the \( 0^{++} \) glueball to be \( \sim 350 \Lambda_L \) with \( \Lambda_L = \Lambda_{\text{mom}}/83.5 \sim 2.5 \text{ MeV} \),
i.e. \( m(0^{++}) \approx 900\) MeV. For the other states, qualitative agreement is not achieved. Ishikawa et al. [25] find other states below 2 GeV, for instance \( m(0^{++}) \approx 1430\) MeV and \( m(2^{++}) \approx 1650\) MeV, whereas Berg and Billoire [24] find no state below 2 GeV if the \( 0^{++}\) glueball is around 900 MeV.

The only consensus which comes out from the various methods used to compute the glueball mass is that the lowest lying glueball is around 1 GeV with \( J^P = 0^{++}\). But it is not clear which and where is the second glueball in the spectrum.

4. WIDTH

Although the width of the glueballs is a crucial parameter for their observability, not much is known about it. One generally thinks that they should be more narrow than normal resonances because, in the decay process, the constituent gluons have to convert to \( q\bar{q}\) mechanism which is expected to be suppressed. More quantitatively, an argument know as the \( \sqrt{OZI}\) rule[6,28] notices that an OZI forbidden decay graph contains two vertices identical to the one existing in the glueball decay

\[ \begin{align*}
\text{Glueball decay} & \quad = \quad \sqrt{OZI \text{ forbidden decay}} \\
\end{align*} \]

One thus estimates that

\[ \Gamma_G \sim \sqrt{\Gamma_h \times \Gamma_{OZI}} \approx 10\text{ MeV} \]

where \( \Gamma_h \sim 100\) MeV is a normal hadron width and \( \Gamma_{OZI} \sim 1\) MeV is a typical width for an OZI suppressed decay. This conjecture is in agreement with the \( 1/N_c\) colour expansion as discussed by Chanowitz [29]. Contrary to these arguments, a computation of Pascual and Tarrach [30], based on the QCD sum rules developed by the ITEP group [31] gives a very broad \( (\Gamma > 700\text{ MeV})\) \( 0^{++}\) glueball. If such a result turns out to be true, the hunt for glueballs may well end up with an empty bag.

5. DECAY MODES

Most of the special decay properties of the glueballs come from the fact that they are flavourless or, in other words, \( SU(3)_F\) singlets. For
instance, they cannot decay into an octet meson and a singlet meson
($\eta\eta'$, $\omega\phi$, ...) even if there is octet-singlet mixing [32,33]. Other
forbidden decays are given in ref. [32] and allowed decays are listed in
[5].

Another consequence of the flavourlessness of glueballs is that
branching ratios to $K\bar{K}+X$ and to pions should be almost equal, apart from
phase space factors of the order of 2 at $M = 1.5 \text{ GeV}$ in favour of pions
[32]. This points out towards the search of glueballs in final states
with kaons [33].

6. Where should one look for glueballs?

The trivial answer to this question is: where there are gluons! We
hereafter list some of the places where one expects to have glueball
production.

6.1 $J/\psi$ radiative decay

The QCD prediction that the $J/\psi$
(and $\Upsilon$) should decay through $c\bar{c}$ ($b\bar{b}$)
anihilation into 3 gluons implies
that it should also decay into $\gamma + 2$
gluons with a branching ratio of the
order of $10\%$ [34,35]. Such a value is
consistent with experimental data on
the $J/\psi$ [36]. Only $10\%$ of that
radiative decays (i.e. $\sim 1\%$ of the
total) leads to a normal $q\bar{q}$ meson
($\pi^0$, $\eta$, $\eta'$, $f$ and $f'$). The $\sim 9\%$ left
could well go to multihadron final
states. However, as the two gluons are in a colourless state, they can
resonate and couple to glueballs [35, 37, 38] with a total branching ratio
of about $1\%$. A PWA of the two gluon system shows that the $0^{++}$, $0^{-+}$ and
$2^{++}$ waves, corresponding to the lower lying glueballs, are significantly
produced [39].

Search for glueballs in the $J/\psi$ radiative decay has been made at
SPEAR by the Mark II and Crystal Ball groups. Two glueball candidates
have been claimed (sect. 8) based on about $2 \times 10^5$ $J/\psi$ produced, but
the statistics is still low. There is no result for the time being from
the $\Upsilon$ decay at CESR and DORIS.
6.2 Double pomeron exchange (DPE)

Glueballs can be produced in hadron-hadron collisions by gluon fusion. However, the glueball signal could be hidden in the combinatorial background from the particles in the central and fragmentation regions. However, if another gluon with opposite colour is exchanged, the incident hadrons fly away undisturbed, leaving a clear glueball signal: this is the double pomeron regime [6]. As the number of gluons increases at small $x$, the cross section will be higher at higher $s$ ($M^2 = s x_1 x_2$); in addition, rapidity gaps should be clearer and other contributions as Regge-Pomeron exchange should be suppressed. Thus, the best place to look for glueballs in DPE should be at the $p\bar{p}$ collider, however its lower luminosity as compared to ISR and SPS-FNAL makes those better suited for such study. Two experiments at CERN have been or are being run. The first one (WA76) [40] has collected $10^7$ triggers (75 ev. nb$^{-1}$) in $\pi^+p+p$ collisions at 85 GeV/c in the $\Omega'$ spectrometer. The second one (R807) [41] is running at the ISR in the Axial Field Spectrometer. A total of $10^6$ triggers will be collected.

6.3 Direct production at medium $p_T$

Glueballs produced via gluon fusion is also enhanced with respect to the background if they are produced at sufficiently high $p_T$. This is the case in the opposite diagram in which an incoming gluon and an exchanged gluon fuse to give a "high" $p_T$ glueball. The production mechanism, expected to be very similar to the direct production pions [42], is a higher twist mechanism which populates the medium $p_T$ range (1-3 GeV/c). An approved experiment (WA77) [43] is dedicated to this search and will look for glueball production in $\pi^-p$ interactions at 350 GeV/c in the CERN $\Omega'$ spectrometer with a sensitivity of 10 000 ev. nb$^{-1}$. According to their estimates, a typical glueball ($M = 1.5$ GeV, $\Gamma = 0.1$ GeV) should be clearly seen as signal few thousand events over a comparable background.
6.4 Proton shake-off

Deep inelastic scattering experiments have shown that half of the proton momentum is carried by gluons. Gluon bound states might therefore be shaken off the proton. In particular, in a diffractive mechanism, an incident proton could interact with a pomeron and dissociate into a proton and a glueball. A specific experiment (R608) is running at the ISR. As a foretaste they showed a KK* spectrum (2500 events) at the Paris conference [44] (fig. 1) which shows a clear D(1285) peak and a structure in the E/\Lambda region. The final statistics in that channel should be of the order of 5 x 10^4 KK* events.

6.5 Suppressed final states

It has been suggested by S.J. Lindenbaum [45] that in any place where the OZI rule is at work, as for instance in the reaction π^-p + φφn, there could be evidence for glueball production, since normal qq mesons are filtered out by the OZI suppression rule. Other possible channels are K^-p + Λ + pions or π^-p + KKn. Let us just note that the φφ system allows one to scan the mass region above 2 GeV only.

Two experiments have studied the φφn channel: one at the Ω spectrometer with 16 GeV/c π^- (150 events) [46], the other, still taking data, at BNL with the MPSII spectrometer (presently 1200 events; 2400 planned) [45]. Two glueballs are claimed by this last experiment. Two other experiments at CERN have taken data on the inclusive φφ system (NA11-ACCMOR and WA67-Ω'). More than 5000 φφ events are expected for the latter. Another inclusive φφ study will be done in the 400 GeV/c pp interaction at FNAL (E623), more than 10 000 events are expected [47].

6.6 Low energy pp annihilations

The main reason [48] to look for glueballs in low energy pp annihilations is that one of the glueball candidate has first been seen in this channel. Several experiments are planned: 2 at BNL (E715 and AGS 771)
and one at CERN with the LEAR facility. Certainly, experiments at LEAR should yield an unambiguous PWA of the KK* system: for example, a 10 day run with ASTERIX could provide a sample of $4 \times 10^5$ events with a mass resolution of $\sim 40$ MeV.

6.7 Others

There has been other suggestions for glueball production (gluon jets, $F^+$ decay, photoproduction). However, no experiment is at present considering them as a major guideline due to the difficulty of extracting a clean signal from high background (gluon jets for instance), or to have sufficient statistics ($F^+$ decay).

7. HOW CAN ONE RECOGNIZE A GLUEBALL?

The answer to that question resembles the answer to, "How can one tell a resonance is $s\bar{s}$ or $u\bar{u}$ ($d\bar{d}$)?". In that case, one compares production mechanisms, decay modes, or one performs a model dependent analysis and in the end, one always finds a mixing angle.

In the 1-2 GeV range, one should examine with the glueball hypothesis in mind any new isosinglet object which has difficulties in fitting in the $q\bar{q}$ model, for instance because of its narrow width, of its $KK/\pi\pi$ branching ratios, ... A major thrust towards a glueball interpretation would be to observe the production of the same object by various mechanisms in which glueballs are expected to show-up. Of course, there is a case of unambiguous identification if a spin-parity analysis can reveal an oddball (i.e. glueball with $J^P = 0^{-+}$ or $0^{++}$, $1^{--}$, $2^{+-}$ ...). Such an analysis may be difficult, but it is for instance sufficient to have a $\pi A_1$ or $\eta D$ or $\eta' D$ system in the S-wave to prove that this system is an oddball [5].

Finally, except for oddballs, there could be mixing of glueballs and normal $q\bar{q}$ mesons. In that case, both the $q\bar{q}$ meson and the glueball candidate would badly fit in the corresponding $q\bar{q}$ nonet.

8. CANDIDATES

There are presently 4 claims for glueballs relying only on the fact that new (?) objects are produced in typical glueball reactions. Their properties and, for most, their existence have to be firmly established. Only the experimental case is made here. A more complete discussion will be found in ref. [2].
8.1 The E/ı candidate

The E/ı (1440) has been seen by two experiments in the J/ψ radiative decay into K Kıπ [49,50]. The signal seen as a ~ 100 event peak at M = 1440 MeV has a width of 50 MeV and is enhanced by the "δ cut" M(K Kı) < 1.1 GeV (fig. 2). The J/ψ branching ratio into γ Kıπ is of the order of 4 × 10⁻³. A spin parity analysis performed by the Crystal Ball group [50] yields J^{PC} = 0⁺⁺ in the Kı mode. This assignment makes it impossible to be the E(1420) meson which is a 1⁺⁺ resonance [51]. The authors of ref. [50] have thus claimed that this object, named the ı(1440), is a glueball decaying to δπ. There are however, many uncertainties especially on the dominance of the δπ decay mode, the strongest one being the absence of any clear signal in the ηππ decay mode (fig. 3). It is also known that a δ cut does not antiselect Kı Kı events. It is thus not definitively proved that the ı is different from the E meson. Let me also note that the E is not a firmly well established member of the 1⁺⁺ nonet as there is a new candidate for the same nonet called D'(1530) [52].

8.2 The θ(1640) candidate(s)

Several peaks in the 1650 MeV mass region have been reported [53,54,2]. The first one (fig. 4) appears in the ηη radiative decay mode of the J/ψ with a width of ~ 200 MeV and a branching ratio of ~ 5 × 10⁻³ (~ 50 events observed) [53]. Other signals with similar parameters have been seen in the ρ⁺ρ⁺ decay mode (fig. 5) [54], in Kı Kı⁻ [2].

A broader structure (~ 500 MeV) which could contain several states has been observed in the ηππ mode [2] (fig. 3), but no signal has been found in the ππ spectrum. More statistics is obviously needed to clear up the situation from the experimental side and to ascertain the PWA which gives J^{P} = 2⁺⁺ based on a sample of ~ 50 events in the ηη mode [53]. Several millions of J/ψ or Ψ should be produced for a comprehensive study if one has in mind that the detection efficiency of the present detectors is for the various channels of the order of 10%.

8.3 The ++ candidates

In 1978 Etkin et al. [55] showed that the OZI forbidden reaction π⁻p → ++n at 22.6 GeV dominates the OZI allowed one π⁻p → K⁺K⁻n. This was confirmed by several experiments [46,56], one of which gave evidence for the existence of two spin 2⁺⁺ waves [46]. An order of magnitude has since been gained by the BNL-CCNY pioneering experiment (1200 events) [57] and from the PWA two 2⁺⁺ resonances at mass 2160 ± 50 MeV and 2320 ± 40 MeV with width ~ 200-300 MeV are claimed.
(fig. 6). Here also more statistics is needed to firmly establish that they are resonances (phase variation!).

8.4 The \( \bar{K}K \) candidates

The \( \bar{K}K \) mass spectrum in the reaction \( \pi^- p \rightarrow \bar{K}Kn \) shows in the 1400 MeV region a shoulder which was usually interpreted as an \( f-A_2-f' \) interference [58]. However, a high statistics experiment at 18 GeV [59] has found that such an interpretation leads to \( f' \) mass and width incompatible with those determined from \( K^-p \) experiments (fig. 7). They reconcile the data by introducing a \( 2^{++} f^*_M (1440) \) resonance with width \( \sim 80 \) MeV predicted as being a glueball by Rosner [60]. Support to that state comes from \( K^0_S K^0_S \) final state in \( \pi^- p \) experiments at 63 GeV [61] and 23 GeV [62], but not from lower energy data nor from \( \pi\pi \) final states.

9. CONCLUSIONS

There is a wide consensus on the existence of gluon bound states. Their absence would cast severe limits or doubts on QCD theory. However, there is no well established theoretical pattern. As an example there is no accepted classification whereas that of \( q\bar{q} \) mesons and baryons is a major success for the quark model. Only qualitative theoretical firm agreement is reached for masses while no prediction is made for widths although this parameter is of first importance for the visibility of glueballs. Till now, only few dedicated experiments have brought results, and there are some indications for new states. Besides the fact that these should be confirmed from the experimental side, none of these experiments is able to prove that they have found glueballs. Their gluonic nature will only be established if these states are seen in other experiments probing other glueball production mechanisms. This is the aim of several present or future experiments. If no glueball is found, theorists will have to cope with (no doubt they will succeed) on the contrary, if they are found, glueball physics should take a major part in hadronic physics and deserve a strong effort in the future, especially with the CERN SPS.

Acknowledgements

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Theoretical context

In the present theoretical context, the importance of polarization experiments resides in the fact that helicity asymmetries in short distance interactions directly depend on fundamental properties of the underlying gauge theory:

In electroweak theory, left handed fermions interact differently from right handed ones. The observable consequences are large parity violations $\sigma(+) \neq \sigma(-)$.

In QCD the left handed and right handed components do not communicate with each other. Helicity is conserved on quark lines. A well known example is $q\bar{q}$ annihilation which can occur only in the antiparallel helicity state. The general observable consequences are large double helicity correlations $\sigma(+)\sigma(-)$.

For the purpose of this workshop, the field of SPS fixed target physics has been subdivided into topics such as muon physics, neutrino physics, hadron physics, etc. Spin physics covers one particular aspect of each of these complementary domains. In fact, although it is natural to define spin independent observables when using unpolarized beam and targets, these observables are always expressed in terms of explicitly spin dependent amplitudes, each of which carries its own specific information on dynamics.

The task of the study group on Use of Polarization in Hadron Physics was, in principle, to examine in each case if important information is lost when averaging or summing over the spin dependence of the amplitudes, and how difficult it would be to restore this information. In practice, attention focussed on a limited number of reactions where spin dependent observables are of particular current interest:

- Drell-Yan production of muon pairs,
- Inclusive production of prompt photons,
- Inclusive production of single hadrons,
- Elastic scattering at large $t$ and total cross-sections,
- Inclusive hyperon production from definite initial spin states,
- Hard scattering and flavour production by polarized photons.

For each reaction there exist specific arguments why it would be important to measure the difference in cross-section for different initial spin states and/or to measure the final state polarization or angular distribution. The motivations are, depending on the case:

- to test the characteristic and strong helicity dependence of the lowest order QCD amplitudes for parton-parton scattering. Here, perturbative QCD directly exhibits its analogy with QED: spinor charged fields interacting through their coupling to gauge vector fields. The relevant observables are the cross-section differences for initial parton helicities parallel and antiparallel respectively (initial helicity correlations). Soft gluon and $k_T$ smearing corrections may be large in the cross-sections, but will cancel out in the asymmetry (difference divided by sum) to the extent where they are the same for both helicity states.
- to learn about spin dependent structure functions in a way that is complementary to polarized deep inelastic lepton-hadron scattering.

- to identify higher order QCD mechanisms by single spin asymmetries that are zero in lowest order, and by the way in which the leading order predictions for double spin asymmetries are modified.

- to verify very general QCD predictions for exclusive processes, in particular for pp elastic scattering at large t.

- to test for the presence of weak interaction contributions by parity violating helicity asymmetries.

- to further explore those reactions where unexpected and large spin dependence has been observed up to the highest energies accessible. This motivation is particularly strong since no fundamental explanation exists so far.

- to obtain sufficient experimental information for model independent determination of the two-body and quasi two-body hadron scattering amplitudes. This had been the motivation for many polarization experiments over the past two decades. Its importance was stressed by the working group for Exclusive Scattering, with particular reference to the dip structure in elastic pp scattering at 50 GeV and to the very large polarization in associated production $\pi^- p \rightarrow K^0\Lambda^0(L^0)$.

In the context of this workshop, and in particular for the present report, it was felt that the point to be stressed was not to review or to develop these physics arguments, but to examine the conditions under which the experiments become feasible.

Feasibility of experiments

The notion of feasibility is used here in the most elementary acceptance of the term: define an assumed luminosity, multiply by the cross-section and by some coefficient for geometric acceptance, and calculate numbers of events in order to decide if the case merits further investigation or if it is hopeless. When sufficient luminosities can be expected only by using high intensity beams, the next question to be studied is an optimisation of detector acceptance versus high beam rate capability.

An important contribution to this workshop is a table (Table 1) with the expected performances of polarized beams and targets for the years 1984–89. This table uses reasonably safe assumptions, not ultimate performances that one may hope to reach. The particular interest of the figures is that they were agreed upon by a representative group of experts on experiments, accelerators and condensed matter physics at a discussion meeting organized in view of this workshop.

From this table one obtains the assumed luminosities for the various configurations of beams and targets, for either elastic scattering or inclusive measurements. This in turn allows to calculate the number of events and the statistical accuracy of the asymmetry measurement for a given cross-section and acceptance. This accuracy is to be compared to the expected order of magnitude of the effect.

In the following are presented a few examples (Table 2), starting with the single helicity asymmetries predicted by weak interaction interference.
1) The parity violating asymmetry $A_L$ in the total cross section is expected to be very small, of the order of $10^{-6}$ to $10^{-7}$. These are difficult experiments, and the statistics is practically irrelevant with respect to the problems of systematic errors.

Recent results are $A_L = -(2.3 \pm 0.8) \times 10^{-7}$ at 45 MeV and $A_L = + (2.6 \pm 0.6) \times 10^{-6}$ at 6 GeV. This has raised questions about the possible role of baryon wave function effects resulting from interactions between quarks belonging to the same hadron. The experiments use accelerated polarized protons on unpolarized targets. A measurement at high energies with an accuracy of $10^{-7}$ would provide important information on the role of weak interactions in hadron physics.

2) In the second example, on the contrary, the expected effects are large. The single helicity asymmetry $A_{LL}$ for production of heavy bosons by longitudinally polarized protons of $p_B = 0.7$ colliding with unpolarized antiprotons is expected to be $A_{LL} = +0.5$ and $A_{LL} = -0.25$ for production of $W^+$ and $W^-$, respectively, when using the SU(6) model to describe the helicity of valence quarks in protons of definite helicity. These large parity-violating asymmetries provide a promising method of extracting the hadron decay of the intermediate vector boson from the high transverse momentum hadronic background.

The following two examples are initial-initial helicity correlation measurement motivated by QCD predictions:

3) Leading order QCD predicts correlations $A_{LL}$ in massive lepton pair production $pp \to (\mu \mu)\chi$ ranging from $A_{LL} = 1$ to $10 \times 10^{-2}$ for $M(\mu \mu)$ increasing from 2 to 10 GeV. Assuming a polarized proton beam of $<I_B> = 10^{10}$ sec$^{-1}$ time averaged intensity and polarization $P_B = 0.7$ incident on a 20 cm long polarized NH$_3$ target and an acceptance of 0.3 at large $M$, the expected statistical accuracy is $\delta A_{LL} < 3 \times 10^{-2}$ out to $M = 6$ GeV, for 100 days of running with 2/3 of data taking.

4) With the same assumptions about beam, target and acceptance, statistical errors $\delta A_{LL} = 10^{-2}$, compared to the leading order QCD prediction $A_{LL} = 5$ to $10 \times 10^{-2}$, can be reached in prompt photon production $pp \to \gamma \chi$ for transverse momenta up to $p_T = 5$ GeV/c.

5) The feasibility of measuring the single spin asymmetry $A_N$ in the same reaction $pp \to \gamma \chi$ was examined by the study group on prompt photon production, assuming a 370 GeV polarized proton beam from $A^0$ decay, with $<I_B> = 2 \times 10^5$ sec$^{-1}$ and $P_B = 0.4$, incident on a 1 m long liquid hydrogen target. This beam corresponds to a project studied for the West Area. Errors of $\delta A_N = 5 \times 10^{-2}$ at $p_T = 5$ GeV/c are obtained for 100 days. The results would test higher order QCD corrections, because $A_N$ is predicted to be zero in lowest order.

6) The study group on photoproduction has contributed an estimate for heavy flavour production by linearly polarized photons of $E = 100$ GeV on an unpolarized target. The observable is the azimuthal asymmetry $\Sigma$ of single muons detected in closed geometry configuration. The large expected asymmetries are due to heavy quark masses and not to higher order QCD terms. The theoretical estimates are $\Sigma = 0.25$ for $\gamma p \to c \bar{c} \chi$ and $\Sigma = 0.50$ for $\gamma p \to b \bar{b} \chi$. A linear polarization of $P_B = 0.35$ can be obtained from bremsstrahlung of 140 GeV electrons on a Silicon crystal. The coherent enhancement of beam intensity, but not the polarization, depends critically on the horizontal divergence of the electron beam, in the range from
0.1 to 0.3 mrad (Fig.1). The expected statistical errors are \( \delta E = 0.01 \) for charm production at \( p_T > 1 \) GeV/c, and \( \delta E = 0.20 \) for beauty production at \( p_T > 2.5 \) GeV/c.

7) Returning to initial state helicity correlations \( A_{LL} \) predicted by lowest order QCD, we now examine inclusive production of neutral pions \( p p \to \pi^0 X \) at large \( p_T \). With the same assumptions about beam, target and running time as used for 3) and 4) one concludes that reasonable statistical errors can be obtained up to \( p_T = 5 \) GeV/c. This represents transverse fractional momenta of \( X_T = 0.75 \) and \( X_T = 0.5 \) at 100 and 200 GeV/c incident momentum, respectively. Here, the expected error is \( \delta A_{LL} = 3 \times 10^{-2} \). This is to be compared to the published predictions for \( A_{LL} \). It may be worthwhile to sketch the outline of such calculations at least once, for this example. The origin of the asymmetry is the difference between the lowest order QCD parton-parton cross-sections with parallel and antiparallel initial parton helicities, calculated in the limit of vanishing quark masses. This driving asymmetry at the partonic level is diluted by the fact that the partons carry at most a fraction of the helicity of the parent protons. The calculation was made for three alternate fragmentation models all of which described about equally well the existing data in 1978. Since then, experiment has clearly favoured one of these models. Finally, the calculation uses a hadronization model to describe the probability for producing the observed \( \pi^0 \). The outline of this calculation is conveniently illustrated by three figures. The Figure 2 shows the fundamental parton-parton cross-sections for definite initial helicities. The Figure 3 shows that the Carlitz-Kaur fragmentation model best describes the extent to which valence u-quarks in protons remember the helicity of the parent hadron. The Figure 4 shows the predicted asymmetry \( A_{LL} \) for each of the three models. From this figure one concludes that a measurement with an error of \( \delta A_{LL} = 3 \times 10^{-2} \) in the region of \( X_T = 0.5 \) to 0.75 would be a significant result.

8) A special class of QCD predictions concerns exclusive reactions, in particular, pp elastic scattering at large \( t \) or at 90°. With present assumptions about beams and target, access to 90° elastic pp scattering is limited to energies below 20 or 30 GeV. With an extracted polarized beam on a polarized target one calculates that cross-sections of \( d\sigma/dt = 10^{-32} \text{ cm}^2/(\text{GeV/c})^{-2} \) lead to statistical errors for double helicity or transverse spin asymmetries \( \delta A_{LL} \) or \( \delta A_{NN} = 5 \) to \( 10 \times 10^{-2} \). This limits the measurements to four-momentum transfers of \( |t| < 10 \) (GeV/c)\(^2\) at 400 GeV.

Measurement of these helicity or transverse spin correlations \( A_{LL} \) or \( A_{NN} \) in pp elastic scattering at largest possible \( s \) and \( |t| \) are of particular interest in view of the surprising results obtained at Argonne: at the highest values of \( s \) and \( |t| \) where \( A_{NN} \) has been measured, \( s = 24 \) GeV\(^2\) and \( |t| = 10 \) (GeV/c)\(^2\), about 80 per cent of the elastic scattering cross-section arises from initial protons with parallel transverse spins (Fig.5).

Note that in all measurements with polarized beam and polarized target the single spin asymmetries are obtained at the same time by summing over one of the the initial polarizations. (For elastic scattering the preferred notation is \( A_{o0kk} \) instead of \( A_{LL} \), and \( A_{oonn} \) instead of \( A_{NN} \), in order to explicitely specify that the experiments sum over final state polarizations).

9) Another important case where new measurements are motivated by surprising effects that have already been observed, is the inclusive production of hyperons from polarized
initial states. For proton induced reactions, many results have been accumulated on the final state polarization from unpolarization initial states, as function of $p_T$, of $X$, and of quark content (Fig. 6). The $\Lambda^0$ polarization is practically independent of energy over the full range from 23 GeV/c to 1400 GeV/c equivalent incident momentum. In pion induced reactions at 16 GeV/c the $\Lambda^0$ polarization is small and is not increasing with increasing $p_T$, in contrast to proton induced reactions at the same energy. The way in which these final state polarizations depend on the initial spins is experimentally totally unknown. All attempts to interpret the observed polarizations are concentrating on specific final state mechanisms. One estimates that precisions of the order of $\delta \Lambda_{LL} = 3 \times 10^{-2}$ for initial helicity correlations can be reached in $\Lambda^0$ inclusive production up to $p_T = 3$ GeV/c. This is a significant precision if one uses as reference the magnitudes of the final state polarizations.

10) Finally, we briefly comment on measurements on pp total cross-sections for definite helicity or transverse spin states in the region of rising total cross-section. This again is unknown territory. At SPS energies the spin averaged cross-section rises by about 2 millibarns. From this one estimates that a precision of the order of 0.1 millibarn should be aimed at when measuring the difference between the cross-sections in definite spin states. The corresponding statistical error can be reached in reasonable time with secondary polarized proton beams of $\langle T_B \rangle = 10^6$ sec$^{-1}$ and $p_B = 0.5$. Comparison with the total cross-section pp in definite spin states would be important. These will be the first experiments in the polarized beam at FNAL.

General context

The few examples given above are illustrative of a possible spin physics activity at the SPS. What would be the general context of such a program with respect to the evolution of the special techniques for beams and target, at CERN and elsewhere, and with respect to the detectors needed?

The beam intensities and energies accessible to different laboratories are shown on Fig. 7. Since in polarization experiments the information is carried not by a number of events but by the difference between two such numbers, these experiments always require statistics larger by one or two orders of magnitude than the corresponding spin averaged measurements. Beam intensities, and energy range, are therefore in most cases the crucial factors of merit.

The figure calls for the following comments concerning beam intensities in general:

- The intensity of accelerated polarized protons is essentially limited by the polarized ion source. The new cryogenic methods to obtain high density polarized stable atomic hydrogen may lead to a break-through in the coming years. This, combined with other improvements, may eventually provide polarized beams of the same intensity as present unpolarized beams. An important consequence would be the possibility of normal beam sharing between all experiments.

- The radiation resistance of the chemically doped polarized target materials had been marginal at the ZGS extracted polarized beam intensities. The new radiation doped materials such as $\text{NH}_3$ have better radiation resistance and can be used with beam intensities up to
\[ <I_B> = 10^{10} \text{ sec}^{-1}. \]

- The "radiation resistance" of many of the present large acceptance detectors is limited to about \( <I_B> = 10^8 \text{ sec}^{-1}. \) It would be important to investigate if and how large acceptance detectors can be made compatible with higher beam rates. A positive aspect of the problem is that the beam transport of an extracted beam produces no halo.

Concerning the energies and intensities, AGS and PS would be approximately equivalent facilities, but the PS will have different higher priority tasks. For the TEVATRON, no plans or official studies for acceleration of polarized particles have been announced. Acceleration of polarized particles in the SPS, even if limited to 150 or 200 GeV per nucleon (acceleration of polarized deuterons), would already allow a second generation program with respect to the approved FNAL polarized beam facility, since the available intensities would be larger by several orders of magnitude.

The FNAL facility uses polarized protons from \( \Lambda^0 \) decay. It is limited to 200 GeV by the beam transport but the energy range can be extended to 400 GeV, with improved intensity, by installing superconducting elements. Because of the high primary energy, the facility can provide 100 to 200 GeV polarized antiprotons from \( \Lambda^0 \) decay with intensities only one order of magnitude less than for protons. At the SPS, a polarized proton beam from \( \Lambda^0 \) decay has been studied for the West Area, with emphasis on high energy, i.e. 370 GeV for 450 GeV primary energy. For this beam, polarized antiprotons from \( \Lambda^0 \) decay would be out of reach.

Reports on polarized secondary beams can be found in CERN studies and in documents on the FNAL beam.

Concerning the evolution of polarized targets, we have witnessed a steady increase of hydrogen content and degree of polarization. Many successful experiments had been carried out with 60 % polarization for 3 % of protons in weight. The \( \text{NH}_3 \) targets will have about 90 % polarization for 18 % protons in weight. Polarized atomic hydrogen gas jet targets are not only pure but also almost 100 % polarized, the present developments aim at achieving densities that are not too small compared to liquid hydrogen which has approximately the same density as polarized free protons in the present solid target materials.

Among the new target materials, \(^6\text{LiD}\) is most important as polarized neutron target. It has already been used in very small samples. Also, when used as an isoscalar polarized nucleon target for inclusive reactions, 50 % of all nucleons, protons and neutrons, are 70 % polarized. This material is also radiation doped. It may be available for high energy experiments within one or two years.

A detailed report on present and future possibilities for polarized targets and sources was given at the parallel session.

Acceleration of polarized particles was discussed at the meetings of the study group, with reports on SATURNE II and on the AGS at the parallel session. The possibilities at the CERN PS and SPS will be presented at this plenary session. This would have obvious implications also for the pp collider physics program at CERN.
Conclusions

Although practically all fields, and the standard electroweak model in particular, are directly concerned by spin physics, the conclusions of the working group on "Use of Polarization in Hadron Physics" emphasize the possibilities to test the fundamental helicity properties of the QCD amplitudes. The helicity correlations in strong interactions are the analog of parity violations in electroweak theory, and contribute to experimentally establish the detailed structure of the fundamental quark-gluon vertex. This requires not only polarized targets but, in most cases, also polarized beams. Since QCD must be tested at short distances, the cross-sections will be small. The larger statistics needed to measure differences between cross-sections cannot be obtained any more by longer running times only. High polarized beam intensities, radiation resistant targets and detectors combining high beam rate capability and good acceptance will be the essential tools for this new class of experiments.

This report summarizes the contributions by many people, experimentalists, accelerator physicists and condensed matter physicists, and reflects the special theory seminars by N.S. CRAIGIE, E. LEADER and J. SOFFER.

APPENDIX I

Meetings of the working group on USE OF POLARIZATION IN HADRON PHYSICS (Theory, Experiment, Techniques)

- 21 September 1982, Westhampton Beach, LI (during the 5th Intern. Symp. on H.E. Spin Physics, Brookhaven, Sept. 16-22).


Informal discussion mostly on experimental techniques, on acceleration of polarized particles and on new possibilities for polarized targets and sources.

- 15-16 November, at CERN


Theory seminars by J. Soffer, CPT Luminy Marseille, E. Leader, Westfield College-London, and N.S. CRAIGIE, ICTP-Trieste, followed by a round table discussion chaired by M. Jacob, CERN.

The motivation for different types of polarization experiments with hadrons was reviewed (Access to the helicity structure of parton hard scattering in leading order QCD;
higher order polarization effects; weak interaction interference, including in $p\bar{p}$ collisions; structure of asymptotic amplitudes; ...). Accelerator experts and condensed matter physicists were questioned about expected performances of polarized beams, about stable atomic hydrogen as polarized sources for accelerators and gas jet targets, and about radiation resistance of target materials. Recommendation was made that the working group should investigate, in particular, the feasibility of a number of typical experiments.

The meeting continued on 16 November (morning) with a report by N.S. CRAIGIE on a draft entitled "Survey of hadron spin physics for high energy laboratories" undertaken after the Brookhaven Symposium, and with a short presentation of the situation in the field of hyperon and antihyperon final state polarizations. Other topics discussed were the luminosity obtainable with internal polarized gas jet targets, and possible schemes to maintain polarization of protons and deuterons in the SPS and to orient the polarization longitudinally. The importance of careful comparison of possible physics programs at CERN with those expected to be carried out by other laboratories has been stressed. Finally, proposals were presented for the agenda of parallel and plenary sessions in December.

- 7 December, at CERN


Informal discussion on acceleration of polarized particles in the PS and SPS, and on H.E. Polarimetry.
APPENDIX II

General formulae and characteristics of polarized beams and target used for order-of-magnitude estimates of event rates and statistical accuracies

- At hadronic level:
  Single Spin Asymmetry.
  \[ A_B = \frac{\sigma(+) - \sigma(-)}{\sigma(+) + \sigma(-)} \]
  or \[ T \]
  Double Spin Asymmetry.
  \[ A_{BT} = \frac{\sigma(++) - \sigma(+-)}{\sigma(++) + \sigma(+-)} \]
  "Raw" Exptl. Asymmetry.
  \[ \varepsilon = \frac{N(++) - N(+-)}{N(++) + N(+-)} = P_B P_T A_{BT} \]
  \( N(++) , N(+-) \) = Numbers of events normalized to same beam flux.
  \( P_B , P_T \) = Beam and target polarizations
  \( \sigma(++) , \sigma(+-) \) = cross-sections for parallel and antiparallel hadron spins, respectively.

- At partonic level:
  QCD predicts
  \[ \hat{a}_{BT} = \frac{\hat{\sigma}(++) - \hat{\sigma}(+-)}{\hat{\sigma}(++) + \hat{\sigma}(+-)} \]
  \( \hat{\sigma}(++) , \hat{\sigma}(+-) \) = cross sections for definite parton helicities \( \lambda \) parallel and antiparallel, respectively.
  Spin dependent structure functions describe the probability to find partons of helicity \( \lambda \) in hadrons of helicity \( \lambda \)
  \[ \frac{D_\lambda}{\lambda} = \frac{D_{-\lambda}}{-\lambda} = \frac{\delta \lambda}{D} (x, Q^2) \]
  \[ \frac{D_\lambda}{\lambda} + \frac{D_{-\lambda}}{-\lambda} = \delta \lambda \]
  Has been measured only for u-quarks in protons (Fig. 3).

- Experiment measures:
  \[ \varepsilon = P_B P_T \left( \frac{\delta \lambda}{D} \right)_B \left( \frac{\delta \lambda}{D} \right)_T \frac{\hat{\sigma}(++) - \hat{\sigma}(+-)}{\hat{\sigma}(++) + \hat{\sigma}(+-)} \]
  Dilution by incompl. parton polariz.
  QCD Amplit.
  Data or Models
  Theoretical predictions for \( A_{BT} \)
- Statistical errors:

\[ \delta_{BT} = \frac{1}{P_B P_T} \times \frac{1}{\sqrt{L \sigma T}} \times (1 + \alpha) \]

\[ L = \text{luminosity} \quad L = \langle I_B \rangle \text{ sec}^{-1} \times N_T \text{ cm}^{-2} \]

\[ \langle I_B \rangle = \text{time averaged beam intensity (sec}^{-1}) \]

\[ N_T = \text{number of target nucleons (cm}^{-2}) \]

\[ \sigma = \text{spin averaged cross-section per nucleon (cm}^2) \]

\[ T = \text{running time (sec)} \]

\[ \alpha = \text{additional error from background events, not considered here.} \]

Figure of merit of beam-target configuration = \( P_B^2 P_T^2 L \)

- Typical double spin accuracies:

\[ \langle I_B \rangle = 10^{10} \text{ sec}^{-1}, 20 \text{ cm long target, } T = 1 \text{ month, for } \sigma = 10^{-33} \text{ cm}^{-2} \]

\[ \text{NH}_3 \text{ exclusive (pp-pp)} \quad \delta_{BT} = 3 \times 10^{-3} \]

\[ \text{NH}_3 \text{ inclusive (pp-hX)} \quad " = 2 \times 10^{-2} \]

\[ ^6\text{LiD} " " " = 1 \times 10^{-2} \]

- Typical systematic errors:

Beam polarization \[ \delta P_B / P_B \approx 5 \times 10^{-2} \]

Target polarization \[ \delta P_T / P_T = 3 \times 10^{-2} \]

"False asymmetries" from errors in \((++)/(+-)\) relative normalization, drifts and fluctuations in: counting rate effects, detector efficiencies, reconstruction efficiencies, etc...

\[ \delta_A \leq 10^{-3} \]

for spin reversals

- Beam: pulse to pulse

and

- Target: several times/day.

Can be improved by hard work (see experiments on parity violation: \( \delta_A \approx 10^{-7} \)).

Absolute normalization of cross sections is irrelevant.
- Typical target densities

<table>
<thead>
<tr>
<th>Liquid Hydr. 100cm</th>
<th>$N_T = 4 \times 10^{24}$ cm$^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pol. Prot. Target 20cm</td>
<td>$N_T \approx 10^{24}$ cm$^{-2}$ (pol. prot.)</td>
</tr>
<tr>
<td>Pol. Jet Target</td>
<td>$N_T \approx 10^{17}$ cm$^{-2}$ (multi traversal)</td>
</tr>
</tbody>
</table>

- Typical beam-intensities

<table>
<thead>
<tr>
<th>Unpol. prim. beam</th>
<th>$\langle I_B \rangle = 3 \times 10^{12}$ sec$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pol. prim. beam</td>
<td>$\langle I_B \rangle \approx 10^{10}$ sec$^{-1}$</td>
</tr>
<tr>
<td>Pol. second beam</td>
<td>$\langle I_B \rangle \approx 10^{6}$ sec$^{-1}$</td>
</tr>
</tbody>
</table>

Upper limits for polarized target radiation damage

- continuous polariz. mode $\langle I_B \rangle \approx 3 \times 10^{11}$ sec$^{-1}$
- frozen spin mode $\langle I_B \rangle \approx 10^{8}$ sec$^{-1}$

Integrated flux to destruction $\approx 10^{17}$ protons cm$^{-2}$

- Typical luminosities (cm$^{-2}$ sec$^{-1}$)

<table>
<thead>
<tr>
<th>Unpol. prim. beam</th>
<th>10$^{37}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pol. prim. beam</td>
<td>2 $\times$ 10$^{34}$</td>
</tr>
<tr>
<td>Pol. second beam</td>
<td>4 $\times$ 10$^{30}$</td>
</tr>
</tbody>
</table>

*Jet cooling to 4°K may improve these luminosities by one order of magnitude.*

- Magnitudes of polarization

<table>
<thead>
<tr>
<th>Pol. prim. proton beam</th>
<th>$P_B \approx 0.7$ (0.6 to 0.8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pol. second. proton beam</td>
<td>$P_B \approx 0.45$ (0.4 to 0.5)</td>
</tr>
<tr>
<td>Pol. targets and jets</td>
<td>$P_T \approx 0.8$ (0.7 to 0.9)</td>
</tr>
</tbody>
</table>

- For inclusive reactions use:

<table>
<thead>
<tr>
<th>$N_{T_{\text{eff}}} = 10^{25}$ cm$^{-2}$,</th>
<th>$P_{T_{\text{eff}}} \approx 0.1$ for alcohols</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{T_{\text{eff}}} = 7 \times 10^{24}$ cm$^{-2}$,</td>
<td>$P_{T_{\text{eff}}} = 0.15$ for NH$_3$</td>
</tr>
<tr>
<td>$N_{T_{\text{eff}}} = 5 \times 10^{24}$ cm$^{-2}$,</td>
<td>$P_{T_{\text{eff}}} = 0.35$ for $^6$LiD</td>
</tr>
</tbody>
</table>
# Table 2

Examples of polarization experiments for the SPS.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Observ.</th>
<th>Theor. Pred. or Results</th>
<th>Precision</th>
<th>Kinem. Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) ( p p \rightarrow X )</td>
<td>( A_L )</td>
<td>( 10^{-6} - 10^{-7} )</td>
<td>( 10^{-7} )</td>
<td>( 200 - 400 ) GeV</td>
</tr>
<tr>
<td>2) ( \bar{p} p \rightarrow W^+ X )</td>
<td>( A_L )</td>
<td>30 - 60</td>
<td>5-10</td>
<td>( \sqrt{s} = 540 ), ( P_T &gt; 20 ) GeV/c</td>
</tr>
<tr>
<td>3) ( p p \rightarrow (\mu \bar{\nu}) X )</td>
<td>( A_{LL} )</td>
<td>( 1 - 10^+ )</td>
<td>3</td>
<td>( M \leq 6 ) GeV</td>
</tr>
<tr>
<td>4) ( p p \rightarrow \gamma X )</td>
<td>( A_{LL} )</td>
<td>( 5 - 10^+ \times 10^{-2} )</td>
<td>1</td>
<td>( P_T \leq 5 ) GeV/c</td>
</tr>
<tr>
<td>5*) ( p p \rightarrow \gamma X )</td>
<td>( A_N )</td>
<td></td>
<td>5</td>
<td>( P_T \leq 5 ) GeV/c</td>
</tr>
<tr>
<td>6**) ( \gamma p \rightarrow e^+ e^- X )</td>
<td>( \Sigma (\mu) )</td>
<td>( 25^{++} \times 10^{-2} )</td>
<td>1</td>
<td>( \forall P_T &gt; 1.5 ) GeV/c</td>
</tr>
<tr>
<td></td>
<td>( bE X )</td>
<td>( \Sigma (\mu) )</td>
<td>50++</td>
<td>( \forall P_T &gt; 2.5 ) GeV/c</td>
</tr>
<tr>
<td>7) ( p p \rightarrow \pi^\pm X )</td>
<td>( A_{LL} )</td>
<td>( 5 - 20^+ ) ( \left{ \begin{array}{l} A_N \text{ is large} \ \text{at } 24 \text{ GeV} \end{array} \right. )</td>
<td>3</td>
<td>( P_T \leq 5 ) GeV/c</td>
</tr>
<tr>
<td>8) ( p p \rightarrow p p )</td>
<td>( A_{LL} ) ( A_{NN} )</td>
<td>( A_{NN} = 60% ) ( \left{ \begin{array}{l} \text{at } 12 \text{ GeV} \ \text{at } 23 - 1400 \text{GeV} \end{array} \right. )</td>
<td>5-10</td>
<td>( \left</td>
</tr>
<tr>
<td>9) ( p p \rightarrow \gamma X )</td>
<td>( A_{LL} ) ( A_{NN} )</td>
<td>( P_{\gamma} = 0.1 - 0.3 ) ( \left{ \begin{array}{l} \text{at } 23 - 1400 \text{GeV} \end{array} \right. )</td>
<td>3</td>
<td>( P_T \leq 3 ) GeV/c</td>
</tr>
<tr>
<td>10) ( p p \rightarrow X )</td>
<td>( \Delta L ) ( \Delta \sigma_{T} )</td>
<td>( 2 \text{ mb rise of } \sigma_{TOT} )</td>
<td>0.1mb</td>
<td>( 200 - 400 ) GeV</td>
</tr>
</tbody>
</table>

* West Area \( \bar{p}^+ \) secondary beam project

** 70-90 GeV \( \gamma \) beam, \( P_B = 0.35 \), from Silicon crystal

++ quark mass effects

+ leading order QCD
Figure Captions.

Fig. 1  Linear polarization (a) and coherent enhancement (b) of high energy photons from bremsstrahlung on Silicon. Communication by G. BOLOGNA.

The region of particular interest are the photon energies from \( k \gtrsim 70 \text{ GeV} \ (X \lesssim 0.5) \) to \( k \lesssim 90 \text{ GeV} \ (X \lesssim 0.67) \). In this region the polarization is of the order \( P = 0.3 \) to 0.4. The shape of the photon spectrum, but not the polarization, depends critically on the horizontal divergence \( \sigma_X \) of the incident electron beam. The coherent enhancement is the coherent bremsstrahlung cross-section \( \sigma_C \) divided by the Bethe-Heitler cross-section \( \sigma_{BH} \).

Fig. 2  Leading order QCD cross-sections for parton-parton scattering in definite initial helicity states, summed over final spin states.

Fig. 3  SLAC results for \( A/D \sim A_T \), which is approximately \( h_u/h_n \), as function of the quark fractional momentum \( X \). The dotted curves represent the three alternate models used by J. BABCOCK et al., Phys. Rev. D19 (1979) 1483:

a) Conservative SU(6),

b) Di-quark model,

c) Carlitz-Kaur. The other curves are lower bounds for the helicity of d-quarks in neutrons, under different assumptions (D.J. BJORKEN, Dec. 1980).

Fig. 4  Leading order QCD predictions for \( A_{LL} \) in \( pp \rightarrow \pi^+ X \) at \( \theta^+ = 90^\circ \), as function of fractional transverse momentum \( X_T = 2 p_T^2 / s \) (J. BABCOCK et al., Phys. Rev. D19 (1979) 1483).

Fig. 5  ARCOONE results for elastic scattering in pure transverse spin states.

a) The ratio of spin-parallel to antiparallel cross-section as function of \( P_T^2 \).

b) The two cross-sections as functions of a variable proportional to \( P_T^2 \).

Fig. 6  Polarization of inclusively produced hyperons from unpolarized initial state,

a) as function of hyperon laboratory momentum at fixed production angle, and

b) as function of total center-of-mass energy at fixed \( P_T \) and fixed fractional longitudinal momentum \( X \). Also shown is the polarization of inclusively produced protons.

Fig. 7  Energies and time averaged intensities of polarized proton beams at different accelerators. The intensities for AGS and PS/SPS are conservative assumptions (see Table 1). The secondary beam for SPS represents the study by D. PLANE, 1981).
PARTON SCATTERING $ab \rightarrow cd$

$$\hat{a}_{LL}^{ab} \equiv \frac{|M_i^{2++} - M_i^{2-}|}{|M_i^{2++} + M_i^{2-}|}$$

LEADING ORDER QCD AMPLITUDES

Fig. 1a

SILICON
$E_0 = 140$ GeV
$\theta_x = 0.27$ mrad
$\theta_y = 15.34$ mrad
$\sigma_y = 0.3$ mrad not critical

Fig. 1b

$\sigma_x = 0.3$ mrad
$\sigma_x = 0.27$ mrad
$\sigma_x = 0.1$ mrad

Fig. 2

$M_{++} = 0$

$|M_i^{2++} = 7.7|M_i^{2+} A$

$|M_i^{2++} = 2.6|M_i^{2+} B$

$M_{--} = 0$

$\frac{\hat{s}}{\hat{t}}$

$\theta_{ab}^{CM}$
Fig. 5a

Fig. 5b
Fig. 7
Polarization asymmetries and gauge theory interactions at short distances

N.S. Craigie

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In this talk, which summarizes the theoretical considerations behind talks given in the plenary sessions of the SPS workshop on the role polarization measurements can play at high energies, we give the arguments as to why spin asymmetries test fundamental properties of the underlying gauge theories of elementary particles, concentrating mainly on electro-weak and QCD interactions, but also looking at the future and possible signatures for supersymmetric strong interactions. We also mention briefly the role helicity asymmetry measurements can play as regards higher order corrections, including higher twist, in QCD. N.S. Craigie (ICTP and INFN, Trieste).

The basic point we wish to emphasize is that when one studies interactions at high energies and momentum transfers (or more generally at short distances) one sees direct evidence of the underlying gauge theories of elementary particles and, furthermore, for these theories helicity plays as fundamental a role as charge. A direct consequence of this is that measurements in pure spin states open up valuable new windows into the nature of these theories. I would like to demonstrate this by focusing briefly on four aspects of gauge theory interactions. I will however make a short excursion into some extra considerations when discussing QCD perturbation theory and its predictions for spin asymmetries. In this talk I will not attempt to deal with the question of feasibility, which is discussed in some detail in the talk given by L. Van Rossum (see also Ref.1).

A. Helicity as a fundamental label or quantum number in gauge theories and observable consequences

If we examine the basic fermion multiplet structure of a grand unified theory (GUT), one sees that the left-handed components of fermion states (or fields) are put in different multiplets of the basic gauge group. There are basically two ways this separation is thought to occur, namely:

1) Theories like those proposed by Pati and Salam, in which one starts with a left-right symmetric gauge theory $SU(4) \times SU(2)_L \times SU(2)_R$, in which for every left-handed particle there is a degenerate right-handed partner, however, after spontaneous symmetry breaking in which parity is also spontaneously broken, the right-handed gauge particles become much heavier than the left, i.e. $W_L \sim 60$ GeV and $W_R \sim 300$ GeV.
11) Theories like the SU(5) model proposed by Georgi and Glashow, in which parity is not respected from the outset, except for the subgroup of strong interactions. Here the right-handed fermions in the first generation are put in a $5^*$, while the left-handed are put in a 10 representation of SU(5)\textsuperscript{3).}

After spontaneous symmetry breaking, one is left with SU(3)\textsubscript{QCD} $\otimes$ [SU(2) $\otimes$ U(1)]\textsubscript{electro-weak} as an effective low-energy theory in both these schemes.

The simplest example of such theories is the Glashow-Salam-Weinberg SU(2)\textsubscript{L} $\otimes$ U(1)\textsubscript{L+R} model of electroweak interactions, in which (e\textsuperscript{−},ν\textsubscript{e})\textsubscript{L} form an SU(2)\textsubscript{L} doublet and e\textsuperscript{−}\textsubscript{R} is an SU(2)\textsubscript{L} singlet. The separation of different helicity components in this way, with respect to the basic gauge interactions, has the obvious and immediate consequence of parity violating helicity asymmetries (i.e. the different helicity components interact differently) $A_L^\pm = \frac{\sigma(+) - \sigma(-)}{\sigma(+) + \sigma(-)}$. One example\textsuperscript{4)} is $\gamma-Z^0$ interference in $p\bar{p}(\pm) \rightarrow l^\pm l^- + X$, where the predictions of the Glashow-Weinberg-Salam model is shown in Fig.1. Another example is in $W^+$ production in $p\bar{p}(\pm) \rightarrow l^\pm + X$, where one has the simple predictions:

\[
A_L^{W^+} = \frac{\int dx_1 dx_2 N(\bar{q}) \frac{d(\bar{q}(x_1) \Delta \nu(x_2))}{dx_2}}{\int dx_1 dx_2 N(q) \frac{d(q(x_1) \Delta \bar{\nu}(x_2))}{dx_2}} \frac{\hat{s}^2 \hat{s}^{-1}}{\hat{s}} \delta(\bar{s} + \bar{t} + \bar{u})
\]

\[
= \frac{2}{3} \text{ in SU(6) model of quark distributions,}
\]

\[
A_L^{W^-} = \frac{\int dx_1 dx_2 N(\bar{q}) \frac{d(\bar{q}(x_1) \Delta \nu(x_2))}{dx_2}}{\int dx_1 dx_2 N(q) \frac{d(q(x_1) \Delta \bar{\nu}(x_2))}{dx_2}} \frac{\hat{s}^2 \hat{s}^{-1}}{\hat{s}} \delta(\bar{s} + \bar{t} + \bar{u})
\]

\[
= - \frac{1}{3} \text{ in SU(6) model of quark distribution.}
\]

\[\sqrt{s} = 540\text{GeV}\]

Fig.1: Parity violating helicity asymmetry in $p\bar{p} \rightarrow l^+ l^- + X$. 

50 60 70 80 90 100 110 120 130
M (GeV)
The SU(6) prediction is a little naive and a more realistic model, which we mention later, predicts for $A^+_{LL}$ a value more like 0.5 on averaging over transverse momentum. One sees that if one identifies $W^+$ from single lepton events, then these events should be accompanied by a very large parity violating helicity asymmetry in going from the proton beam in positive and negative helicity states, respectively. In fact, with a 70% polarized beam, one is already above the statistical background with 10 events.

B. Even in L-R symmetric theories like QCD helicity is as fundamental as charge

We can illustrate this by considering the example of prompt photon production at high $p_T$. There are two basic Born processes in QCD perturbation theory leading to prompt photons at large transverse momentum namely:

\[
\begin{align*}
q\bar{q} &\rightarrow \gamma + g \quad \text{annihilation} \\
sg &\rightarrow \gamma q \quad \text{Compton}
\end{align*}
\]

To untangle these one could vary the number of quark anti-quark pairs available to annihilate into a photon and gluon, for example, by considering the difference between

\[
\begin{align*}
\pi^- &\rightarrow u \gamma \quad \text{(a)} \\
\pi^+ &\rightarrow d \gamma \quad \text{(b)}
\end{align*}
\]

\[
\begin{align*}
p^- &\rightarrow \gamma + X \\
p^+ &\rightarrow \gamma + X
\end{align*}
\]

Fig.2: Annihilation contribution to prompt photon production in (a) $\pi^-$ and (b) $\pi^+$ collisions.

However, one can accomplish the same by using a longitudinal polarized proton beam on a polarized target, i.e. $\bar{p} + p \rightarrow \gamma + X$. The reason is that the annihilation only goes through if the quark is in an opposite helicity state to the anti-quark, whereas the Compton process involves predominately the quark and gluon being in the same helicity state (i.e. both positive or both negative). Hence the Born processes $q\bar{q} \rightarrow \gamma g$ and $sq \rightarrow \gamma p$ contribute differently to $P^+ + P^+ \rightarrow \gamma + X$ and $P^+ + P^- \rightarrow \gamma + X$. The basic quantity to measure is the double symmetry $A^+_{LL} = \frac{d\sigma(++) - d\sigma(+-)}{d\sigma(++) + d\sigma(+-)}$. 
and for many short distance processes QCD predicts $A_{LL} \sim 10-50\%$ reflecting a basic property of QCD perturbation theory, which can be stated as follows: If we can neglect masses, for example, in the scaling region of $u$ and $d$ quark interactions, then by noting that the basic interaction can be decomposed as follows:

$$\overline{q}_\mu A^\mu q = \overline{q}_L \gamma_\mu q_L A^\mu + \overline{q}_R \gamma_\mu q_R A^\mu$$

we see that the left and right-handed helicity states do not communicate, i.e. helicity is always conserved on quark lines no matter how complicated the interaction is. Further, a quark and antiquark can only annihilate into gluon and photon states when they have opposite helicities. This simple fact leads to very large double helicity correlations in the basic Born processes of QCD. In the following table we give a few illustrations and refer to Ref.1 and the literature cited therein for more details. [We denote a helicity correlation in the initial state by $a_{LL}^{ii}$ and an initial-final state correlation by $a_{LL}^{if}$.]

<table>
<thead>
<tr>
<th>$ab \rightarrow cd$</th>
<th>diagram</th>
<th>$a_{LL}^{ii}$</th>
<th>$a_{LL}^{if}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ud \rightarrow ud$</td>
<td><img src="image1" alt="Diagram" /></td>
<td>$s^2 - u^2$</td>
<td>$1$</td>
</tr>
<tr>
<td>$\overline{u}u \rightarrow \overline{s}s$</td>
<td><img src="image2" alt="Diagram" /></td>
<td>$-1$</td>
<td>$\frac{t^2 - u^2}{t^2 + u^2}$</td>
</tr>
<tr>
<td>$g\overline{g} \rightarrow g\overline{s}$</td>
<td><img src="image3" alt="Diagram" /></td>
<td>$-1$</td>
<td>$\frac{u^2 - t^2}{u^2 + t^2}$</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

In Fig.3 we compare all the basic Born asymmetries $a_{LL}^{ii}$ in QCD and in Fig.4 we compare two initial-final asymmetries. The point we are making here is that these basic asymmetries are clear signatures as to the underlying QCD mechanism, thus providing a very valuable test of QCD; complementing those done by using different charge states. In fact, if one considers ISR experiments, such as the CERN collaboration, in which two high $p_T$ pions are identified in the final state, then there is evidence 6) that particular Born processes can be singled out by triggering on configurations with opposite
Fig. 3
The basic Born asymmetries $a_{LL}$ of QCD.

Fig. 4
Transmitted Born asymmetries for $\tilde{g}g \rightarrow \tilde{s}s$ and $\tilde{u}u \rightarrow \tilde{s}s$. 
pions having different charge correlations. If this is indeed the case then combining the latter with an asymmetry measurement would provide a particularly simple and striking test of QCD in high \( p_T \) reactions.

Before leaving this subject I should say a few words on how the basic Born asymmetries at the constituent level are communicated to the asymmetry seen at the hadronic level. This can be summarized schematically as follows (we refer to Ref.\(^4\) for details)

The basic parton asymmetries are communicated to a hadron process at short distances by virtue of the so-called factorization "theorem" of QCD perturbation theory

\[
\sigma^{AB}(p_A, p_B, \ldots) = \int d\chi_a \int d\chi_b \prod_{a} D_A^a(\chi_a) D_B^b(\chi_b) \cdots \sigma^{ab}(x_a p_A, x_b p_B, \ldots)
\]

\[
\Delta \sigma^{AB}(p_A, p_B, \ldots) = \sigma^{A^+ B^+} - \sigma^{A^- B^-} = \int \Delta D_A^a \Delta D_B^b \cdots \Delta \sigma^{ab} \ldots
\]

where \( D_A^a(\chi_A) \) represents the probability of finding parton \( a \) in hadron \( A \) carrying fraction \( \chi_A \) of the momentum and \( \Delta D_A^a = D_A^a - D_A^{-a} \) represents corresponding helicity transfer probability.

In principle one might imagine that the helicity transfer probabilities could be small and thus depleting any observable effect, however, there are a number of theoretical arguments why they must be large and in the case of quark distributions inside the proton there is some direct experimental evidence.
The most important theoretical argument is a sum rule due to Bjorken, which follows from quite general arguments and when expressed in terms of parton densities $\Delta u_\rho = u(x)$, $\Delta d_\rho = d(x)$, etc., reads

$$\int_0^1 dx \left[ \Delta u(x) - \Delta d(x) + \Delta s(x) - \Delta b(x) \right] = \frac{c_A}{c_V} \left[ 1 - \frac{q^2}{\pi} + \ldots \right] \sim 1.23 .$$

This sum rule tells us $\Delta D/D \sim 1$ for valence quark distributions inside a proton of definite helicity. Carlitz and Kaur 5) constructed a model of the proton densities, which satisfied the Bjorken sum rule and has the leading quark helicity rule of Brodsky, Blankenbecler and Gunion, namely $\Delta u(x)/u(x) \rightarrow 1$ as $x \rightarrow 1$ (see Ref.4). This model is consistent with data from SLAC 6), see Fig.6. If one combines the Carlitz-Kaur leading quark model with a gluon bremsstrahlung model to calculate $\Delta G(x)/G(x)$ for the gluon distribution inside the proton (we refer to this as the leading quark gluon bremsstrahlung or LQGB model), then a large number of predictions of QCD can be made using the factorization theorem, including:

$$\bar{p} p \rightarrow \bar{\mu}^+ \mu^- + X$$

$$\rightarrow \psi/J + X$$

$$\rightarrow \pi^+, K^+, K^0, A, A_c, \ldots$$

$$\rightarrow \text{jets, prompt } \gamma$$

$$\bar{p} p \rightarrow \bar{A} + X \quad \text{(transmitted asymmetries)}$$

$$e^+ p \rightarrow e h + X ; \quad h = \pi, K, P, A, \ldots$$

$$e^+ p \rightarrow \pi^+ + X \quad \text{(transmitted asymmetry)}$$

$$e^+ e^- \rightarrow \bar{A} + X$$

and many others.

To give an idea of the sort of effects I am taking about, we give in Fig.7 the prediction for $\bar{p} p \rightarrow \pi^+ + X$ at a CMS trigger angle of 90°, using the Carlitz-Kaur model for the quark distribution function. Also in Fig.8 the transmitted asymmetry in $\bar{p} p \rightarrow A + S + X$ is plotted as a function of $x_T$ for different trigger angles using the LQGB model as input. The change of sign is a direct reflection of the shape of the dominant Born process $gg \rightarrow ss$ at high $p_T$ (see Fig.4). (In Fig.8 $a_{s\Lambda} = \left\langle \Delta D_{s\Lambda}/D_{s\Lambda} \right\rangle_{\text{Ave}}$).
Fig. 6

SLAC data on $G_L$ structure function, compare with the Carlitz-Kaur model.

Fig. 7

Example of reflected double helicity asymmetry prediction by QCD perturbative theory.
Higher order corrections to the basic picture in QCD

The factorization theorem described above means that the parton distribution can be extracted from one process and used as input in the predictions for another. For example, they can be measured directly in deep inelastic scattering. However this is strictly only true in leading order in QCD and there are corrections of order $q_0^2$. These turn out to be very large in the case of the Drell-Yan mechanism for massive lepton pair production. However to a reasonable approximation these corrections can be factored into a multiplicative constant (or slowly varying) factor, the so-called K factor (for lepton pair mass from 3-15 GeV $K \sim 2-2.5$. The first question that arises is does such large corrections to the normalization considerably influence the asymmetry prediction. However an explicit calculation shows that the K factor drops out of the asymmetry prediction. The reason is that the large corrections to the normalization are due to ultrasoft gluon exchange, which does not significantly influence the helicity propagation. Recall the basic rule that helicity is conserved in the scaling region on a quark line no matter how complicated the process is. In higher order QCD perturbation however there are more routes for the quark line. Despite this, it appears that the large corrections come from diagrams involving - soft gluon radiation from and - exchange between - the hard momentum lines in the leading order, resulting in little effect on the asymmetry predictions. Hence a clean way of seeing the predictions of the leading order in QCD is to single out processes which are driven by a single Born process, like massive lepton pair production. If more than one Born process in QCD is involved, then the K factor will play a role because the relative normalization becomes important.

In contrast to corrections to the leading power scaling behaviour, higher order corrections can have a profound influence on the helicity prediction. This is demonstrated in some recent calculations, which indicate that double helicity asymmetries may be a most valuable way to identify higher power mechanisms in QCD and disentangle them from the leading scaling behaviour.

As a final note, one firm prediction of QCD is that there should be no single spin asymmetry at short distances. There is a disturbing experimental example, namely $pp \rightarrow \Lambda + X$, which at FNAL energies shows a significant transverse spin asymmetry for a $p_T$ larger than 3 GeV. This is certainly indicative of a gap in our understanding and needs to be pursued most earnestly experimentally. [We refer to Ref.10 for references and a more detailed discussion].
Fig. 8

Example of a transmitted double asymmetry predicted by QCD perturbative theory.
C. **Helicity asymmetries as a future probe of supersymmetric interactions at very short distances**

In recent years there has been some considerable interest in the possibility that a supersymmetric version of SU(5) can avoid the gauge hierarchy problem due to the very different mass scales in breaking SU(5) → SU(3)\text{colour} \oplus U(1)_\text{em}. In the supersymmetric version of SU(5) SuSy QCD is the effective low energy strong interaction theory. Presumably SuSy is also broken at some mass scale, making the SuSy partner of the gluon, namely the gluino, heavy. If the latter mass scale is sufficiently low (e.g. ≲ 100 GeV), then one could ask where one might see evidence of supersymmetric strong interactions. The answer is in gluon-gluon collisions at high energies:

\[ gg \rightarrow gg \]
\[ \rightarrow \tilde{g} \tilde{g} \] (gluino production)

Also

\[ gq \rightarrow gq \]
\[ \rightarrow \tilde{g} q_s \ldots \] (q_s = scalar SuSy partner to the quark)

In proton-proton collisions at very high energies and transverse momentum there are two signatures for gluino production.

1) **Missing transverse energy**

Gluinos form a new kind of hadronic matter, which decay only by new SuSy weak and electromagnetic interactions \(^2\), e.g. \[ \tilde{g} \rightarrow \widetilde{\gamma} + q\bar{q}, \] where \( \widetilde{\gamma} \) is a photino, the inert partner of the photon. Hence there will be a large number of events, with missing transverse energy \( E_T^{(1)} \neq E_T^{(2)} \) (see Fig. 9a)

![Diagram of missing transverse energy](image)

Two large \( E_T \) jets. Dashed line represents inert photino \( \widetilde{\gamma} \)
11) Helicity asymmetry

If we examine the basic Born cross-sections for gluons in a definite helicity state, we see that $gg \rightarrow \gamma \gamma$ has a very different asymmetry $a_{LL}$ to the main reaction $gg \rightarrow gg$ (see Fig. 9). In fact it has the opposite sign.

Hence if events with missing transverse energies are accompanied by a change of sign of the basic asymmetry, then one has a pretty unambiguous signal of supersymmetric interactions. *) One has of course to calibrate the gluon beam and its polarization, and from the previous remarks about double asymmetries in QCD, we see that there is a number of processes by which this could be done (see Ref.10 for a more detailed discussion).

D. Fermion scattering off a monopole

As a final illustration of the fact that helicity is as fundamental as charge when we consider gauge theories, we briefly consider the intriguing effect that takes place when a fermion scatters off a GUT monopole. Our aim here is not to suggest eventual measurements, but to use this example as a novel example of our opening remark.

When a charged fermion scatters off a monopole, the $z$-component of total angular momentum contains, in addition to the usual orbital part, a part $h_z = -\frac{1}{2} \frac{e}{r}$ coming from helicity of the fermion and a part $e^2 \frac{\gamma}{r}$ due to the monopole field, where $r$ is the position vector of the fermion with respect to the monopole core. The Dirac condition is $eg = \frac{1}{2}$, hence in the $J = 0$ partial wave these two terms exactly balance. However as the fermion passes the core $\vec{r} \rightarrow -\vec{r}$, hence in order to conserve angular momentum, either $h_z \rightarrow -h_z$ (helicity flips) or $e \rightarrow -e$ (i.e. fermion changes charge or identity). A GUT monopole is in fact an indefinite state of fermion number and in fact both things can happen in principle due to the distortion of the fermionic vacuum around the core of the monopole. This point has been made by Rubakov [11] and Callen [12] who give arguments as to why it is the fermion identity that changes as the it passes the core. A profound consequence of the physics involved here is that monopoles can catalyse proton decays with a strong interaction rate. The latter dramatic effect is observable if the monopole flux is sufficiently high and it is due to the belief that helicity conservation is more fundamental for this problem than charge or baryon number conservation.

With the above four sets of remarks concerning the role helicity plays in gauge theories and the observable consequences of this, I hope to convince you of the tremendous value measurements in pure helicity states.

*) The rate for heavy flavour production is calculatably lower and should be a small background.
would have if sufficiently high luminosity was obtainable for these experiments. Before concluding this talk, there is another area we would like to mention in which spin asymmetries could provide some interesting physics and tests of QCD, namely, transverse spin angular correlation in heavy quark flavour production. Here the quark masses cannot be neglected so different helicity components can communicate. In particular, there will be the potential of large single spin asymmetries. These remarks apply to the sort of energies and momentum transfers of current day experiments. A photon beam would be a particularly nice way of probing this large quark mass physics. (Transversely polarized beams will have final state angular distributions which are strongly influenced by quark masses $^{13}$.) With this note we end this brief resume.

REFERENCES


SPIN STRUCTURE AT THE PARTONIC LEVEL

II QCD TESTS IN HADRONIC REACTIONS

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ABSTRACT

Knowledge of the spin and momentum distribution of partons inside a polarised nucleon, as deduced from lepton scattering, is combined with lowest order QCD to calculate spin dependent parameters in large \( p_T \) hadronic reactions. Clear predictions emerge in some cases and are in conflict with present experimental results. There is a real challenge to improve both theory and experiment.

1. INTRODUCTION

The crucial information that can be learnt about the fundamental internal structure of hadrons from deep inelastic lepton scattering with polarised beams and targets, as discussed in I in this volume, \(^*)\) is here utilised in studying spin dependent phenomena in hadronic reactions. We thus assume that we have some knowledge of the distribution in momentum and spin of the partons inside a polarised hadron and use perturbative QCD to predict the behaviour of spin dependent observables in various kinds of large \( p_T \) hadronic reactions.

We stress that the spin-structure of QCD, at a perturbative level, is very simple and precise, so that clean and restrictive predictions emerge that can be used to test the basic validity of the theory. Indeed, it should be remembered, that although QCD is intuitively and aesthetically seductive, there is really very little concrete evidence in its favour. Tests, therefore of its detailed coupling-structure are very important. Since, however, we are only able to do perturbative calculations, it is essential to study reactions in those kinematic regions (usually high energy, large \( p_T \)) where there is some chance of these being valid. It is also important to remember that the actual polarising power \( P \) is only one of many spin-dependent parameters, and one may well have \( P=0 \) and, at the same time, important spin effects.

In the following we shall talk at the level of the simplest parton picture used in conjunction with lowest order QCD. It is expected, though not rigorously demonstrated, that higher order QCD effects will only minimally affect the spin-dependent observables (see contribution by Craigie). In this picture the polarised beam and polarised target simply act as the sources of wide-band polarised parton beams which then interact via lowest order QCD. This is illustrated below for an inclusive reaction \( A+B+C+X \)

\(^*)\) See page 23.
2. **INCLUSIVE REACTIONS :** $A + B + C + X$

If, for example, $A$ and $B$ are fully polarised with helicities $\lambda_A, \lambda_B$ one has the generic formula:

$$d\sigma_{\lambda_A\lambda_B} \sum_{\text{Helicity}} \sum_{\text{Flavours}} \int dx_a dx_b \frac{a,\lambda}{G(x_a)} \frac{b,\lambda'}{G(x_b)} \frac{C}{D(z)d\sigma_{\lambda\lambda}'} \cdots$$  \hspace{1cm} (1)

where $G(x_a)$ is the number density of flavour "a" partons of helicity $\lambda_a$, and $d\sigma_{\lambda\lambda}'$ is the lowest order QCD cross-section for the parton reaction $a + b = c + X$ starting with partons of helicity $\lambda$ and $\lambda'$. For valence quarks the $G$ functions are presumed known from deep inelastic lepton scattering while for sea quarks and gluons, models have to be constructed. This should not be a source of great uncertainty provided one keeps to kinematic regions where the valence quarks dominate.

A most important characteristic feature of QCD is that the helicity of a fast quark is unchanged during the reaction. It then follows that if only the beam or only the target is polarised, or if one measures the polarisation of $C$ for an unpolarised beam and target, one should get zero. In other words:

$$\text{All single-spin asymmetries} = 0$$  \hspace{1cm} (2)

The experimental situation is fascinating.

a) **Unpolarised beam and target:** The reactions

$$pp \rightarrow \text{hyperon} + X$$

wherein the hyperon is self-analysing have been studied for $\Lambda, \bar{\Lambda}, \Xi^-$ and $\Sigma^+$. 
All except $\bar{\Lambda}$ have significant polarisations (20-30%), and for $\Lambda$ this has been shown to be true all the way from PS to ISR energies. The $p_T$ involved ($\leq 3$ GeV/c) could be considered to be too small to trust perturbative QCD, but there is no sign of any decrease in the polarisation as $p_T$ increases, nor any sign of energy dependence. Some feeling for the data\(^1\) can be obtained from the figures below.

![Graph showing polarization vs $p_T$ for different energy regions.]

\[ p+p\rightarrow \Lambda^0 + X \]

$p_T$ in GeV/c
- $0.2 < p_T < 0.4$
- $0.4 < p_T < 0.6$
- $0.8 < p_T < 1.0$
- $1.0 < p_T < 1.2$

400 GeV

There are several somewhat ad hoc models designed to explain these features\(^2\). None are very fundamental and all predict $P>0$ as $p_T$ increases.
Measurements at larger \( p_T \), and in pp collisions (especially of \( \bar{\Lambda} \) polarisation) are vitally needed.

b) **Polarised Target only**: The reaction \( pp^+ \to p^0X \) shows an asymmetry of about 30\% at all measured energies\(^3\). The asymmetry is zero according to lowest order QCD. Again the escape clause is that \( p_T \) is not large enough. Tests at larger \( p_T \) must be carried out!

c) **Polarised Beam and Target**. Various asymmetries in \( A^+B^+ \to CX \) are possible with polarisations either longitudinal (L), transverse (T) in, or normal (N) to, the ABC plane. All are non-zero in lowest order QCD and, indeed, are sometimes very large at the partonic level, but the latter get diluted because the partons in a 100\% polarised hadron beam are not themselves fully polarised. Nonetheless significant and measurable asymmetries are predicted.

The theoretical formulae are quite transparent. For example, for longitudinal polarisations of beam and target one has

\[
\frac{d\sigma(A^+B^+ \to CX) - d\sigma(A^-B^- \to CX)}{d\sigma(A^+B^+ \to CX) + d\sigma(A^-B^- \to CX)} = \frac{\sum_A \left[ q^A(x_a) - q_\perp^A(x_a) \right] \sum_B \left[ q^B(x_b) - q_\perp^B(x_b) \right]}{\sum_A q^A(x_a) \sum_B q^B(x_b)} \left\{ \frac{d\sigma^+}{d\sigma^0} - \frac{d\sigma^-}{d\sigma^0} \right\}_{ab=acX} D_C^C(z) \tag{5}
\]

where the sum is over flavours and the integral over \( x_a, x_b \). The number densities \( q^A, q_\perp^A \) of partons with spin parallel or anti-parallel to the parent hadron's spin were defined in I, eqn.(1).

If we ignore the effects of the smearing due to the momentum integration and flavour sum, we get a remarkably simple and intuitive result:

\[
\hat{A}_{LL}^{\text{Hadronic}} = \langle \hat{P} \rangle_A \langle \hat{P} \rangle_B \hat{A}_{LL}^{\text{Partonic}} \tag{4}
\]

where e.g. \( \langle \hat{P} \rangle_A \) is the average polarisation of the partons in hadron A, \( \hat{P} \) itself being defined by

\[
\hat{P} = \frac{q^A(x) - q_\perp^A(x)}{q^A(x) + q_\perp^A(x)} = \frac{q^A(x) - q_\perp^A(x)}{q(x)} \tag{5}
\]

the last step following from I eqn.(1), and the partonic \( \hat{A}_{LL} \) is

\[
\hat{A}_{LL} = \left\{ \frac{d\sigma^+}{d\sigma^0} - \frac{d\sigma^-}{d\sigma^0} \right\}_{ab=acX} D_C^C(z) \tag{6}
\]

Eqn.(4) could be a little dangerous, since the \( \hat{A}_{LL} \) vary considerably\(^4\)
for $qq$, $\bar{q}q$, $qg$, $gq$ etc., but numerical calculations show it to give a correct order of magnitude estimate.

To get some feeling for the magnitudes we show below the results\textsuperscript{4) }for $\lambda_{LL}$ for $pp \rightarrow \pi^0 \chi$ and $pp \rightarrow \pi^+ \chi$, computed using the Carlitz-Kaur parton number densities which were discussed in I.

![Graphs showing CARLITZ & KAUR DISTRIBUTIONS](image)

Detailed predictions can be found in ref.\textsuperscript{4).} $\lambda_{LL}$ is clearly large enough to measure. Generally $\lambda_{NN}$ comes out much smaller.

$$\lambda_{NN} = 10^{-3} \lambda_{LL}$$

and so might be impossibly difficult to pin down. We conclude that measurements with longitudinal polarisations will provide a very interesting test of the whole picture.

3. **EXCLUSIVE REACTIONS AT LARGE $p_T$**

Exclusive reactions, such as $pp \rightarrow pp$ at large $p_T$, are much more difficult theoretically because several different mechanisms could be important even within the framework of the simple parton model and lowest order QCD. It could then happen that one particular mechanism dominated the differential cross-section whereas a different one is responsible for the main spin correlation. In such a situation it is meaningless to compute spin asymmetries from either one mechanism alone. The problem is exacerbated by the fact that the relative normalisation of the various contributions is usually unknown, so they cannot just be added together.

There are three main types of contribution, illustrated below.

![Diagram illustrating exclusive reactions at large $p_T$](image)
It should be realised that the hadron vertices which look so similar in the inclusive and exclusive diagrams, are really quite different, as is indicated schematically below:

\[
\text{INCLUSIVE} = \sum_i \int dx_2 \cdots dx_n |\psi(x_1, x_2, \cdots, x_n)|^2
\]

\[
\text{EXCLUSIVE} = \psi(x_1, x_2, x_3)
\]

What distinguishes the mechanisms is that in the "end point" diagrams of Szwed\(^5\) and Preparata\(^6\) only one quark gets a large \(p_T\) kick, whereas in the "Landshoff"\(^7\) or "Brodsky-Lepage"\(^8\) diagrams all quarks share the \(p_T\). For large \(p_T\), the "end-point" mechanism can only be important when \(x\) of the active quark is close to 1. But outside this region one expects the "Landshoff" mechanism to dominate, though it is now believed that these contributions may be suppressed by so-called Sudakov factors\(^9\), and, in the end, the "Brodsky-Lepage" diagrams might control the large \(p_T\) differential cross-section.

We are convinced that all mechanisms are important for spin effects, and that it is therefore difficult to make precise numerical predictions. Nevertheless, all mechanisms have \(P=0\), so it appears to be an unambiguous prediction that

\[ P = 0 \]

\[ \ldots (8) \]
for large $p_T$ elastic or two-body scattering.

The two-spin correlation parameters are non-zero in all mechanisms, but their values depend upon which diagram one takes, and since, e.g.

$$\sum_{i}^{\text{total}} A_{NNi}^{\text{th diagonal}}$$

it is a little meaningless to quote results. Nonetheless, we indicate briefly what is found for the nucleon-nucleon helicity amplitudes $\Phi_j$ ($j=1..5$) and for some of the spin parameters:

**Szwed:**

- Only $\Phi_5 = 0$
- $A_{NN} = 0.5$ to $0.7$; $A_{LL} = -0.3$ to $-0.5$

**Brodsky-Lepage:**

- $\Phi_2 = \Phi_5 = 0$
- $A_{NN} = -A_{SS}$
- In any reaction $\Sigma \lambda_i = \Sigma \lambda_f$

the sum being over the initial (i) and final (f) hadron helicities.

4. **CONCLUSIONS:**

We believe that the spin dependent data in hadronic reaction presents a great challenge to both theorists and experimentalists. Taken literally the present data is in contradiction with perturbative QCD and the parton model. But we have an uneasy feeling that the theoretical treatments are too naive and it is vitally important for the experimentalists to plunge ahead and establish firmly what exactly is happening, especially at larger values of $p_T$. Do the single spin asymmetries vanish?

Finally, although it has nothing to do with large $p_T$, we cannot help reminding our experimental colleagues of the classic reaction $\pi^- p + n^0 n$ and of the cataclysmic role played by its polarisation measurements in destroying theories in the past. We still do not know whether the Pomeron has an odd-signatured twin (the Odderon$^{10}$), small in magnitude but very different in phase. A measurement of $P$ in $\pi^- p + n^0 n$ at SPS energies could settle this once and for all.

**REFERENCES**

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POLARIZATION AS A TOOL FOR STUDYING THE PHYSICS OF WEAK INTERACTIONS

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ABSTRACT
Realistic possibilities exist now to obtain high-energy polarized proton beams with high luminosity and to measure the polarization of a stored beam. This will be our motivation to discuss parity violating weak effects in inclusive hadron and jet production with polarized beams. There are also interesting predictions for helicity asymmetries in $W^\pm$ and $Z$ production in $pp$ and $\bar{p}p$ collisions.

1. INTRODUCTION
Our knowledge of the weak forces between hadrons comes from two sources: non leptonic decays of charmed and strange particles and weak asymmetries in hadronic scattering processes. This last class of reactions, which will be discussed below, shows the importance of polarized beams and/or targets\(^{(\#)}\) to identify weak from strong interaction effects, in particular through parity violation effects. These experiments require the measurement of very small asymmetries with longitudinally polarized protons, except for the production of $W^\pm$ and $Z$ where we expect large predictions from the standard WS electroweak model.

2. HELICITY DEPENDENCE OF PROTON–PROTON TOTAL CROSS SECTIONS
Let us consider the weak helicity asymmetry defined as

$$A_L = \frac{\sigma_{\text{tot}}(+) - \sigma_{\text{tot}}(-)}{\sigma_{\text{tot}}(+) + \sigma_{\text{tot}}(-)} \quad (1)$$

where $\sigma_{\text{tot}}(\pm)$ are total $N-N$ cross sections with one of the nucleons in a definite helicity state ($\pm$). This asymmetry is a direct measure of the parity violation effect in a purely hadronic reaction. Two very low energy measurements\(^{1,2}\) of $A_L$ on a hydrogen target give a negative value of the order of $10^{-7}$, which is consistent with theoretical estimates based on an effective parity-violating Lagrangian arising from light boson exchanges. However at Argonne, on a water target for $P_{\text{lab}} = 6$ GeV/c, they have observed\(^{3}\) a positive and large asymmetry

$$A_L = (26.5 \pm 6) \times 10^{-7} \quad (2)$$

This cannot be understood by assuming that the parity non-conserving $N-N$ interaction is dominated by the exchange of $\Upsilon$, $\Phi$ and $\omega$ mesons. It leads to a value of $A_L$ at least one order of magnitude smaller than the data, even after including the strong interaction corrections\(^{4}\). This cannot be explained either in the standard WS electroweak model by invoking only $Z$ and $W$ exchanges between the two interacting nucleons\(^{5}\). This mechanism gives also a contribution to $A_L$ one order of magnitude smaller than the 6 GeV/c data.

\(^{(\#)}\) For recent progress in obtaining polarized beams of high luminosity and new techniques to measure and to keep their polarization, see the other talks at this working group. See also the talks on polarized targets and gas jets.
The experimental result of eq.(2) can be only explained, up to now, by parity violating wave function effects arising from the interaction of Z and W among the three quarks of a single nucleon. This interesting idea has been successfully applied to derive a parity violating N-N potential for the calculation of $A_L$ at very low energies. It deserves further checking for example in elastic N-N scattering or in single particle inclusive production.

3. WEAK ASYMMETRIES IN $\tau^+\tau^-$ 

a) $p \rightarrow nX$ or $n \rightarrow \pi K \rightarrow jet X$

These asymmetries are analogous to that discussed previously (eq.(1)) where $\sigma_{tot}$ is replaced by the single particle inclusive cross section with one hadron in a given helicity state. In the large $p_\perp$ region, this cross section is described by means of the parton-parton scattering process (qq, qg, etc.) determined by adding coherently the strong and the weak amplitudes. The resulting asymmetry comes from the interference term and roughly at the parton level it is of the form

$$a_L \sim \frac{G_F}{\alpha_s} \frac{M^2}{p_\perp^2}$$

where $G_F$ is the Fermi constant and $\alpha_s$ the QCD running coupling constant. Therefore the hadron helicity asymmetry arising from $a_L$ after dilution, is expected to be of the order of $10^{-4}$ and growing with $p_\perp$, which are the mean features of more detailed calculations.

b) $p \rightarrow t\bar{t}X$ (with $2 < M_{t\bar{t}} < 10$ GeV)

The effect in these Drell-Yan reactions comes from the $\gamma^*Z$ interference and it is complementary of the parity violation observed in the deep inelastic scattering, because it involves the spin dependent structure functions of the proton $G_1$ and $G_2$. There is a special physics interest in the $\pi^-p$ collisions where it is possible to separate the spin distributions in $u$ and $d$ quarks. Since in $\pi^-p$ the annihilation $\pi^-p$ dominates, in the asymmetry the $\pi^-p$ drops and one finds roughly

$$A_L^{(u\bar{u})} \sim \frac{G_F}{\alpha_s} \frac{M^2}{p_\perp^2} \Delta_{u\bar{u}}$$

which grows with the lepton pair mass and is completely known from the SLAC experiment. Similarly in $\pi^+p$ dominated by the annihilation $\pi^-d$ one finds

$$A_L^{(d\bar{d})} \sim \frac{G_F}{\alpha_s} \frac{M^2}{p_\perp^2} \Delta_{d\bar{d}}$$

which is another way to learn about the $d$ quark inside a polarized proton.

Finally in pp collisions, since we have both contributions $u\bar{u}$ and $d\bar{d}$, one gets different predictions whether or not the sea is SU(2) symmetric.
4. HELOCITY DEPENDENCE IN W AND Z PRODUCTION AT pp AND pp COLLIDERS

In a Drell-Yan generalized model, the estimated production rates of $W^\pm$ and $Z$ in pp and $p\bar{p}$ collisions are strongly depending on the helicity of the colliding hadrons\(^{12}\). In particular because of the V-A nature of the W couplings, only left handed quarks will produce W and since the quark helicity is strongly correlated to the proton helicity, one expects the W production to come mainly from left handed protons. If we want to detect W and Z by hadronic jets, we must remember that these cross sections are at least two orders of magnitude below the QCD jet cross sections. A practical way to remove this background is to use polarized beams, provided the vector boson peaks remain above the weak asymmetries. Although the situation seems hopeless for a pp collider, in the case of a p\bar{p} collider, both W and Z are expected to give a clear signal in parity violating asymmetries\(^{13}\).

The standard WS electroweak model predicts also very large helicity asymmetries in the leptonic decays of W in $\ell\bar{\ell}$ and of Z in $\ell\bar{\ell}$, if they are produced in polarized hadron collisions\(^{14}\). As we have seen above for the Drell-Yan reactions (eqs. (4) and (5)), the asymmetry in the case of $p\bar{p} \rightarrow Z + \gamma \rightarrow \ell\bar{\ell}$ will grow like $M^2_{\ell\bar{\ell}}$ and it is expected to be as large as 20% at the Z mass as shown in Fig. 1. For the W leptonic decay, if one neglects the sea contribution and if one uses the SU(6) model for the helicity dependence of the quarks distributions, one finds in $p\bar{p}$ collisions an asymmetry of the order of 2/3 for $W^\pm$. This is shown in Fig. 2 for different values of the lepton transverse momentum. In the case of the $W^-$ production the asymmetry is of the order of -1/3.

These examples show the importance of polarized beams for additional tests of the standard model.

**REFERENCES**

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Fig. 1: The parity violating asymmetry in $\bar{p}p \rightarrow e^+e^-X$ versus the lepton pair mass at the CERN collider energy (taken from Ref. 14).

Fig. 2: The parity violating asymmetry in $\bar{p}p \rightarrow W^+W^-X$ versus the polar angle of the lepton in the $W$ rest frame at the CERN collider energy (taken from Ref. 14).
THE ACCELERATION OF POLARIZED PROTONS AT CERN
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The purpose of this paper is three-fold. First, we introduce the reader to the basic problems associated with acceleration of polarized protons. We include a discussion of depolarizing resonances, the behavior of the spin in the neighbourhood of resonance, and the standard cures for the problem of resonant depolarization. The first section is concluded with a discussion of the "Siberian Snake", a "global cure" which is appropriate for large machines such as the SPS. In the next section polarized protons for the PS is discussed with the view towards the SPS. There is much experience which can be directly applied to the PS, and thus the problems associated with such an effort are treated in some detail. Finally, we conclude with a discussion of polarized protons in the SPS. The cure for depolarization selected here is a "Siberian Snake". Details such as the magnets required, location of the device, and mode of operation are discussed.

1. THE BASIC THEORY

To begin recall that a major problem for proton accelerators and storage rings is orbit resonance (both linear and non-linear). For the orbit most of these resonances can be avoided by a careful choice of the frequencies of transverse oscillation. However, for the spin degree of freedom the situation is different because the natural precession frequency increases with energy.

To understand the basic problem consider a circular accelerator. The particles are kept on an essentially circular orbit by a guide field which is mostly a vertical magnetic field. In this field the spin of a particle precesses about the vertical with a frequency

\[ \kappa = \gamma G = \gamma(g/2-1). \]  \( \text{(1)} \)

where \( G = 1.79 \) for protons. More precisely, if the orbit of a particle is bent by an angle \( \Delta \theta_o \), then the spin precesses by an angle

\[ \Delta \theta_{\text{spin}} = \gamma G \Delta \theta_o \]  \( \text{(2)} \)

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when compared to the bent orbit. In a perfectly vertical magnetic field
the motion is a pure precession, and thus, the projection of the spin
vector \( S \) is preserved,

\[
S_z = \text{const.} \tag{3}
\]

Therefore, if a vertically polarized beam were injected, the polarization
would be maintained.

However, the story is not yet complete. In order to keep particles in
the neighbourhood of the ideal orbit, focussing fields are also necessary
(in particular, vertical focussing). So from time to time a particle must
pass through horizontal magnetic fields which bend it back to the
neighbourhood of the design orbit. This causes the spin to precess out of
the vertical. On the other hand, these horizontal fields must average to
zero since the average position is nearly a planar circle.

Thus we have the situation that the field experienced by a particle
on its orbit is a vertical magnetic field plus fluctuating horizontal
fields. This leads to a precession of the spin around the vertical plus
small fluctuations out of the vertical. These fluctuating terms average to
zero unless the precession frequency is the same as the frequency of
oscillation of the horizontal fields (as seen by the particle). If these
frequencies are the same, the resonance condition, then each of the small
precessions around the horizontal axis adds in phase with all of the
others, a situation which can lead to depolarization.

So what are the frequencies at which resonance occurs? The vertical
orbit of a particle in an accelerator is composed of two parts. Let \( z \) be
the vertical deviation from an ideal design orbit. Then

\[
z = z_{CO} + z_8 . \tag{4}
\]

An accelerator is never built quite perfectly. These errors (magnet
misalignments, etc.) drive the oscillations in the vertical direction at
the frequency with which they occur. In terms of the turning angle of the
accelerator, the errors are periodic, and thus a Fourier decomposition
yields all integer frequencies. Thus \( z_{CO} \) (co - closed orbit), the
"inhomogeneous response" of this oscillator, is a function of the
accelerator only, and

\[
z_{CO} \text{ + integer frequencies, } \, k, \tag{5}
\]
"imperfection resonances".
On the other hand, not all particles are exactly on this orbit, and therefore, they oscillate about it with the natural frequency of the focussing system, "the homogeneous solution". This betatron oscillation, \( z_B \), consists of an oscillation at a frequency \( Q \), the vertical tune, modulated periodically in phase and amplitude. Thus, if the accelerator has \( P \) identical periods, then

\[
z_B \propto \text{frequencies } kP \pm Q, \text{ } k \text{ an integer,}
\]

"intrinsic resonances".  

If the imperfections in quadrupole gradients are also included, then the exact periodicity is unity, and we find

\[
\text{Gradient errors, } z_B \propto k \pm Q.
\]

This discussion concerned the orbits, but since the field on the orbit is just linearly related to the orbit, then these are also the frequencies of the magnetic field on the orbit. Of course, the actual situation is even more complex since there are higher order effects also.

The general resonance condition is

\[
k = \gamma G = k_1 + k_2 Q + k_3 Q_X + k_4 Q_S,
\]

where \( Q_X \) and \( Q_S \) are the horizontal and synchrotron oscillation tunes respectively.

To illuminate the problem consider just the imperfection resonances. Then during acceleration a resonance is encountered every .52 GeV, clearly a frequent occurrence for a high energy accelerator. In the next sections we give a quantitative treatment of these resonances to understand depolarization mechanism and to understand the methods that have been developed for avoiding depolarization.

1.1 The Spin Resonance

1.1.1 The Equations of Motion

The spin of a particle, taken as a classical normalized vector, in a static magnetic field obeys the equation

\[
\frac{d\hat{S}}{dt} = \frac{e}{\gamma m c} \hat{S}_x [ (1 + \gamma G) \hat{B}_\perp + (1 + G) \hat{B}_\parallel ]
\]

\[
= \hat{S}_x \hat{A}.
\]

where \( \hat{S} \) is in the rest frame, \( t \) and \( \hat{B} \) are in the lab, and \( \hat{B}_\perp (\hat{B}_\parallel) \) are the components of the magnetic field which are perpendicular (parallel) to the instantaneous velocity. The orbit equations are given by

\[
\frac{d\hat{v}}{dt} = \frac{e}{\gamma m c} \hat{v} \times \hat{B}.
\]

The difference between the bending of the orbit and precession of the spin in a transverse magnetic field is clear from the difference in the coefficients in Eqs. (9) and (10).
It has become customary and also convenient to express the above equations in spinor notation. To do this we let

$$\tilde{S} = \psi^\dagger \sigma \psi$$  \hspace{1cm} (11)

where $\sigma$ stands for the Pauli matrices. Then the equation of motion for $\psi$ is given by

$$\frac{d\psi}{dt} = i \frac{1}{\tau} (\sigma \cdot \Gamma) \psi$$  \hspace{1cm} (12)

Note that Eqs. (11) and (12) are exactly equivalent to Eq. (9).

If in addition we go to a coordinate system which rotates with the velocity of the particle and change the independent variable to the bending angle, then Eq. (12) becomes

$$\frac{d\psi}{d\theta} = i \frac{1}{\tau} \left( \zeta^3 \right) \psi$$  \hspace{1cm} (13)

where $\zeta = -\left( 1 + \gamma G \right) \left( \rho z'' + iz'' \right) + \gamma \left( \frac{1}{2} (1 + G) \left( \rho S'' + iz'' \right) + \text{higher order} \right)$  \hspace{1cm} (14)

Thus, the horizontal fields on the orbit of the particle have been expressed in terms of the vertical deviation from the ideal orbit, $z$, and the instantaneous bending radius, $\rho$. The primes indicate $d/ds$, where $s$ is the distance along the ideal orbit. This expression for the perturbing fields is convenient for calculations since commonly the orbit in an accelerator is well known.

Notice that $\zeta$ has been expressed as a series with coefficients $\epsilon$. In general for the first order effects, we need to include all frequencies mentioned in the introduction. However, it is useful, provided the frequencies are well separated, to consider each resonance separately. To begin, we consider the perfect machine.

1.1.2 The Perfect Machine

For the perfect machine there is only a vertical field; thus, setting $\zeta$ equal to zero in Eq. (13) yields

$$\frac{d\psi}{d\theta} = -i \frac{1}{\tau} \kappa z \psi$$  \hspace{1cm} (15)

which has the solution

$$\psi(\theta) = \exp \left[ \frac{-i}{\tau} \int_0^\theta \kappa d\theta z \right] \psi_0$$  \hspace{1cm} (16)

or if we define (for future reference)

$$\chi(\theta) = \int_0^\theta \kappa d\theta'$$  \hspace{1cm} (17)
then Eq. (16) becomes, explicitly,

$$\psi(\theta) = (e^{-i\chi/2} \sigma_z e^{i\chi/2}) \psi_0.$$  \hspace{0.5cm} (18)

This is a precession around the z axis at an instantaneous frequency, $\kappa$. Thus, the projection on the z axis is preserved, i.e.

$$S_z = \psi^* \sigma_z \psi = \psi_0^* \sigma_z \psi_0 = S_{z0}$$  \hspace{0.5cm} (19)

1.1.3 An Isolated Resonance

The problem for an isolated resonance is only slightly more difficult than that for a pure vertical field. For this problem let $\kappa = \text{const}$ ($\gamma = \text{const}$) and consider one resonance with strength $\epsilon$ at frequency $\kappa_0$ ($\kappa_0$ can be anyone of the resonances discussed previously). Thus, we must solve the equation

$$\frac{d\psi}{d\theta} = \frac{i}{2} \left( \frac{-\kappa}{\kappa_0} \sigma_z \epsilon e^{i\kappa_0 \theta} + \epsilon e^{-i\kappa_0 \theta} \right) \psi.$$  \hspace{0.5cm} (20)

Now change to a coordinate system which rotates at the frequency of the perturbation, $\kappa_0$. In this frame the perturbing field appears stationary rather than oscillating. Explicitly we let

$$\psi = e^{-i\kappa_0 \theta} \sigma_z \frac{\epsilon}{\kappa} \phi$$  \hspace{0.5cm} (21)

and obtain

$$\frac{d\phi}{d\theta} = \frac{i}{2} \left( \frac{-\delta}{\epsilon} \sigma_z \epsilon \phi = \frac{-i}{2} \lambda \left( \hat{n} \cdot \sigma \right) \phi,$$  \hspace{0.5cm} (22)

where

$$\delta = \frac{\kappa}{\kappa_0}, \quad \lambda = \sqrt{\epsilon^2 + \delta^2},$$

$$\hat{n} = \epsilon/\lambda \hat{x} + \delta/\lambda \hat{z}. \hspace{0.5cm} (23)$$

The solution is simply

$$\phi(\theta) = e^{i\lambda \hat{n} \cdot \sigma \theta/2} \phi_0.$$  \hspace{0.5cm} (24)

This is a precession about $\hat{n}$ and the projection along $\hat{n}$ is invariant; however, now $\hat{n}$ is no longer along the vertical. (In addition, if we transform back to the original coordinates, $\hat{n}$ is precessing about the vertical). Thus, the perturbation creates an effective field which is precessing at frequency $\kappa_0$ and tipped out of the vertical by an amount $\epsilon/\lambda$.

Consider the following thought experiment: Let $\delta$ be very large and negative so that $\hat{n} = -\hat{z}$. Now vary $\delta$ adiabatically through zero (resonance) to a large positive value ($> \epsilon$). Then $\hat{n}$ rotates and finally
\( \hat{n} \) and -\( \hat{n} \) change places. However, since it is the projection along \( \hat{n} \) which is preserved, this means that the spin flips. This spin flip is completely analogous to that which takes place in Nuclear Magnetic Resonance.

Thus, we have an interesting situation: if \( \varepsilon = 0 \), then the resonance does nothing; and if \( \varepsilon \neq 0 \), then the spin flips (provided we change \( \gamma \) and thus \( \kappa \) slowly enough to be adiabatic). This is quite a contrast to orbit resonances which can drive the beam out of the beam pipe. In fact this process of adiabatic spin flip was used with some success at the Argonne ZGS\(^2\) and has been used now quite successfully at Saturne II\(^3\).

The question is now to understand what "adiabatic" is in the context of acceleration through a spin resonance. In any system an adiabatic variation is one which occurs during a time which is large compared to the inverse of the frequency. Near a spin resonance the frequency, \( \lambda \), is \( \sim \varepsilon \); \( \varepsilon \) is also the "width" of the resonance since it determines the variation in \( \delta \) necessary to flip \( \hat{n} \). Thus if we change \( \delta \) at rate \( \alpha \) \( (\alpha = d (\kappa-\kappa_0)/d\theta) \), the "time", \( \Delta \theta \), for passage through the resonance is

\[ \Delta \theta = 2\varepsilon/\alpha . \]  

(25)

For this passage to be adiabatic there should be many oscillations within this "time", i.e.

\[ \varepsilon \Delta \theta \gg 2\pi \Rightarrow \varepsilon^2/\alpha \gg \pi . \]  

(26)

Therefore, the resonance must be sufficiently strong or the rate of passage sufficiently slow for spin flip to take place. On the other hand it is clear that if \( \varepsilon \) is small enough, the resonance has no effect at all. The question is then what happens in the intermediate cases; the answer is depolarization.

1.1.4 Passage Through Resonance

The depolarizing effect of a single isolated resonance can be calculated in terms of known special functions in the case of linear variation of \( \kappa \). The result is particularly simple if we integrate the spin motion from -\( \omega \) to \( \omega \); i.e. if we start far from the resonance and end far from the resonance on the opposite side. The depolarization in this case is given by\(^4\)

\[ S_2^{\text{final}} = (2 e^{-\pi \varepsilon^2/2\alpha} - 1) S_2^{\text{initial}} . \]  

(27)
Thus, we see again that the parameter $\epsilon^2/\alpha$ plays the key role. Notice also that both spin flip and non-spin flip are contained in this formula; if $\epsilon^2/\alpha$ is small enough then the polarization is unchanged, while, if $\epsilon^2/\alpha$ is sufficiently large, we find the spin flip described previously. In the first case the spin precession frequency is changing so rapidly that the spin vector does not have time to follow the change in direction of the effective field; while for the second case the change in frequency is sufficiently slow to allow the precessing spin to follow the reversal of the effective field.

1.2 Cures for small machines

There are basically four approaches based on the Froissart and Stora formula, Eq. (27), for eliminating the depolarizing effects of resonances.

a) Make $\epsilon$ small (spin transparency). In the case of imperfection resonances this is accomplished by tuning out the harmonic of the orbit which is causing the trouble by using correction dipoles. In practice, the change in the orbit is so small that the polarization of the beam must be used as an indicator. This method was used quite successfully at the Argonne ZGS and is now used at Saturne II for some of the depolarizing resonances. This method is also planned for the AGS at BNL to tune out the 50 or so imperfection resonances that will be encountered.

In principle this idea can also be used to tune out the effects of intrinsic resonances\(^1\). In this case correction quadrupoles are necessary and the correction requires a calculation with the existing lattice. Correction quadrupoles are also necessary to eliminate the resonances due to errors in quadrupole gradients. Thus far, correction quadrupoles have been used successfully at Saturne II to correct errors in gradients; however, this method has not yet been attempted with intrinsic resonances.

b) Increase $\alpha$. From Eq. (27) we see that decreasing the strength of the resonance, $\epsilon$, is equivalent to increasing the rate of passage through the resonance, $\alpha$. Since there are limitations on the acceleration rate in any accelerator, this method is not very useful for imperfection resonances. However, this method can be and has been used quite successfully for intrinsic resonances. The important difference here is that for intrinsic resonances, the frequency depends upon the vertical tune, $Q$. Therefore, it is possible to cross resonances by changing the tune of the machine abruptly as the precession frequency comes close to a resonance. This is illustrated in Fig. (1). Note that it is necessary to maintain the tune shift for some time until the normal acceleration rate has separated the spin precession frequency from the resonance.
This method has been used quite successfully at the Argonne ZGS and is the method which is planned at the AGS at BNL.6) There are, however, limitations to this method in that the tune shifts must be small enough not to damage the orbit of the beam yet large enough to clear the "tails" of the resonance. Of course, the rate of the tune shift must be quite high also. The design at the AGS is probably close to the feasible limits. In this case the tune shift is .25 in a time of 2 usec. With these finite changes in frequency it is also necessary to use a modified formula for calculating the depolarizing effects7,8).

c) Make $\epsilon$ larger. If an individual resonance is quite strong, then, provided that other resonances are well separated, it is possible to use the resonance to flip the polarization of the beam. This can be accomplished in the case of imperfection resonances by the same method of closed orbit correction; however, in this case the "correction" is shifted in phase to enhance the resonance. This method is used successfully at Saturne II (100 % spin flip).

d) Decrease $\alpha$. By similar arguments one can change the rate of passage through a resonance to enhance its effect. One can, of course, vary the acceleration rate, but in addition it is possible to again use a tune shift to change the rate of passage through the resonance. This method was used with only moderate success at the Argonne ZGS. Based on this ZGS experiences, this method is not the primary one to be used at the AGS.

Finally we mention that there have been new effects observed at Saturne II, most likely due to synchrotron frequency side bands, that have yielded unusual interference effects. These effects have not limited performance.

1.3 The cure for large machines - the "Siberian Snake"9,13

For high energy accelerators or storage rings such as FNAL and the SPS at CERN, there are hundreds of resonances which are stronger than those for lower energy machines. Thus, the standard approaches of resonance jumping and spin flip are not so attractive. In particular, resonance jumping becomes technically unfeasible. One can imagine a spin flip at each resonance; however, a global solution which would eliminate all the resonances is desirable. This solution exists in the form of the "Siberian Snake".

To understand the basic principle consider Fig. (2) (taken from Ref. 10). Assume that at the point $S$ on the circumference of the accelerator there is a device which: a) precesses the spin by $180^\circ$ around the longitudinal direction, and b) yields no net orbit deflection or displacement.
Now imagine the spin of a particle pointing in some arbitrary direction traversing the ring once, from the point A and back. During this circuit the spin gets precessed first by an angle around the z axis

$$\Delta \theta_{1/2} = \gamma G \pi,$$

then it gets precessed around the longitudinal axis by

$$\Delta \theta = \pi,$$

and finally it once again precesses by $\Delta \theta_{1/2}$ in returning to its starting point. Fig. 2 shows how each of the three projections of the spin are treated by such a succession of transformations. The key point is that the snake effectively reverses the vertical direction so that the two $\Delta \theta_{1/2}$ precessions exactly cancel, with the net effect that the spin is rotated about the longitudinal direction by 180°. Thus, as you see in Fig. 2 the longitudinal projection of the spin is preserved at the point A. In addition, the spin tune, as been changed to $Q_p = 1/2$ independent of energy.

Thus the normal precession frequency has been changed to a non-resonant point independent of energy and the mode of operation has been changed; a polarized beam is injected so that it is longitudinal at the point A. Knowing the polarization at A, it is then easy to calculate it (as a function of energy) at other points in the ring.

There are still problems associated with the operation of a snake. The general resonance condition in Eq. (8) becomes

$$\frac{1}{2} = k_1 + k_2 Q_z + k_3 Q_x,$$

neglecting $Q_S$. Thus the choice of tunes is limited by the avoidance of the condition in Eq. (30). This corresponds to more forbidden lines in two dimensional tune space. The design of the snake is not difficult and simply requires free space and aperture. The aperture is necessary because although the precession of the spin in a transverse magnetic field is independent of energy, the bending angle of the beam is not. Thus the excursion of the beam varies with energy. This and other questions regarding a snake for the SPS are discussed in Section 3.

2. POLARIZED PROTONS IN THE PS

Polarized protons for the SPS would have to pass through its injector, the PS. The hardware and effort needed to inject polarized protons into the PS and to accelerate them up to a suitable transfer energy, say 15 GeV, can be "scaled" from the work done at Saturne II to reach 2.4 GeV and from the programme which is under way at Brookhaven to reach 25 GeV in the AGS with 80 % polarization. In addition, information can be drawn from a feasibility study of polarized beam acceleration in the PS which was performed in 1975\textsuperscript{11}. In the following subsection we
recall the conclusions of this 1975 study and update them in the light of recent experience at Saturne II and the AGS.

2.1 Components necessary for polarized beam acceleration (PS)

A source of polarized protons would have to be developed (or purchased) and installed on the high voltage platform of the Linac. Presumably Linac 1 (the good old PS Linac) would be used leaving the new Linac 2 as the normal proton injector. As Linac 1 might still be busy supplying test protons and negative hydrogen ions for LEAR and also light ions for the PS and SPS, a careful scheduling is necessary.

In this context the development of an RF quadrupole section for the Linac front end (presently under study) would be helpful. This allows the source to be at (almost) ground potential rather than at 750 kV, thus permitting a rapid switch over from one source to another.

Polarized beam from the Linac could be injected into the PS at 50 MeV, where multturn injection (about 10 effective turns) would have to be rejuvenated. The alternative of going first to the PS booster should, however, be reevaluated. This would simplify the PS cycle and probably permit an easier multturn injection. In the 1975 study the detour via the booster was not judged to be worthwhile.

Once in the PS the main problem is to avoid the resonant depolarization mentioned in the first section. From Fig. 3 (from Ref. 11) one concludes that 6 intrinsic resonances must be crossed up to 15 GeV and 2 more up to 24 GeV. Of these 6(8) resonances at least 4(6) seem capable of strong depolarization. From the first section recall three of the standard cures for intrinsic resonances: 1) Spin flip with possible enhancement of the depolarizing field, 2) correction of the resonant harmonics causing depolarization and 3) resonance jumps by rapid tune changes. The last two, and probably the first one, of these methods require correction quadrupoles, but only the tune jump relies on rapid pulses which require expensive magnets and expensive power supplies. We would therefore aim to use the first two methods as much as possible, especially for the resonances at higher energy, where tune jumps are very demanding. In fact, a fair amount of the Brookhaven effort goes into the combination of very fast and powerful tune jump lenses. Limiting our scope to injection for the SPS, we would hope to avoid this difficulty.

The next problem to deal with is the imperfection resonances which are driven by errors in the bending field. In Fig. 4 (also from Ref. 11) the strengths of these resonances is illustrated. We plot the concurrent harmonics of the vertical distortion of the closed orbit in the PS calculated (using the smooth approximation) for an rms magnet misalignment of 0.1 mm. The programme at Brookhaven aims for a similar
precision as it seems well feasible with present day survey techniques. One concludes from Fig. 4 that an even better alignment and stability of the magnet position is desirable (say 0.05 mm) to keep the depolarizing effects below the 1% level.

Figure 5 gives the results of an orbit measurement\textsuperscript{12}) performed in 1975. It is clear from this picture that the field errors at that time corresponded to position errors in excess of 0.1 mm. To be able to relax the alignment and stability problem, it is important to have a means of tuning out the imperfection resonances.

As indicated in the first section this is accomplished by using correction dipoles. Since the corresponding orbit distortion is unobservably small at high energy, the standard approach is to monitor the beam polarization to judge the success of the orbit correction. An internal polarimeter such as the one being developed at Brookhaven will be indispensable in saving time. The method of ejecting the beam near each resonant energy as used at the Argonne ZGS and at Saturne seems prohibitive in our case.

In principle, two dipoles per resonance are required to cancel the driving harmonic both in amplitude and phase. Since the compensation at a given harmonic needs only to be efficient when the beam is close to a resonant energy, the same dipoles equipped with programmable supplies can be used to compensate several harmonics one after the other.

2.2 Operational aspects

The PS has and will have a complicated supercycle, where 10 GeV (or 14 GeV) pulses for the SPS or 26 GeV pulses for antiproton production may alternate with $\bar{p}$ deceleration to 200 MeV for LEAR or electron and positron transfer for LEP. The depolarizing resonances are closely linked to the magnetic conditions of the machine which in turn depend critically on the history and the form of the supercycle. For normal operation small changes of the magnetic conditions are unimportant, but for the accuracy of tuning out field errors as required for polarized beam acceleration special care is indispensable.

Probably "quiet" periods have to be chosen, where the same supercycle can be used for days or weeks. A special "polarized beam cycle" has to be included, which is used to set up the polarized acceleration during normal operation employing the pulse to pulse modulation facility of the PS. This will permit the long machine developments (hopefully) unnoticed by the other PS users.

To tune out depolarizing resonances, it will be desirable to have small flat tops at certain energies so that a fair amount of flexibility of the "polarized beam cycle" will be required. Clearly in all these respects the PS as a multipurpose machine is in a more delicate situation than the AGS or Saturne.
Other scenarios are possible such as having long dedicated periods of polarized beam only, especially if the setting up turns out to be more time consuming than foreseen. Surely these operational aspects need great attention and further study before polarized acceleration could be implemented.

From Figs 3 and 4 it is clear that the number and the strength of depolarizing resonances increases as one goes up in energy: 15 GeV/c seems still feasible with a fair amount of work, but at 24 GeV/c the very strong structural resonance $\gamma G = 50 - Q$ introduces a "natural" limit.

2.3 Performances to be expected

The intensity in the PS can be estimated to be $10^{11}$ polarized protons per 1 mA source current. This assumes multishot injection (10 effective turns) and 50 % overall efficiency from the source to the PS. For normal protons which are produced abundantly, this efficiency is more like 20 %. Present day ground state sources give about 0.1 mA - 0.2 mA polarized protons in a pulse length much exceeding the 100 $\mu$s sufficient for our purpose. Improvements by a factor $> 10$ have been discussed. Thus one can hope for $10^{11}$ and may be even for $10^{12}$ polarized protons per PS pulse. Filling the SPS with several PS pulses one could then have SPS intensities almost comparable to normal proton runs. The AGS programme calls for charge exchange injection of polarized negative hydrogen as it uses the same technique for normal running. This will permit hundred or several hundred turn injections at 200 MeV and thus a $\sim 10$ fold gain in intensity if the $\text{H}^-$ source can give a current comparable to an $\text{H}^+$ source. At the PS and its booster charge exchange injection is not foreseen and it might be difficult to find space if one wanted to implement it.

The energy of the polarized PS beam could be between 14-24 GeV as discussed above depending on the effort available and the success in compensating resonances on a busy multi-purpose machine. As to the degree of polarization, the work at the ZGS and at Saturne has shown that 75 % polarization can be preserved up to high energy, provided the resonances are carefully tuned out.
To summarize prospects for the PS we refer the reader to the following two tables:

**TABLE 1**

Hardware and effort for PS polarized protons


2. Internal polarimeters.

3. Precise magnet alignment.

4. Installation of special cycle into PS-supercycle.

5. Correction dipoles and their supplies to tune out imperfection resonance (maybe existing ones can be used).

6. Slowly pulsed quadrupoles to tune out intrinsic resonances.

7. Eventual fast tune-jump quadrupoles.

8. Lots of machine development time under well defined magnetic conditions.

**TABLE 2**

Performance for the PS

Intensity: $10^{11}$ $p^+$ per 1 mA source current

assumptions: 10 turn injection
50% overall efficiency
(at present 20%)

* present day sources: ~ 0.1 mA
improvements by > 10 discussed at this workshop

* H$^-$ injection into PS not foreseen.

Energy: 14-24 GeV
depending on effort and luck

Polarization: 75%.
3. **POLARIZED PROTONS IN THE SPS**

The acceleration of polarized particles has never been achieved in large accelerators and no such project is actually under way, but studies have been made for the FNAL machine, for ISABELLE and for LEP. Although no detailed study has been done yet for the particular case of the SPS, we shall elaborate here mainly on the possible implementation of a Siberian snake which seems to be a necessary and probably sufficient device to prevent depolarization during the acceleration in the SPS.

In order to avoid a too large aperture in the snake magnets, which are described below, injection should be done at the highest possible energy that the PS can provide. The present multturn extraction system from the PS can go to 14 GeV/c only, and we shall assume this energy for transfer. Since the SPS injection system can stand no more than 11 us pulses filling half the machine circumference, two or three batch injections from the PS would be required as it is the case for normal proton physics.

The intensity of more than $10^{11}$ particles foreseen in Section 2 would pose no particular problems for monitoring nor for acceleration. An additional spin matching section would have to be implemented in the transfer line so that the protons reach the SPS with the right spin direction.

If we consider an injection at 14 GeV/c and an acceleration to top energy, the number of depolarizing resonances to go through is considerable:

\[ \sim 800 \text{ imperfection resonances } (\gamma G = k) \]

\[ \text{many intrinsic resonances } (\gamma G = kE \pm qE) , \]

and the methods which are adopted for lower energy machines exemplified in Sections 1 and 2 above (Q-jump, spin transparency and spin flip), can probably not be applied because of the high number of parameters involved.

Fortunately in big machines the space for a Siberian snake (of the order of 20 m) can be found without too much trouble, and we are going to describe this possibility for the SPS in some detail.

Various combinations of transverse rotations of the spin by $\pi/2$ or $\pi/4$ have been invented by several authors to produce the wanted overall rotation of $\pi$ around the beam direction. Among the schemes presented by Teng\textsuperscript{13}) we choose the snake by Steffen\textsuperscript{18}) which seems the most economical in terms of the necessary magnetic field volume.
This snake, illustrated in Fig. 6, would consist of ten dipoles distributed over 20.5 m and is computed for an injection momentum of 14 GeV/c. The excursion of the closed orbit is antisymmetric along the first half and the second half of the snake, which can be used to minimize the required aperture by an appropriate decentering (see Fig. 7). Knowing the nominal aperture of the SPS one can establish that 200 mm diameter is adequate to contain the envelope of the beam in the two halves of the snake.

A preliminary study of the snake dipoles has been made (Ref. 15) and the most significant parameters are shown in the following Table.

**TABLE 3**

Snake dipole magnets

<table>
<thead>
<tr>
<th>Type</th>
<th>Short Dipole</th>
<th>Long Dipole</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>Spin rotation angle</td>
<td>(\frac{\pi}{4})</td>
<td>(\frac{\pi}{2})</td>
</tr>
<tr>
<td>(J_{Bd1})</td>
<td>1.375 Tm</td>
<td>2.75 Tm</td>
</tr>
<tr>
<td>Gap diameter</td>
<td>200 mm</td>
<td>200 mm</td>
</tr>
<tr>
<td>Overall length</td>
<td>1'250 mm</td>
<td>2'000 mm</td>
</tr>
<tr>
<td>Width</td>
<td>1600 x 850 mm</td>
<td>1600 x 850 mm</td>
</tr>
<tr>
<td>Weight</td>
<td>8.4 t</td>
<td>15.5 t</td>
</tr>
<tr>
<td>Total snake power</td>
<td></td>
<td>1.5 MW</td>
</tr>
<tr>
<td>Power for SPS physics</td>
<td></td>
<td>80 MW</td>
</tr>
</tbody>
</table>

Since these magnets will be used at a unique field level the uniformity of \(J_{Bd1}\) needed for the machine can be reached by shimming.

A possible location for the snake in the SPS would be in LSS4 as shown on Fig. 8 and Fig. 9. Consequently the spin is invariant in LSS1, which is ideal for injection, but it changes direction with momentum at the extraction points in LSS2 and LSS6. Therefore, quantized extraction energies would have to be selected (modulo 1.5 GeV/c) in order to get the same spin alignment. This departure of the extraction points from the spin invariant point also introduces some depolarization due to chromatic smear-out estimated to be less than 10 % for both extraction points.

If only the extraction from LSS2 was considered, the snake could be located in LSS5 and there would be no energy quantization nor chromatic depolarization.

Slow extraction from the SPS will be delicate to tune to get a good effective spill when the total intensity is only a few percent of the normal proton intensity. No doubt some work will have to be done there.
Thereafter the transportation of p+ would pose no problem in the primary beams, and would end up with a beam split in three parts in the North Area and a unique beam in the West Area. These four beams would by-pass targets T2, T4, T6 and T1 respectively and would then be channelled into the secondary beam lines which all can stand the top energy of 450 GeV/c. The intensity of these beams could then be modulated according to the experimental needs with Be attenuators. For those beams used at more than 10^8 p+ per pulse, special shielding would have to be provided in EHW1 and EHN1. Spin matching sections would be implemented in front of each experiment in order to match the spin direction with the needs of the detector geometry. But the frequent spin flip necessary during the data taking to avoid systematic errors would be provided at the p+ source.

The implementation of a snake in the SPS would not be a negligible project, but it could be done in stages. Each dipole magnet would first have to be carefully measured in the laboratory in presence of the two adjacent magnets because of their mutual influence on the fringe field. The $\beta$81 could be adjusted by shimming and the higher order field components could be reduced to acceptable levels.

The snake magnets could then be installed in the SPS tunnel during a yearly shut-down and their transparency for normal proton acceleration could be tested during MD sessions. The beam behaviour could reveal some effects which would require further shimming. And only when proton acceleration would be perfect with the snake on would one begin with the injection of polarized protons.

The study with polarized protons would have to rely on a means to measure the beam polarization during the whole acceleration cycle and we understand that the experimental physicists would have to provide an adequate instrument to do so. UA6 detector is not ideally located since it is far from the position with invariant spin direction.

Let us mention here some further studies that are still to be made before any decision could be taken.

**Further steps to implement p+ in the SPS**

i) An evaluation of the SPS resonances with the computer programme of E.D. Courant (DEPOL),
ii) an optimization of the snake taking into account the real optics of the SPS machine,
iii) a study of the spin matching sections both for the transfer from the PS to the SPS and in the beam lines leading to experiments,
iv) a design of an internal polarimeter (would UA6 be adequate?),
v) a cost estimate.
4. CONCLUSIONS

PS machine

1. Acceleration of p⁺ to a respectable energy in the PS seems technically feasible.

2. A certain amount of hardware and careful ways of operating the PS are necessary to avoid resonant depolarisation.

3. A large amount of machine development time is indispensable to implement such a project. Fascinating, but "staff intensive" accelerator physics.

4. The outcome of the AGS-project will permit more precise conclusions.

5. Items which should be developed in advance are source and internal polarimeter.

SPS machine

6. Acceleration of p⁺ in the SPS seems technically feasible.

7. It would rely upon the implementation of a Siberian snake.

8. MD sessions and successive shimming of the snake magnets will be needed to reduce higher order effects.

9. An internal polarimeter is essential to keep track of the beam polarization and is to be provided.

REFERENCES


5. As pointed out by Alex Chao.


15. A. Arn, J. Vlogaert, CERN/SPS/EMA/Note 83-3.
Normal acceleration

\[ K_0 = K + Q_z \]

\[ K = G \cdot \gamma (\ast) \]

Insert \( \Delta Q_z \) at resonance

\[ K_0 = K + Q_z \]

\[ K = G \cdot \gamma (\ast) \]

\[ \Delta Q_z \]

Fig.1: Resonance jump
Fig. 2 The Principle of the Siberian Snake
Intrinsic depolarising resonances in the PS

The bars give the harmonics of the vertical betatron oscillation. The tolerance curves are for large amplitude particles (2 x rms width of the beam).

Fig. 3
Steffen’s snake adapted for the SPS

Fig. 6
Fig. 7 - SPS tunnel cross section

Fig. 8 - Layout of the Siberian snake in the SPS
Fig. 9. Layout of the snake in the SPS machine
CROSSING OF DEPOLARIZATION RESONANCES AT SATURNE (SACLAY)

E. Grorud and A. Nakach
LNS, CEN-Saclay, 91191 Gif-sur-Yvette Cedex, France.

. 1975 : Theoretical analysis and computations (Leleux) showed that spin flip should occur on most of the resonances, Saturne being a quite strong focusing machine. Depolarizing transverse fields due to the main quadrupoles (defocusing)

. 1981 1982 : Resonance crossing experiments. Partial and complete spin flip have been observed throughout the acceleration up to 2.4 GeV. Corrections were made to achieve 78 % polarization at 2.4 GeV. Now 80 % polarization is obtained in the whole energy range from 500 MeV to 2.4 GeV.

. 1982 : Physics experiments with \( \hat{p}, \hat{\Omega} \) are regularly planned and performed from 500 MeV up to 2.4 GeV (30 % of operational time is dedicated to \( \hat{p}, \hat{\Omega} \)).

RESONANCES IN SATURNE (Fig. 1)

1. Closed orbit resonances : \( \gamma G = n \)
   \( \gamma G = 2, \ldots, 7 \)  
   (closed orbit amplitude) (vertical)

2. Systematic linear resonances : \( \gamma G = v_z, 8-v_z \) (main QP)

3. Non systematic resonances (noticeable) :
   \( \gamma G = 7-v_z, v_z+1, v_z+3 \)  
   (Difference between fields)

4. Non linear resonance \( \gamma G = 11-v_x-v_z \) (Sextupolar field)

How to deal with a resonance?  (Strength - crossing speed)

. Action on resonance strength by correction circuits
   - Creation of a field directly opposed to the depolarizing field \( \rightarrow \) Polarization remains unchanged.
   - Increase the depolarizing field in order to reverse the spin \( \rightarrow \) Polarization changes sign but keeps the same modulus (spin flip).

. Action on crossing speed
   - Increase of the crossing speed by changing \( \hat{b} \) or \( \hat{\nu} \). Polarization remains unchanged.
   - Decrease of the crossing speed. Spin-flip.

. When extraction near a resonance is needed, one can push the resonance further away by changing the vertical tune (impossible for closed orbit resonances).
Deuterons

The only two resonances to be considered in the energy range \( W \leq 2.3 \text{ GeV} \) are:

1. \( \gamma G = v_z^{-4} \) if \( v_z > 3.72 \) (standard \( v_z = 3.6 \))
2. \( \gamma G = 7 - v_z^{-2} \). This resonance has been experimentally checked and no depolarization has been noticed.

It is then quite sure that no resonance strong enough to depolarize the beam appears in the energy range.

In fact, full polarization has been reached up to 2.3 GeV.

**Resonance strength in Saturne**

Froissart and Stora: \( P = P_o \left( \frac{2e^{-A^2}}{A^2} - 1 \right) \)

(isolate resonance)

can be written as: \( P = P_o \left( 2e^{-\frac{\pi e^2 \omega_o}{2(\gamma G+5)}} - 1 \right) \)

\( \omega_o = \frac{8c}{K} \): revolution frequency

\( e \): resonance strength

\( \gamma G+5 \): crossing speed

<table>
<thead>
<tr>
<th>( \gamma G )</th>
<th>( A^2 )</th>
<th>( e )</th>
<th>( \gamma G )</th>
<th>( A^2 )</th>
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<td>2</td>
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<td>6 (-v_z)</td>
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<td>( v_z )</td>
<td>1200</td>
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<td>7</td>
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<tr>
<td>4</td>
<td>&gt;5</td>
<td>&gt;1.65 \times 10^{-3}</td>
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<td>8 (-v_z)</td>
<td>746</td>
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<tr>
<td>( v_z+1 )</td>
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<td>2.2 \times 10^{-4}</td>
<td></td>
<td></td>
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<tr>
<td>5</td>
<td>&gt;5</td>
<td>&gt;1.65 \times 10^{-3}</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
For Saturn: depolarizing 'zone':

1% depolarization: \( A^2 = 5 \times 10^{-3} \) \( \epsilon = 5 \times 10^{-5} \)

99% complete spin flip: \( A^2 = 5 \) \( \epsilon = 1.65 \times 10^{-3} \)

Then for \( 5 \times 10^{-5} < \epsilon < 1.65 \times 10^{-3} \) we observe all the possible depolarizations.

![Diagram of depolarization resonances in Saturn](image)

**Fig. 1** Depolarization Resonances in Saturn

(1): \( \text{GAMMA} \times G = 2 \) (0.198 GeV)

(2): \( \text{GAMMA} \times G = 3 \) (0.631 GeV)

(3): \( \text{GAMMA} \times G = 7 - \text{NUZ} \)

(4): \( \text{GAMMA} \times G = 4 \) (1.154 GeV)

(5): \( \text{GAMMA} \times G = 8 - \text{NUZ} \)

(6): \( \text{GAMMA} \times G = \text{NUZ} + 1 \)

(7): \( \text{GAMMA} \times G = 5 \) (1.671 GeV)

(8): \( \text{GAMMA} \times G = 6 \) (2.201 GeV)

(9): \( \text{GAMMA} \times G = 7 \) (2.274 GeV)
BEAM POLARIZATION MEASUREMENTS AT HIGH ENERGY

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The absolute calibration and the monitoring of the polarization of high energy (accelerated, stored, extracted or secondary) polarized proton beams are non-trivial and can be crucial for the correct handling of the polarized beams and for the accuracy of spin dependent experiments.

According to their application, various types of polarimeters have been envisaged and can be classified as absolute or relative, instantaneous or continuous. Typically, for tuning accelerated polarized beams, fast, relative polarimeters are adequate and can be even destructive for the beam. Alternatively, for monitoring spin experiments, both with stored and extracted (or secondary) polarized beams, relative polarimeters of continuous type, introducing minimum perturbation of the beam, are preferable.

Absolute calibration of beam polarization is achieved by measuring with high accuracy a process where spin dependence is precisely calculable or accurate measurements have been performed with a polarized target.

Beam polarization is obtained from the asymmetry of numbers of events measured with been polarization in opposite directions \( P_B = \frac{1}{A} \frac{N^+ - N^-}{N^+ + N^-} \); the accuracy on beam polarization is \( \delta P_B = \frac{1}{\sqrt{A}} \).

Requisites for polarimetric processes are:

a) large (and well known) analyzing power \( A \) and cross-section \( \sigma \), possibly weak energy dependence;

b) minimum perturbation of the beam (continuous monitors);

c) clear signature of the events, to be detected with a relatively simple apparatus.

Various methods for measuring the polarization of high energy proton beams have been proposed \(^1\); the most dependable involve measurements of processes directly related to electromagnetic interactions, which are calculable with great accuracy.

A - SCATTERING OF THE POLARIZED PROTON BEAM ON POLARIZED ELECTRONS \(^2\): double spin asymmetries \( A_{\text{LL}} \), \( A_{\text{NN}} \), \( A_{\text{LS}} \), calculated in QED using the electromagnetic proton form-factors, are large at backward CM angles, with little variation over wide energy ranges. (Fig. 1).

An interesting feature of these observables is that while \( |A_{\text{NN}}| \) is larger than 50 % between 10 and 30 GeV/c, \( |A_{\text{LL}}| \) and \( |A_{\text{LS}}| \) are large for \( p_0 > 30 \) GeV/c up to the maximum energies and therefore this method would be applicable to a scheme where N-polarized protons are accelerated up to 15 GeV/c in the PS and are then transferred to the SPS (equipped with a Siberian Snake) where polarized protons will be in L- or S- directions.

\(^1\) First label refers to electron spin, second to protons; L indicates spin aligned with beam direction, N and S indicate spin transverse to beam direction, in the vertical and horizontal plane respectively.
At $s = 1$ GeV$^2$ the elastic $\pi e$ cross-section integrated over the backward angles of relevance is approximately $10^{-30}$ cm$^2$.

As external beam polarimeter a longitudinally magnetized iron foil (5\mu thick) would provide a target with $10^{21}$ electrons/cm$^2$ with about 8\% polarization; about $10^5$ events are needed for a precision $\delta P_B \approx 0.05$. With a polarized beam of $10^{10}$ pol. protons sec$^{-1}$ this is achieved in about 3 hours. High precision magnetic analysis and particle selection will be required to suppress the large hadronic background from nuclei.

As internal polarimeter for accelerated or stored beams, an L-polarized electron pulsed beam (or a low-energy storage ring) intersecting the circulating polarized proton beam would have better conditions: polarization close to 100\% and negligible hadronic background; separation of scattered electrons from the main proton beam can be a problem. In the hypothesis of $10^{11}$ electrons/cm$^2$ in a 2m long intersection region, with $10^{15}$ stored protons, a beam polarization measurement with $\delta P_B = \pm 0.05$ would take about one hour.

**B - ELASTIC SCATTERING OF POLARIZED PROTONS ON PROTONS AT SMALL ANGLES** : while the analyzing power for pp elastic scattering at intermediate angles is steadily decreasing with energy, indicating an asymptotic vanishing of the hadronic spin-flip amplitude, it has been pointed out that in the Coulomb-Nucleon interference region ($|t| = 10^{-3}$ GeV$^2$) there should be a significant polarization (Fig. 2) due to the interference between the hadronic non-flip amplitude and the electromagnetic spin-flip amplitude, originating from the interaction between charge and anomalous magnetic moment.

Very accurate calculations of this effect, taking into account higher order corrections, exist in the literature (4); recently also possible contributions coming from the single helicity-flip amplitude (expected to become negligibly small at high energy) have been estimated (5), indicating that the asymptotic value for the asymmetry is indeed approached with a weak energy dependence.

The elastic cross-section in the Coulomb region ($0.001 < -t < 0.01$ GeV$^2$) is about 1 mb giving, with a luminosity of $10^{30}$ cm$^{-2}$ sec$^{-1}$, about 100 events/sec. With $A = 0.05$ a beam polarization calibration with an accuracy $\delta P_B = \pm 0.05$ would be obtained with about $10^5$ events, taking a few minutes.

The measurement could be performed at high rates with relatively simple equipment: for external beams a small acceptance, high resolution spectrometer complemented with a recoil sensitive target (6) would be adequate, while for an accelerated or stored beam a jet target with semiconductor detectors to measure the recoil protons would be used (7).

**C - COULOMB DIFFRACTIVE DISSOCIATION** (8) : the process $pA \rightarrow p\pi^0A$ can be related via Primakoff effect to the low energy photoproduction $\gamma p \rightarrow \pi^0p$ (9). For this reaction the polarized target

---

\* This would be only one of the many interesting applications of the jet target facility for SPS, in connection with spin physics; for what concerns the specific subject discussed here, the same device operated in polarized mode (also planned in ref. (7)) would allow to measure the same analyzing power with unpolarized beam and polarized target at all energies in the SPS range, thus providing an excellent reference for the beam polarimeter.
asymmetry has been measured in a wide range of photon energies (400 - 1500 MeV). In particular, around 600 MeV, corresponding to \( M_{p\gamma} \approx 1400 \text{ MeV} \), such asymmetry is approximately 80 % at angles close to 90° between the photon and pion. The cross-section of Primakoff effect on Pb is about 20 mb at 200 GeV/c in the \(|t|\)-range where it is possible to clearly separate Coulomb production from strong diffractive processes (\(|t'|<0.001 \text{ GeV}^2\)).

By using a Pb foil target and selecting \( M_{p\gamma} \approx 1400 \text{ MeV} \), the measurement of the pion angular distribution in the Gottfried-Jackson frame would allow to determine the beam polarization: the final state \( p\pi^0 \) system has to be detected with high angular (\( \approx 0.01 \text{ mrad} \)) and momentum (\( \pm 3 \)) resolution in a small acceptance apparatus consisting of a spectrometer for the proton and a shower counter for the pion.

A measurement of beam polarization with \( 10^7 \) incident polarized proton/spill will give \( \delta p_B = \pm 0.05 \) in about 10 pulses.

The measurement is undoubtedly delicate but seems rather promising for calibration of external beams and possibly also for internal machine polarimeters, in the case where a metal vapour jet target could be used.

D - INCLUSIVE PROCESSES:

Large asymmetries (\( \approx 30 \) - 50 %) have been observed in inclusive production of pions up to 24 GeV/c.

If these asymmetries remain large at higher energies these processes might be used for monitoring the beam polarization stability.

A precision of \( \pm 0.05 \) in beam polarization will be achieved in about 100 pulses of \( 10^7 \) polarized protons with large \( X \), small \( p_T \pi^- \) production \(^1\) and in about \( 2 \times 10^5 \) pulses for \( x = 0 \), large \( p_T \), \( \pi^0 \) production.

Both reactions can be detected with relatively simple apparatus involving in one case a spectrometer and Cerenkov counters, and shower counters in the other case.

Also, in the process \( pp \rightarrow \Lambda^0 X \), it can be speculated that the fast forward hyperon retains the polarization of the parent proton; if this is the case the \( \Lambda^0 \rightarrow p\pi^- \) decay distribution would be an excellent analyser of the proton beam polarization, both transverse and longitudinal.

The cross-section in the forward direction is about 0.1 mbarn; about 200 events could be counted in a small acceptance spectrometer for \( 10^7 \) polarized protons/spill on a 1 m liquid hydrogen target; a precision of \( \pm 0.05 \) in beam polarization could be obtained with 20 machine pulses, in the hypothesis that the polarization transfer parameter from proton to \( \Lambda^0 \) is larger than 50 %.

E - OTHER METHODS specific to accelerated or stored beams have been discussed:

- it has been suggested that the loss of polarization when crossing depolarizing resonances in an accelerator may be practically the same during acceleration and deceleration.

This would allow to measure the beam polarization first at sufficiently low energy with standard polarimeters, then accelerate to full energy and finally decelerate to the same
low energy and perform a second measurement: the high energy polarization will certainly be intermediate between these two results\textsuperscript{(*)}.

It would certainly be appealing to use some "macroscopic" method to measure the beam polarization\textsuperscript{(**)} (for instance via NMR or similar techniques): up to now the polarized beam intensities seem too small for this purpose.

CONCLUSIONS

One of the major concern of experimentalists planning experiments with polarized proton beams at high energy, the rapid and precise determination of beam polarization during the tuning of the beam and the running of experiments, might find a variety of solutions and the methods listed in Table I are only indicative of a number of polarimetric processes which are worth consideration.

Some of these methods are envisaged for the FNAL secondary beam originated from $\Lambda^0$ decay, where beam polarization is already well defined by the geometry of the beam: a comparative study of various possibilities would then be possible.

In Table I are also listed developments needed to bring the proposed high energy polarimeters to the stage of reliability and rapidity presently achieved at the various lower energy laboratories.

\textsuperscript{(*)} It has been proposed to test this method at Saturne II.
\textsuperscript{(**)} This point was raised during the workshop by M. Svec.
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   (16-22 Sept. 1982).
   Brookhaven Nat. Lab.

2) This method has been discussed during the workshop by J. SOFFER, on the basis of:
   Also private communication by L. DICK.


5) N.H. BUTTOMORE, Proc. of the 5th Int. Symposium on High Energy Spin Physics
   (16-22 Sept. 1982).
   Brookhaven Nat. Lab.

6) H. AZAIEZ et al., Proc. of the 4th Int. Symposium on High Energy Spin Physics,
   Lausanne, 497 (1980).


8) D.G. UNDERWOOD, ANL-HEP-PR-77/56.


<table>
<thead>
<tr>
<th>POLARIMETRIC PROCESS</th>
<th>ANALYZING POWER AP</th>
<th>USEFUL INTEGRATED CROSS-SECTION (at 200 GeV/c)</th>
<th>APPARATUS</th>
<th>TIME FOR $\pm 0.05$ ERROR IN $P_B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic $p\rightarrow p$ backward angles (QED+proton F.F.)</td>
<td>$A_{NN}^L \sigma L, A_{LL}^L \sigma L &gt; 0.5$ (10-30, &gt;60 GeV/c) Magn. iron foil AP=0.03 Pol. el. string AP=3</td>
<td>$\sim 10^{-3} \ \text{cm}^2$</td>
<td>High res. spectrometer el./hadron discrimin.</td>
<td>1 hour</td>
</tr>
<tr>
<td>Elastic $p\rightarrow p$ forward angles (Coul. Nucl. Interf.)</td>
<td>$A_N = 0.05-0.03$ ($0.02 &lt; t &lt; 0.02 \text{ GeV}^2$) &gt;20 GeV/c</td>
<td>$\sim 10^{-27} \ \text{cm}^2$</td>
<td>High res. spectrometer Recoil lens target or Jet target+semiconductor detectors for recoil</td>
<td>&lt;30 min</td>
</tr>
<tr>
<td>Coulomb diffract. prod. $pPb\rightarrow pX Pb$ (Primakoff effect)</td>
<td>$T(\theta_{gg}) = 0.8$ ($\theta_{gg} = 90^\circ, M_{XX} = 1.4 \text{ GeV}$)</td>
<td>$\sim 10^{-28} \ \text{cm}^2$</td>
<td>High res. spectrometer * = photon detect.</td>
<td>(1 min)</td>
</tr>
<tr>
<td>Inclusive process:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$pp\rightarrow \pi X$</td>
<td>$A_N = 0.35$ (12 GeV/c) ($x &gt; 0.1, p_t &lt; 1.5 \text{ GeV/c}$)</td>
<td>$\sim 10^{-29} \ \text{cm}^2$</td>
<td>Spectrometer (forward detector?)</td>
<td>5 min</td>
</tr>
<tr>
<td>$pp\rightarrow \Lambda X$</td>
<td>$D_{NN}^L = 0.4$ (12 GeV/c)</td>
<td>$\sim 10^{-30} \ \text{cm}^2$</td>
<td>Cerenkov counters</td>
<td>&quot;</td>
</tr>
<tr>
<td>$pp\rightarrow \Lambda X$</td>
<td>$A_N^L = 0.6$ (24 GeV/c) ($x = 0; p_t &gt; 1.5 \text{ GeV/c}$)</td>
<td>$\sim 10^{-31} \ \text{cm}^2$</td>
<td>Shower photon detect.</td>
<td>3 hours</td>
</tr>
</tbody>
</table>
Fig. 1: Polarized elastic electron-proton asymmetries (from Ref. 1)
Fig. 2: Cross-section and polarization in pp elastic scattering in Coulomb-Nuclear Interference.

Fig. 3: Polarized target asymmetry $T(\theta_{GD})$ in $\gamma p \rightarrow \pi^0 p$ (Ref. 10)
HADRON PHYSICS AT THE SPS: THEORETICAL REMARKS

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ABSTRACT

A few simple remarks are given about the relevance of the present experimental programme of hadron physics at the fixed-target SPS for quantitative tests of quantum chromodynamics.

The discussion is divided into three parts: the first deals with the tests of QCD in the "generalized scaling limit", where the simple scaling laws of the parton model are modified by usually mild logarithmic corrections. The second concerns a brief analysis of the effects which are suppressed by inverse powers of the large kinematical invariants characterizing a given process ("higher twists"); and the third reviews the relevance of exclusive processes (like the elastic scattering) which, for particular kinematical conditions, have a rather simple description in perturbative QCD.

Concerning the first part, the general pattern of predictions of perturbative QCD for hadron physics is in good qualitative agreement with the experimental results accumulated in the past few years. Can we now go further and establish an agreement on a more quantitative basis? There are a few obvious limitations to this: the first comes from the machine energy (SPS-fixed target mode) which puts a bound on the hardness reachable in a scattering process. The second is the still rather poor knowledge of some structure/fragmentation functions (the sea and the gluon distributions) in terms of which the normalization of different hard processes is settled; this is particularly crucial for those reactions, such as large $p_T$ one-particle inclusive spectra, which involve many subprocesses at the parton level. A third limitation is the theorist's energy: while a complete calculation of next-to-leading corrections to all relevant hard processes seems feasible (in many cases, it has already been done), the next to the next order appears to be a formidable task. Finally, the influence of phenomenological parameters like the "intrinsic $p_T$" introduced in order to get a good agreement with the data, can obscure the analyses of the effects which are genuinely predicted by perturbative QCD.

The knowledge of various hadron beam energies and intensities and of different parton structure functions allows us to deduce the parton beam facilities available at CERN: in Fig. 1 are reported the number of particles per pulse of valence up-quarks, sea up-quarks and gluons coming from a 400 GeV proton beam with $10^7$ ppp, the number of valence up-antiquarks from a 300 GeV $\pi^-$ beam with $10^7$ ppp and, for further comparison, the spectrum of the photon beam.
As one can see, the monochromaticity of the hadron beam is lost at the parton level; in particular, the way the hadron beam energy is transmitted to the partons depends on the type of hadrons: indeed, anti-up-quarks coming from $\bar{p}$ at 400 GeV are roughly equivalent to those coming from $\pi^-$ at 300 GeV. The worst-known beam is clearly the gluon one; therefore, a first criterion according to which various experiments can be graded is their sensitivity to the gluon distribution. Figure 2 contains a list of processes, a sketch of the lowest order diagrams and a "Michelin" type note for each of them. Obviously, the large $p_T$ jet/one-particle inclusive processes get the lowest note. For reactions where $g-q$ and $q-\bar{q}$ channels are both present, and an electromagnetic current is coupled to the quarks (direct $\gamma$ at large $p_T$ on- or off-shell, photoproduction), the subtraction of $\pi^- - \pi^+$ either in the incoming beam or in the outgoing particle can isolate the contribution of the $qq$ annihilation (or $\gamma q$ for photoproduction) and subtract, at the same time, most of the purely hadronic background ($\pi^0$ for direct $\gamma$ at large $p_T$).

The picture in terms of lowest order diagrams is credible only if the process is "hard" enough. This statement can only be made quantitative by calculating the higher order corrections. It is precisely the test of these higher order corrections which can bring the agreement of the theory with the experiments from a qualitative level to a quantitative one.
Unfortunately, the actual normalization of next-to-leading corrections depends in general upon the renormalization scheme used: for, the electromagnetic corrections to low energy $\mu e$ scattering are very large if $a_{\text{e.m.}} (\mathcal{M}_{\text{Planck}})$, the fine structure constant renormalized at the Planck mass, is used.

Various optimization procedures have been proposed for fixing the proper renormalization scheme\(^1\); the best seems to be the one proposed by P. Stevenson\(^2\) (PMS) which tries to make the result of the optimization stable against mild readjustments of the scheme adopted. These gymnastics often result in a reabsorption of the largest part of the correction by lowering the scale entering the running coupling constant.

Sometimes, the size of the correction cannot be hidden by a change of scheme: one then gets "observable" large corrections, which it is useful to test. A popular quantity which is quoted in these cases is the $K$ factor defined as

$$K \equiv \frac{d\sigma^{(1+2)}}{d\sigma^{(1)}}$$

(1)

i.e., as the ratio of the prediction including the next-to-leading correction over that with the leading term only. In Fig. 3a and 3b are reported the "$K$" factors for the total Drell-Yan cross-section in pp scattering\(^3\) and the one differential in the transverse momentum in ($\pi^- - \pi^+$)p scattering\(^4\).

In the case of the total cross-section, the parton distribution functions used have been extracted from deep inelastic electroproduction (DIS). In the case of $p_L$ distribution, one can alternatively use parton densities normalized in DIS or fit the rapidity distributions of the Drell-Yan reaction itself: the resulting $K$ factor is quite different in the two cases.

<table>
<thead>
<tr>
<th>\text{DY}</th>
<th>\text{Direct} $\gamma p_L$</th>
<th>$\gamma N \rightarrow \text{jet} + X$</th>
<th>$\gamma N \rightarrow \gamma + X$</th>
<th>$h h \rightarrow \text{jet}$</th>
</tr>
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<tbody>
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<td>$\ast \ast \ast$</td>
<td>$\ast \ast$</td>
<td>$\ast \ast$</td>
<td>$\ast \ast \ast$</td>
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</tbody>
</table>

- Fig. 2 -
The second order calculation for the deep Compton process has recently been completed\textsuperscript{5}): no major corrections have been found to the y distribution except for a dip around \( y = 1 \pm 2 \) at \( p_\perp = 2 \) GeV and \( E_\gamma = 200 \) GeV (see Fig. 4). However, this comes from the gluon contribution to the higher order corrections and is therefore subjected to some amount of undetermination. As a counter-example, see the dashed line in Fig. 3a giving the gluon contribution in that case. The prompt photons at large \( p_\perp \) have been studied beyond the leading order only in the soft gluon approximation\textsuperscript{6}): the corrections found are of the order of 20 - 30\%, at \( p_\perp \) of the order of 8 GeV. To summarize, next-to-leading corrections are nice if large enough to be observable, if they can be resummed to be credible and if they are not constant over the explorable range of kinematics, so as to be unmistakable.

An interesting sector of large perturbative corrections are those arising from terms which behave as

\[
\left[ \alpha_s(Q^2) \ln^2 \frac{Q^2}{Q_0^2} \right]^n
\]  

(2)

where \( n \) is the order of the perturbative expansion and \( Q^2/Q_0^2 \) are two scales sufficiently different to make the expansion parameter \( \alpha_s \ln^2 Q_0^2 \) of order one. The origin of those double logs is the emission of soft gluons and the imperfect balance of the terms left from the cancellation of infra-red singularities between real and virtual diagrams. The techniques aiming to resum
the terms like in Eq. (2) have been applied to several processes, such as to the muon pair production at $p_\perp$ relatively lower than their invariant mass\(^7\) or the $E_T$ distributions in hadron-hadron scattering\(^8\). Notice that the techniques are applicable only if two different mass scales can be identified, both characterizing the hardness of the process: in particular, the medium $p_\perp$ prompt photon cross-section cannot be handled in this way.

The impossibility of extending the predictive power of perturbation theory down to low $p_\perp$ makes many processes very vulnerable to the contamination of the "intrinsic $p_\perp$" effects. In Fig. 5 one can see as a rough indication the effect of having on or off an intrinsic $p_{i\perp}$ of 1 GeV through the ratio $R$ of the cross-section with the $p_{i\perp}$ on over the one with the $p_{i\perp}$ off. In this case, the single particle inclusive gets an inverse star. In the case of Drell-Yan, the resummation which we already mentioned drastically reduces these effects: the data can be fitted down to $p_\perp = 0$ with only a $p_{i\perp} \sim 0.4$ GeV and the value of $R$ at $p_\perp = 3$ GeV is 1.3 only.

The summary of the notes given to the different reactions according to: i) the complication in terms of elementary processes, ii) the visibility of higher order corrections and iii) the sensitivity to phenomenological smearing procedures is given in Fig. 6. For the large $p_\perp$ jet cross-section, a complete second order calculation is still lacking: there are, however, indications that they would suggest an "effective" scale for the process much lower than the ones commonly used. Incidentally, this might have important effects on the normalization of this cross-section at the collider.

<table>
<thead>
<tr>
<th>$p_\perp$ Jet Cross-Section</th>
<th>$p_\perp$ (GeV)</th>
<th>$R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma p + hX$ $E = 100$ GeV</td>
<td>$p_\perp = 3$ GeV</td>
<td>$\sim 1.4$</td>
</tr>
<tr>
<td>$pp + \pi^0X$ $E = 200$ GeV</td>
<td>$p_\perp = 3$ GeV</td>
<td>$\sim 13$</td>
</tr>
<tr>
<td>$pp + \gamma X$ $E = 200$ GeV</td>
<td>$p_\perp = 3$ GeV</td>
<td>$\sim 4.2$</td>
</tr>
<tr>
<td>$pp + \mu^+\mu^-X$ $E = 400$ GeV</td>
<td>$p_\perp = 3$ GeV</td>
<td>$\sim 2$</td>
</tr>
<tr>
<td>$pp + \mu^+\mu^-X$ $E = 400$ GeV</td>
<td>$p_\perp = 6$ GeV</td>
<td>$\sim 1.3$</td>
</tr>
</tbody>
</table>

- Fig. 5 -
<table>
<thead>
<tr>
<th>Subprocesses</th>
<th>K factors</th>
<th>intrinsic $p_{t}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>DY</td>
<td>***</td>
<td>***</td>
</tr>
<tr>
<td>$DYP_{t}$</td>
<td>*</td>
<td>***</td>
</tr>
<tr>
<td>Direct $\gamma$</td>
<td>*</td>
<td>* (?)</td>
</tr>
<tr>
<td>Photoproduction</td>
<td>*</td>
<td>/</td>
</tr>
<tr>
<td>Deep Compton</td>
<td>* * *</td>
<td>*</td>
</tr>
<tr>
<td>$h-h + \text{jet/}$</td>
<td>*</td>
<td>/</td>
</tr>
</tbody>
</table>

- Fig. 6 -

What I have been discussing so far might be considerably shaken if the factorization theorem of perturbative QCD should be proved to fail in hadron-hadron reactions. The situation at present is still controversial\(^9\), but there are some encouraging results indicating the absence of the problem\(^10\).

Another problem which might severely affect the discussion is the presence of nuclear effects of the type observed by the EMC collaboration at CERN\(^11\): the Drell-Yan experiments seem to be the best placed to verify those effects\(^*\). In particular, if the effect is due to "sea" (pion) quarks\(^12\), the ratio of $\pi^-$ over $\pi^+$ cross-sections as a function of $p_{t}$ should approach 1/4 in a different way on deuterium or platinum targets.

We turn now to the discussion of the effects which die as inverse powers of the large invariants: the higher twist effects. I will make a distinction between inclusive higher twists and exclusive ones. The first are those arising from the participation of more than one parton per hadron to a hard reaction. In general, they involve multiparton reactions like the one depicted in Fig. 7. The picture in terms of multiparton processes is not unique: through the equations of motion, the off-shellness can be traded for more partons incoming\(^13\). This makes the parametrization of higher twist effects simple in some "languages" (operator basis) and complicated in others\(^14\). A difficulty which cannot be avoided anyway is the inclusion of many more input functions with respect to the leading twist case. Models

\(^*\) The observed A dependence for the total cross-section might come from a compensation of the EMC effect over the $x_{1} - x_{2}$ range of values explored.
are therefore required to provide good ansätze for those new functions and, at present, it is hard to believe that they can be fully determined on an experimental basis. This makes the analysis of inclusive higher twists rather problematic for the moment.

Exclusive higher twists originate from processes where, at the price of a form factor decreasing as an inverse power of some invariant, hadrons are directly produced (not through a standard fragmentation process) at small distances. In Fig. 8a there is an example of a diagram describing, in the lowest order, the direct production of a meson at large $p_\perp$ in photoproduction\(^{15}\). For a pion, this contribution is suppressed by $f_\pi^2/p_\perp^2$ with respect to the leading twist large $p_\perp$ cross-section. These effects, which, however, are generally rather small, have the advantage of having a rather clear signature ("prompt" hadrons in the final state) and of requiring a modest $p_\perp$ range to be detected. In Fig. 8b there is another example of these reactions, where a pion is completely "eaten" (at least its valence quarks are) during a high $p_\perp$ scattering\(^{16}\). The signature of this process is the reduction of pion fragments in the forward direction; if this should become an important contribution in some kinematical configurations (forward angles and large $p_\perp$), a similar mechanism, with a $\rho$ meson incoming (Fig. 8b) could be a worrying background to three-jet events in photoproduction, which are taken as signatures of a direct coupling of the photon (Fig. 8c). If the significance of testing the exclusive higher twists is well established, the actual estimate of their size is still at a rather qualitative level; one should look more at the clearness of the signature than at the absolute normalization of these effects.
The last part of this discussion concerns the exclusive processes like the elastic pion-pion scattering. Two different mechanisms can contribute to the regime \( s \geq t \gg \Lambda_{QCD} \) : they are reported in Figs. 9a and 9b. The first, originally due to Brodsky and Farrar (BF)\(^{17}\), is very close to the mechanism acting in the e.m. form factor and, the second, due to Landshoff\(^{18}\) (L), imagines that the scattering takes place for each constituent independently. The two interpretations lead to rather different predictions: (BF) predict

\[
\sigma_{\text{elastic}} \sim \frac{1}{s^{10}} f(\theta)
\]

and (L) predicts

\[
\sigma_{\text{elastic}} \sim \frac{1}{t^{8}} f(\theta)
\]

The experiments at PS energies and large angles seem to favour the BF mechanism, while at SPS-ISAR energies and \( 3 \leq -t \leq 14 \text{ GeV}^2 \) one observes a very clear \( t^{-8} \) behaviour. The SPS energy seems the one where there is the cross-over between the two regimes, and it would certainly be interesting to have more experimental information.

In the framework of the BF picture, Mueller has proposed an interesting test, where a pion hits a nucleus producing a pion, a proton and an unbroken nucleus\(^{19}\):

\[
\pi N'(A) + \pi p \rightarrow N''(A-1)
\]

(3)

The \( N' \) remains unbroken because in the BF mechanism the pion wave function before the scattering shrinks down to dimensions of the order of \( 1/|t| \), becoming transparent then to the nuclear matter. In the (L) type of approach, the pion maintains its normal shape during the scattering and it would certainly re-interact with the nuclear matter: the reaction in Eq. (3) may then serve as a useful way of separating the two mechanisms. In the field of exclusive processes, there are still some unsolved problems, mainly for what concerns the proton: for example, its electromagnetic form factor, which is predicted to behave as \( \propto s^3(q^2)/(q^2)^2 \), does not show experimentally
any signal of the sizeable dependence on \( \alpha_s \). Also, there is still some
debate as to whether the (L) type of contribution would not be partially
depressed by a Sudakoff form factor.

Let me stress a few points in the conclusion. The "generalized scaling"
regime of QCD is the only one which can be quantitatively tested at present.
On this I would remark that:

A) the reaction of hadron-hadron scattering into a jet or a single particle
at large \( p_t \) seems a rather hopeless domain, given that:
   i) the "effective" scale is probably much lower then the natural one;
   ii) the sensitivity of the predictions to the smearing of the
   "intrinsic \( p_t \)" is very large (the contamination only becomes
   reasonable for \( p_t \gtrsim 8 \text{ GeV} \));
   iii) there are too many subprocesses contributing to the reaction

B) For a quantitative test of large \( p_t \) Drell-Yan pairs it is important
to have a precision of the order of 20% at \( p_t \sim 5 \) and both \( \pi^- \) and \( \pi^+ \)
beams.

C) The high \( p_t \) obtainable with prompt \( \gamma \) hadroproduction can compensate
for the rather large sensitivity of this process to intrinsic \( p_t \) smearing
effects. In this respect, large \( p_t \) hadrons in photoproduction are
rather insensitive to this contamination and may become an important
testing ground of QCD.

Exclusive higher twists should be looked for: this type of search fits
very nicely with the energy range and the operation mode (fixed target) of
the SPS.

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P.V. Landshoff, K. Pretzl, D. Schiff and D. Treille.

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12) See the talk by C.H. Llewellyn Smith at the workshop.


NUCLEAR BEAMS FROM PS AND SPS

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ABSTRACT
The history of light ions at CERN is presented and the possibilities are outlined on how to accelerate heavier nuclei than deuterons and \( \alpha \)-particles. Intensity estimates are given and the problems of the different accelerators are discussed. There are difficulties and limitations, not only due to the low intensities, but also due to the low charge to mass ratio.

1. INTRODUCTION
Light ions have already a long history at CERN. The first deuterons had been accelerated in the CERN 50 MeV Linac back in 1964\(^1\). Later on they were injected and accelerated in the PS and transferred and stacked in the ISR. Studies were made several times\(^2\) to investigate the possibilities to accelerate heavier masses but only \( \alpha \)-particles were finally used in the PS and ISR. The growing interest of the physics community in (light) ions was made evident with a letter of intent to the PSCC\(^3\). At that moment it was decided to have a new look\(^4\) to what might be possible with the CERN machines. This paper will give an overview of what has been done at CERN, the technological complications and what might be possible in the future.

2. HISTORY
Due to a certain interest expressed by some physicists some thoughts were given to light ions\(^5,6,7\) after the first deuteron acceleration in 1964. But it took 12 years before another attempt was made to accelerate deuterons with the Linac (Linac 1), profiting from the fact that Linac 2 (the "New Linac") supplied now the CERN machines with protons and that Linac 1 was available for lengthy machine studies.

Not only was the pulse-length increased by a factor 10, but also the current was almost doubled. The deuterons were finally injected into the PS, accelerated and stacked in the ISR\(^8\). The production of \( \alpha \)-particles was also tried, but acceleration in the PS was very lossy. Actually, it turned out later that the source supplied a beam of deuterons and \( \alpha \)-particles mixed together. Trials to produce a pure \( \alpha \)-beam resulted in a fairly low intensity in the Linac. It was only due to the interest of certain experimental groups in the ISR that \( \alpha \)-particle production was pursued. The method selected finally was production of a \( \text{He}^{1+} \) beam and stripping at 516 keV to produce \( \alpha \)'s which could be injected into the first tank of the Linac (Linac 1). The result was very good and gave currents similar to running with deuterons, making acceleration in the PS and stacking in the ISR a not too difficult
a procedure\textsuperscript{9}). Table 1 gives a summary of what has been achieved in the past.

Table 1

<table>
<thead>
<tr>
<th>Year</th>
<th>Particle</th>
<th>Linac</th>
<th>Destination</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Current [mA]</td>
<td>Pulse-duration [\mu s]</td>
</tr>
<tr>
<td>1964</td>
<td>d</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td>1976</td>
<td>d</td>
<td>12</td>
<td>100</td>
</tr>
<tr>
<td>&quot;</td>
<td>(\alpha + d)</td>
<td>2</td>
<td>100</td>
</tr>
<tr>
<td>1977</td>
<td>(\alpha)</td>
<td>0.7</td>
<td>100</td>
</tr>
<tr>
<td>1979</td>
<td>(\alpha)</td>
<td>2</td>
<td>100</td>
</tr>
<tr>
<td>1980</td>
<td>(\alpha)</td>
<td>6</td>
<td>100</td>
</tr>
<tr>
<td>&quot;</td>
<td>(\alpha)</td>
<td>10</td>
<td>100</td>
</tr>
</tbody>
</table>

3. HOW TO ACCELERATE IONS WITH PROTON MACHINES

Apart from protons and \(^3\)He nuclei all other stable ions have a charge to mass ratio \((q/A)\) less or equal to half the proton value \((q/A = 1)\). In a circular machine these ions can in principle be accelerated up to the same momentum per charge as protons. Because of their larger mass the accelerating voltages must be increased or acceleration will simply take longer. In a linear machine, which, like an Alvarez Linac, depends on a certain velocity profile, the situation is more complicated.

3.1 Acceleration in the Linac

3.1.1 Ions with \(q/A = 0.5\) (e.g. deuterons and \(\alpha\)-particles)

Acceleration of protons in an Alvarez structure must fulfill the condition that the particles take one cycle of the applied RF field to move from one gap to the next \((2\pi \text{ or } 2\beta \lambda \text{ mode})\. Acceleration of ions would require the field levels to be increased by a factor of 2 - far above what is practicable in the CERN Linac. In addition this would lead to particles with twice the proton momentum which could not be handled by the magnetic focusing elements neither in the Linac nor in the subsequent injection line.

One way out of this problem is to accelerate ions with half the proton velocity, so that the time taken by an ion to move from one accelerating gap to the next is twice the RF cycle \((4\pi \text{ or } 2\beta \lambda \text{ mode})\. The corresponding cell is then \(2\beta \lambda \) instead of \(\beta \lambda \) for protons. This mode has also the advantage of producing ions with almost the same momentum (per charge) as protons. The mode has however a poor efficiency because of the reduced longitudinal acceptance. Fig. 1 shows schematically acceleration in the two modes.
3.1.2 Ions with $q/A < 0.5$ (e.g. not fully stripped ions)

Following the arguments for ions with $q/A = 0.5$ it might look attractive to accelerate in the $38\lambda$ mode or in even higher modes, but unfortunately the longitudinal acceptance would approach zero. Therefore, the only possibility is to increase the accelerating (and focusing) fields such as to keep the velocity of the ions equal to half the proton velocity. Table 2 shows just a few examples.

<table>
<thead>
<tr>
<th>Ion</th>
<th>$q/A$</th>
<th>RF field increase as compared to $q/A = 0.5$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C$^{4+}$</td>
<td>0.33</td>
<td>50</td>
</tr>
<tr>
<td>C$^{5+}$</td>
<td>0.42</td>
<td>20</td>
</tr>
<tr>
<td>O$^{6+}$</td>
<td>0.38</td>
<td>33</td>
</tr>
<tr>
<td>O$^{7+}$</td>
<td>0.44</td>
<td>14</td>
</tr>
<tr>
<td>Ne$^{7+}$</td>
<td>0.35</td>
<td>43</td>
</tr>
<tr>
<td>Ne$^{8+}$</td>
<td>0.40</td>
<td>25</td>
</tr>
</tbody>
</table>

Measurements have shown that the Linac 1 at CERN will just be able to cope with a field increase of 33% putting a lower limit of 0.38 on the charge to mass ratio of the ions to be accelerated.

The focusing requirements could be dealt with because of the complete absence of space charge forces - even for the most optimistic assumptions about ion sources.

It should be pointed out that acceleration with half the proton velocity of ions with $q/A = 0.5$ would need in theory only half the accelerating voltage, but due to the bad transit time factor (which takes the variation of the voltage during the passage through the gap into account) one needs on a few places even higher voltages than for normal proton operation.

Protons leaving the Linac with 50 MeV have a velocity of $\beta = 0.3$, ions accelerated in the $28\lambda$ mode have $\beta = 0.15$. This value is sufficiently high to allow passage through a stripper foil with complete stripping up to masses around 40 (Ar, Ca).

3.2 Acceleration in a proton synchrotron

3.2.1 The PS situation

Experience in the PS is available from the d- and a-runs for the ISR$^{8,9}$. Provided the ions are fully stripped there is no difference between them for the PS. Partially stripped ions cannot be accelerated anyhow due to the
residual gas pressure which would cause beam losses. As pointed out above, there are no fundamental problems with the acceleration of ions. However, there is a slight complication due to the fact that the injected ions circulate with only half the proton velocity. This could be dealt with by increasing the frequency range of the accelerating RF by a factor of 2, which is a complicated procedure. In the case of d- and α-acceleration a frequency scaling scheme based on harmonic number switching has been used instead. The injected ions were trapped with the same RF frequency as the protons (2.998 MHz) but this frequency corresponds to the harmonic number h = 40 (instead of h = 20). The beam was then accelerated from β = 0.15 to β = 0.5 which corresponds to the upper frequency limit of the RF system (9.55 MHz) in the h = 40 mode. At this energy the beam was adiabatically debunched by reduction of the RF voltage and left coasting on an intermediate magnetic flat top at 515 G. After retuning to half frequency (4.77 MHz) of the RF system (corresponding to h = 20) the beam was adiabatically trapped and accelerated through transition. The same scheme could be applied to other ions.

3.2.2 The Booster

The problem and the solution to ion acceleration in the Booster is basically the same as for the PS\(^{11}\). It must be noted that the PS is in any case heavily loaded with its present and future programme. Therefore, it is essential that the ions are not injected directly into the PS, but rather into the Booster, and that the complicated RF-gymnastics are dealt with by the Booster. The additional problems of lengthening kicker-pulses (due to the lower β-value of ions as compared with protons at maximum momentum per charge) are not easy in terms of manpower and money but straight-forward in operation.

3.2.3 The SPS

In spite of the almost constant β a change of the harmonic number with debunching and adiabatic recapture will be needed\(^{11}\). This is due to the extremely small frequency swing of the 200 MHz accelerating system. For setting up, a high intensity beam of p's, d's or α's will be needed.

4. Low Intensity Problems

Except for very light ions like deuterons or α-particles there are no ion sources that would give currents of the order of magnitude of the proton currents the CERN accelerators are usually running with. Any operation with other ions would therefore be hampered by the low intensities available. There are different kinds of instrumentation necessary to monitor the beam and to achieve successful operation.

4.1 Linac instrumentation

In the Linac there are beam current transformers to measure the beam
intensity especially as a function of time. The ones installed at present can measure currents of the order of 1 mA. At other laboratories there are designs available which can measure down to 100 nA for short pulses\textsuperscript{32}). For successful PS injection it is also necessary to measure precisely the energy spread and the emittance of the beam. Both measurements imply cutting down the primary beam intensity drastically. Special SEM grids as developed for antiproton injection into LEAR could provide the necessary sensitivity. It must be stressed that appropriate beam measurements are vital for adjustments of Linac 1 as this machine has no precise acquisition for RF and focusing parameters. This is valid in particular for adjustments far outside the normal operating range i.e. when operating with ions with $q/A < 0.5$.

4.2 Synchrotron instrumentation

In the PS beam transformers and pick-up monitors to measure the closed orbit position as well as for beam control (RF acceleration) are necessary. Some improvements have been made recently to allow for low intensity antiproton operation. In case of direct injection the limiting factor appears to be the injection procedure which required $7 \times 10^8$ charges in half-turn injection to make closed orbit measurements with a necessary resolution of 3 mm. This corresponds to 17 μA of injected current. To cope with this low current would require installation of additional equipment. As far as instrumentation is concerned the situation is similar for the Booster and the SPS but not as stringent because no attempt would be made to measure the closed orbit with the low-intensity beam.

5. AVAILABLE ION SOURCES

5.1 Conventional sources

Conventional ion sources as used for proton production (e.g. duoplasmatron) cannot supply sufficiently high charge states. Penning sources are frequently used for this purpose. Their technology is well known and several laboratories have operational experience with them.

Present sources of this type can give modest currents at fairly high charge state. Table 3 shows some examples for light ions\textsuperscript{12}).

The number of particles in 100 μs corresponds to the maximum pulse length the Linac could produce. This number would be interesting in case of acceleration via the Booster. For the PS the maximum pulse length that could be used is around 60 μs. Above this value efficient injection would not be possible. However, this statement is only valid if the beam emittance, as delivered by the Linac, would have the same value as for deuterons or α-particles. There is some hope that due to the almost complete absence of space charge the emittance blow-up during acceleration may be smaller. This would increase the multturn injection efficiency and would make longer pulses useful.
Table 3

<table>
<thead>
<tr>
<th>Particle</th>
<th>Charge/mass ratio</th>
<th>Current [particle μA]**</th>
<th>Current [μA]</th>
<th>Number of particles in 100 μs</th>
</tr>
</thead>
<tbody>
<tr>
<td>C⁵⁺</td>
<td>0.417</td>
<td>0.4</td>
<td>2</td>
<td>0.25 × 10⁹</td>
</tr>
<tr>
<td>O⁶⁺</td>
<td>0.375</td>
<td>5.0</td>
<td>30</td>
<td>3.13 × 10⁹</td>
</tr>
<tr>
<td>Ne⁷⁺</td>
<td>0.350⁺</td>
<td>1.4</td>
<td>9.8</td>
<td>0.87 × 10⁹</td>
</tr>
</tbody>
</table>

*) Note that the Ne⁷⁺ cannot be accelerated in Linac 1!
**) "Particle current" is equivalent to electric current where the "charge unit" is not the elementary charge unit but the unit of one particle. From this follows that:
   Electric current = particle current × number of electric elementary charges of that particle.

Another ion source which seems attractive for application to Linac 1 is the ECR (electron cyclotron resonance) source built by Geller (Grenoble). These sources use large amounts of microwave power to pump energy into the electrons of a plasma inside a homogeneous magnetic field. For O⁶⁺ ions, currents of 14 particle μA have been reported. This is considerably better than what has been achieved with Penning sources. It must also be mentioned that these currents can be delivered continuously. Pulsing the source, which is possible when being used for Linac 1, might -because of a certain storage effect of the plasma- yield considerably higher currents.

These two types of ion sources seem to be realistic approaches for light ion acceleration in the near future at CERN. However, their installation and operation can by no means be compared with a standard source. Their volume, their weight and their power consumption are one or two orders of magnitude larger than the corresponding parameters of proton sources.

5.2 Special sources

There are other types of sources but none that could deliver in a reliable way reasonable current intensities with high charge states. The special procedure used to produce α-particles, i.e. acceleration of a He⁺ beam to 516 keV cannot be applied successfully to larger masses. Stripping efficiency at that energy level is only around 30% for He⁺. To get complete stripping of heavier ions much higher energies are needed (e.g. for Li already 2 MeV). A scheme like this is impossible with the equipment existing now on Linac 1.

6. ESTIMATED INTENSITIES IN THE CERN MACHINES

6.1 PS situation

Assuming that a Penning or ECR source would be installed in the Faraday cage of Linac 1 and that it would be run somewhere between full (= proton) and half (= deuteron) voltage, such as to achieve the appropriate β value
for injection in the $2\beta\lambda$ mode into tank 1, and that acceleration in Linac 1
would be followed by subsequent injection and acceleration in the Booster
and in the PS, Table 4 may be a reasonable guess for the possible intensities
in the PS.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Current from source [particle $\mu$A]</th>
<th>Current out of Linac after stripping [$\mu$A]</th>
<th>Estimated number in the PS of accelerated charges/pulse</th>
<th>particles/pulse (injection via Booster)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.4</td>
<td>0.24</td>
<td>$5.4 \times 10^7$</td>
<td>$9.0 \times 10^6$</td>
</tr>
<tr>
<td>O</td>
<td>5.0</td>
<td>4.0</td>
<td>$9.0 \times 10^8$</td>
<td>$1.1 \times 10^8$</td>
</tr>
<tr>
<td>Ne</td>
<td>1.4</td>
<td>1.4</td>
<td>$3.1 \times 10^8$</td>
<td>$3.1 \times 10^7$</td>
</tr>
</tbody>
</table>

With the ECR source:

| O  | 14 | 11 | $2.5 \times 10^3$ | $3.1 \times 10^8$ |

(The upper 3 cases are taken from Table 3).

This table assumes a 10% efficiency for the Linac and an overall efficiency (transfers, injection and trapping) of about 30% during a useful injection time of 100 us for the Booster. The corresponding values were for deuterons and direct PS injection:

- from source: 150 mA
- from Linac: 12 mA
- accelerated in the PS: $4...6 \times 10^{11}$.

The Linac efficiency used in Table 4 may be too pessimistic because there are certainly no space charge problems. On the other hand monitoring the beam and therefore adjusting the machine will be considerably more difficult. The same argument holds for the 30% efficiency given for the subsequent machines. A certain emittance blow-up of the beam because of the stripping must also be considered and a possibly inferior beam quality coming from the Linac must be taken into account.

Due to the problems with low intensity instrumentation, and due to the required increases in the tank fields of the Linac, of the cases listed in Table 4, only the oxygen beam of the ECR source looks interesting.

6.2 SPS situation

Subsequent ejection from the PS should not be a lossy process. This statement holds also for transfer to and acceleration in the SPS, provided that the adequate low intensity instrumentation is available. Transfer to the SPS could be done at 7 GeV/nucleon using 5 turn ejection from the PS.
Resonant extraction from the SPS will be possible from PS transfer energy up to 13 GeV/nucleon and at energies above 50 GeV/nucleon. Extraction at low energies would cause some losses because the extraction channel has an acceptance of only $1\pi$ mrad in both transverse planes. Because 5 turn ejection from the PS fills only 5/11 of the circumference of the SPS and because of the ripple current of the SPS quadrupoles a duty cycle of about 30% for resonant extraction can be estimated. At higher energies this would improve. One could then profitably also consider double batch injection into the SPS.

7. **POSSIBLE IMPROVEMENTS**

The interest in physics with high energy ions seems to be growing, at least when judging from the number of workshops and other meetings devoted to this subject. It is therefore interesting to see what possible improvements could be made to achieve higher intensities and heavier masses.

If we assume for the moment no improvements on the ion source, it is clear that in theory there is a factor of 30 that could be gained by improving the efficiency of the Linac and of the subsequent injection into the Booster.

7.1 **Injection into the PS Booster**

It must be pointed out that the use of the Booster increases the intensity by a factor 3 as compared to direct injection into the PS\(^{10}\). Although the Booster was built to increase the space charge limit of the PS, it has a larger transverse acceptance which allows more efficient injection even of the full Linac pulse length (i.e. 100 $\mu$s instead of 60 $\mu$s). It should be pointed out that "charge exchange" injection as with H\(^+\) ions would also basically be possible by going for example from O\(^{6+}\) to O\(^{4+}\). This process would guarantee a highly efficient injection and could make use of even longer Linac pulses. (Note: already 100 $\mu$s are hard enough with the present Linac 1 equipment).

7.2 **Improvements on the Linac**

The efficiency of the Linac, in the scheme described, seems to be fairly poor. It is given mainly by the longitudinal acceptance of this machine in the $2\beta\lambda$ mode. The tilt on the RF field in tank 1 is such that there is no room for improvements, at least not in the case of ions with $q/A = 0.375$. It is possible that a radiofrequency quadrupole could improve the situation drastically. This device is like a long electrostatic quadrupole which is driven by RF in order to provide alternating gradient focusing and, with a special modulation on the pole tips, to achieve longitudinal field components for simultaneous acceleration. Actually there is a collaboration between CERN and LANL (Los Alamos) to try to replace the 500 kV preinjector of the CERN Linac 1 by an RFQ\(^{13}\). This RFQ is intended for protons only, but if it
turns out to be a success, building of a special one to cope with ions could be envisaged. The RFQ itself has a capture efficiency which can approach 100%. This is better than a conventional scheme for protons using bunchers (e.g. Linac 1 : 60%, Linac 2 : 85%). In addition, because of the adiabatic trapping in the RFQ, the longitudinal emittance can be made very small - at least for low space-charge situations. This could increase trapping efficiency of tank 1 which is now very limited because of the small longitudinal acceptance in the 28λ mode.

A further advantage of an RFQ is the low voltage (~50 kV) which is needed on the ion source. Thus the installation of a source of Penning or ECR type would be greatly simplified. This means not only a simpler technology and less money, but also better access to the source and more freedom in its layout, which in turn may well yield a higher intensity.

The simplest and safest, but not the cheapest, way to higher intensity has been pointed out already in 1975\(^{13}\). The method is to have the ion source running with lower charge states, giving much higher currents, a special structure to cope with low charge states at low velocities and stripping to higher charge states before entering tank 2. This is a well known principle other machines, e.g. at GSI, are making use of. An updated proposal has been made recently by an LBL-LANL collaboration\(^{14}\). A schematic layout is shown in Fig. 2. This arrangement (called "Silicon injector") is composed of a Penning source, an RFQ and a special Alvarez tank working in the 28λ mode. The injection into the RFQ is at 8.5 keV/nucleon, the output energy of the RFQ is around 300 keV/nucleon and the output energy of the Alvarez is 2.5 MeV/nucleon to fit to the present tank 2 of Linac 1. At this energy intermediate stripping to a charge state the existing machine could cope with would be done with an efficiency between 20 and 80% depending on the ion species.

As the RFQ and the Alvarez would be designed to accelerate low charge states the currents from the (PIG) source could be of the order of 1 particle mA. In the case of Si for example, use of this facility would yield final PS intensities (measured in charges/pulse) approaching those achieved with α-particles. For O one could count on intensities equal to the α-intensities.

Table 5 shows measured intensities obtained from Penning sources at low charge states\(^{14}\). These numbers allow for a rough estimate of the possible improvement and should be compared to the 14 pμA figure obtained for O\(^{6+}\).

The possibility of using a DC source in connection with a storage ring, where even, under certain conditions, electron cooling might be used, should also be mentioned. It seems, however, not likely that this solution would be cheaper or could provide higher intensities than the "Silicon injector".
Table 5

<table>
<thead>
<tr>
<th>Ion</th>
<th>Intensity [pA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}\text{C}^{2+}$</td>
<td>1000</td>
</tr>
<tr>
<td>$^{16}\text{O}^{3+}$</td>
<td>1000</td>
</tr>
<tr>
<td>$^{28}\text{Ne}^{3+}$</td>
<td>1000</td>
</tr>
<tr>
<td>$^{28}\text{Si}^{4+}$</td>
<td>500</td>
</tr>
<tr>
<td>$^{40}\text{Ca}^{6+}$</td>
<td>(estimate)</td>
</tr>
</tbody>
</table>

7.3 Improvements on ion sources

There is little hope that existing ion sources can be improved to give much higher intensities or charge states. Cold cathode Penning sources have been investigated over a long time and they are used on several accelerators. No major break-through is in sight. The situation is somewhat different with the ECR sources where it might be reasonable to have some hope for a certain improvement, especially for the case of pulsed applications. It must be remembered in this context that high charge states are normally produced by successive collisions, which implies a longer time to produce them, and that, when aiming for fully stripped ions, the ionisation energy for the last electron is proportional to $Z^2$. It seems that only a basically new approach may result in high enough electron densities and temperatures to produce fully stripped ions with heavy masses.

For a long time it has been believed that the EBIS source would be a promising device. Several laboratories (e.g. Berkeley, Frankfurt, Saclay), including CERN\(^{15}\), have been working on it.

This source, which uses an electron beam with high intensity and high energy inside a solenoidal magnetic field to produce and store the ions, seems to be an ideal approach to the problem. In spite of this fact there is actually some stagnation as far as higher intensities are concerned. Beam instabilities and also some technological problems make it unlikely that this source could be interesting in the very near future for the CERN accelerators. There is, however, some optimism at Saclay\(^{16}\).

Other possibilities, like production of ions with intense laser beams, are, at the present moment, not very attractive.
8. SOME GENERAL CONSIDERATIONS ON IONS AND ION SOURCES SUITABLE FOR THE CERN MACHINES

8.1 Production of ions

There are lots of different ion sources. They can be described in general by the electron energy (electron temperature) of the plasma and the product of the confinement time of the ions and the electron density ("nt"), at least in case of successive ionisation which is the dominant process. Fig. 3 shows where more or less conventional ion sources operate\(^1\)). It is clear that the electron energy must be larger than the ionisation energy of the ion that is to be produced. The role of the confinement time is best illustrated in Fig. 4 which shows the decay of lower and the development of high charge states (in the case of oxygen ions coming from an EBIS source \(^2\)) as a function of the time the ion spends in the electron beam. It is not surprising that for the production of O\(^{6+}\) ions the ECR source looks -at the moment- to be the most interesting one. It combines a high electron temperature with a large \(nt\) product both necessary to achieve high charge states.

8.2 Charge states available for acceleration

As mentioned above there are two main problems when accelerating ions: the intensity and the q/A ratio. Below certain values acceleration in the present Linac 1 and in the subsequent machines is not possible. The q/A limit is determined by the first tank of Linac 1 and must be larger or equal to 0.38. The intensity of a specific beam from a specific ion source is more difficult to estimate. As a very rough guess it can be helpful to use the ionisation energy as measure of the beam intensity that can be achieved from an "average" source. If we choose as limit an ionisation energy of \(\leq 138\) eV (i.e. of O\(^{6+}\)) we can use Fig. 5* to work out which ions are available in a sufficient quantity fulfilling the q/A \(\geq 0.38\) requirement. It is surprising to see that, using these criteria, apart from H\(^+\), He\(^{2+}\) and Li\(^{3+}\) only O\(^{6+}\) can be accelerated in the CERN machines.

If, however, q/A \(\geq 0.143\) is taken as limit, as in the "Silicon-injector" proposal\(^3\)), then Fig. 6 shows that the range of ions that can be accelerated is rather large and may extend up to Ca. It must again be emphasized that concluding from the ionisation energy to the possible beam intensity of an ion source is a very rough estimate of what is going on and does not take into account e.g. the intermediate stripping before injection into tank 2 nor the better efficiency that might be achieved with an RFQ. Nevertheless, Figs. 5 and 6 give an impression of what might be possible and what not.

* Only the most abundant isotope of each element is listed.
8.3 Stripping

The proposed scheme of accelerating oxygen ions is based on stripping O$^{6+}$ to O$^{8+}$ at 12.5 MeV/nucleon. In the case of the silicon-injector intermediate stripping will be done before entering tank 2. The inverse process, i.e. electron recapture, is possible for fully stripped ions when passing again through a "stripping medium" even if it is as thin as the residual gas in an accelerator. Fig. 7 can be used to illustrate the point$^{19}$. Stripping results in general in a charge state distribution. This distribution is independent of the initial charge state and depends only on the energy of the incoming projectile - provided the stripper is thick enough. There is, however, a small dependence on the stripping material, and some difference between a gas and a foil stripper. To first approximation stripping an electron from an ion is possible in the classical Bohr-model if the speed of the orbiting electron equals the speed of the ion. It can be seen from Fig. 7 that the maximum of the charge state distribution moves towards higher charge states as the energy increases. If the energy is high enough only one charge state will remain, i.e. the one corresponding to the fully stripped nucleus. It follows from this that stripping O$^{6+}$ to O$^{8+}$ at 12 MeV/nucleon is 100% efficient, whereas intermediate stripping yielding not fully ionized ions is in general associated with some beam loss if not all of the produced charge states can be accepted for further acceleration.

Beam losses due to electron capture of the fully stripped ions are becoming more and more unlikely as the energy of the beam goes up. The cross-section for recapture goes at least with $E^{-3}$ for higher energies$^{12}$. There will be no problems due to recapture in the CERN accelerators.

9. OPERATIONAL PROBLEMS AND CONCLUSION

It is obvious that the CERN machines could provide ion beams with light masses and modest intensities by having a special ion source in the pre-accelerator of the Linac, or with heavier masses and higher intensities by installing essentially a replacement of tank 1, capable of accelerating low charge states, and subsequent partial stripping.

There is no serious technological problem. The amount of money is comparably modest, i.e. a few MSF for the first option and one order of magnitude more for the second one. The amount of manpower on the other hand would be by no means negligible if the other CERN programmes would continue.

This point is illustrated in Fig. 8$^{20}$ for the PS division. It shows clearly the increasing amount of activities accompanied by a reduction in staff number. Any additional activity could only be taken on to the detriment of others. The main concern in this context is not only the installation work necessary for the ions and the additional upgrading of different systems (in
particular the Linac RF and the beam control and monitoring equipment on all machines) but rather the complexity of the whole layout and of the subsequent operation. Figs. 9 and 10 show the Linac site. Installation and operation of yet another facility in that area is certainly not trivial. Fig. 11 given an impression of the complexity of the whole PS area and cf the competition for a light ion program. It is rather this aspect which may determine the future of light ions at CERN.

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* * * *

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Figure 1 - Acceleration in the $\beta \lambda$ and $2\beta \lambda$ mode with an Alvarez structure.

Figure 2 - Schematic layout of light ion facility replacing tank 1.

Figure 3 - Operating conditions of ion sources.

Figure 4 - Charge state distribution as function of confinement time.
### Figure 5 - Charge states available for acceleration with the present Linac 1.

### Figure 6 - Charge states available for acceleration with an improved Linac 1 (Silicon-injector).
Figure 7 - Charge state distribution as a function of beam energy.

Figure 8 - Evolution of PS staff activities 1976-1986.
Figure 9 - Schematic layout of beam lines in Linac 1 area.

Figure 10 - Linac 1 with possible location for "Silicon-injector".
Figure 11 - CPS complex. Overall layout.
EXPERIMENTS WITH NUCLEAR BEAMS AND TARGETS

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ABSTRACT

After a general introduction to the fundamental interest of studying high energy nucleus-nucleus collisions, some specific signatures of quark-gluon plasma formation are considered from an experimental viewpoint. We then discuss the use of existing and new detectors for an experimental programme at the SPS.

To most particle physicists nuclei are complicated objects, far removed from the seeming simplicity of interactions between fundamental fields (e.g. $e^+e^-$), and they would prefer never to use them. Many experiments use them anyway for practical reasons such as the requirement of massive, dense and cheap targets and several particle physics experiments have specifically studied nuclear effects with different targets. Experimental effects have emerged that are surprising and likely to give us information on the behaviour of hadron constituents which cannot be obtained in other ways. Moreover, there is a rapidly growing interest among particle physicists in the use of nuclei, following theoretical developments in Quantum Chromodynamics (QCD) which predict with increasing certainty the existence of a phase transition [1,2].

A nucleus is a loose collection of "bags" containing valence quarks and gluons, see Fig. 1a, interspersed with space or physical vacuum. The medium inside the bags, the "perturbative vacuum" in which the quarks and gluons propagate, is somehow different from the space outside. The latter space, although Lorentz Invariant, can still be a complex medium (not just "nothing") and its properties may be changeable. We know (from years of hadron physics) that the bag surface is not impenetrable. Imagine squeezing this nucleus (and/or pumping in energy) to increase its density really significantly, say an order of magnitude. It is most reasonable to expect that the individual nucleons will coalesce resulting in (eventually) a single bag containing all the quarks, and this expectation is supported by theoretical calculations. This would be a phase transition between a "nucleon gas" and a quark-gluon "gas" or plasma.

Let's look at this in another context, with a flashback to sometime during the first millisecond of the Universe when (probably) there were no hadrons but quarks, antiquarks, gluons (and other fields) in a hot plasma, Fig. 1b. Then quarks and gluons were unconfined and could move everywhere (with the speed of light if massless). If this picture was ever correct, nowadays things are very different and a phase transition must have occurred as the Universe expanded and cooled resulting in the formation of hadrons and the creation of the physical vacuum (Fig. 1a). Today regions of quark gluon plasma may still exist deep in the cores of neutron stars or other astrophysical objects. Its study is thus of relevance not only to particle physics (especially QCD) but also to astrophysics and cosmology; indeed the very nature of space (rather, space-time) is in question.
We can conceive of no way to enter this field experimentally other than colliding high energy nuclei, preferably large nuclei (there are > 1400 valence quarks in U + U!). The use of lighter and technically more practical nuclear beams like $^{16}$O may still allow us to achieve the necessary conditions although probably less frequently, i.e., perhaps in the one event in $10^8$ where a large fluctuation from the usual "nuclear transparency" has occurred. The question is experimental, and much of this workshop session was devoted to the possible signatures of a transition and experimental techniques to observe them, following on from the Bielefeld Workshop in May 1982 [3]. Although theoretical calculations of the space-time development of nucleus-nucleus collisions cannot yet be considered reliable, purely for orientation Fig. 2 shows a possible path in the temperature: density plane for a 3.6 GeV/nucleon $^{16}$O + $^{107}$Ag head-on collision [4]. The passage of the $^{16}$O into the Ag nucleus can cause compression and heating of the nuclear matter into the plasma phase which hopefully lasts long enough (a few x $10^{-23}$ sec.) for thermalisation - only then is temperature actually meaningful.

Before discussing experiments with nuclear beams on nuclear targets, a short digression on hadron beams with nuclear targets is in order. We are now convinced that high transverse momentum ($p_T$) hadrons result from hard scattering mainly of quarks and gluons. If the hard scatter occurs deep inside a nucleus the scattered constituent has to propagate through nuclear matter... how does it do so? In 1974, the experiment of J. Cronin and collaborators [5] observed an enhancement in high $p_T$ production on nuclei, the cross sections rising with atomic mass number A faster than $A^1$. A parametrization of the form $\sigma \sim A^\alpha$ gives $\alpha > 1$ for $p_T > 1.5$ GeV/c, Fig. 3. Remembering that $p_T$ spectra fall steeply, only modest additional small kicks to the outgoing object (q, g, qq, meson...) are required to give an enhancement. Notice however that the effect is largest for $K^-$, $\bar{p}$ and p triggers. We are now learning from ISR results combined with QCD calculations that $K^-$ and $\bar{p}$ at high $p_T$ come
predominantly from gluon fragmentation (they do not share a valence quark in common with the p or n of the target) while π± and K± come more often from quarks. Thus if gluons undergo stronger multiple scattering (than quarks) on the spectator constituents, as expected in QCD, we have a natural explanation for at least the sign of that effect: \( \alpha(K^+, \bar{p}) > \alpha(\pi^+, K^+) \). If protons (much more abundant than \( \bar{p} \)) and therefore not all from gluons) result from diquark (qq) fragmentation then \( \alpha(p) > \alpha(\pi) \) is also natural. That the physical reason for the enhancement occurs predominantly after the hard collision is suggested by the A-dependence of lepton-pair production which shows no significant effect. While we may thus have a reasonable qualitative understanding of this "Cronin effect", data from \( \alpha p \) and \( \alpha \alpha \) collisions at the ISR [6] still seem surprising. At high \( p_T \) (\( \sim 6-8 \text{ GeV/c} \)) the \( \alpha p + \pi^0 \) cross-section is a factor 4 higher than \( pp + \pi^0 \) at the same (nucleon-nucleon) c.m. energy, see Fig. 4.

On the other hand \( \alpha\alpha + \pi^0 \) (strictly speaking, an e.m. shower) is 30-40 (not 16) times higher than \( pp + \pi^0 \) in the \( p_T \) range 5-7 GeV/c. Apparently the recoiling jet looks very similar in the two cases. Hopefully more data, at higher \( p_T \) and also with jet triggers will be obtained in one more \( \alpha-\alpha \) run at the ISR in 1983.

A most striking nuclear enhancement has recently been reported by Experiment E557 at Fermilab [7]. A 400 GeV proton beam passes through a \( \mathrm{H}_2 \) target and thin metal (Al, Cu, Pb) foils, and the vertex position of an interaction is measured. They applied an "interacting beam trigger" (minimum bias) and then the vertex distribution shows (Fig. 5a) most of the interactions in the \( \mathrm{H}_2 \) and a few in the metal foils.
Requiring then a large transverse energy ($E_{T} > 15$ GeV) in the central region, $|\eta| < 0.75$ in the nucleon-nucleon frame, nearly all the interactions occur in the heavy elements (Fig. 5b). Had their triggering calorimeter been at a larger angle the effect would be even more dramatic (it is known that dN/dy peaks at larger angles in p-nucleus than in p-p collisions). Fig. 6 shows the large $E_T$ cross-sections as a function of atomic mass number and (excluding H$_2$) $\alpha \approx 1.25$ at $E_T \geq 15$ GeV. This enhancement factor gives much larger high $E_T$ cross sections than obtainable in pp collisions, with much higher multiplicities, namely the environment in which one is interested to start searching for signatures of a new state of matter. No doubt the effects seen by E557 would be much more dramatic with nuclear (rather than hadron) beams.

Fig. 5

Fig. 6

What are the possibilities for very high energy nuclear beams at CERN? So far we have only had deuteron and alpha-particle beams in the ISR for p$^d$; d$d$; p$^\alpha$ and $\alpha\alpha$ collisions. The $\alpha\alpha$ run (approximately 1 week in 1980) with centre of mass energy of 15 GeV/nucleon ($\sqrt{s} = 126$ GeV) will be repeated in 1983 with some more powerful detectors. A proposal [8] by the GSI Darmstadt-LBL-Heidelberg-Warsaw Collaboration to accelerate $^{16}$O at 9-13 GeV/nucleon in the PS and do experiments with nuclear targets in the Plastic Ball detector (Fig. 7) and a streamer chamber presently awaits Research Board approval. If this goes ahead, to quote from Research Board minutes [9]:

1. "It should be possible to accelerate $^{16}$O also in the SPS" with energies up to 225 GeV/nucleon (3600 GeV $^{16}$O)

2. "The source and beam should be considered as a new facility open to all experimenters".
It follows that any experiments which can take a directly extracted (primary) SPS beam, or use the internal beam, should consider the possibilities that such a beam would provide. Unfortunately the study of $^{16}$O-$^{16}$O collisions in the higher ISR energy range is excluded by its closure.

![Diagram](Fig. 7)

I now consider nucleus-nucleus collisions at SPS energies and possible signatures of plasma formation, with reference to practical, or existing, experiments. For orientation Fig. 8 shows schematically an equal-$A$ collision of small impact parameter, $b \leq 1$ fm., in the c.m. frame. In general the nuclei are transparent enough that the nuclei, seen as Lorentz contracted discs, pass through each other with however multiple collisions and excitation. Three regions are here distinguished: the nucleon-rich (high "chemical potential") target and projectile fragmentation regions (nuclear fireballs) and a central region of low net baryon number density. In longitudinal rapidity (i.e. velocity, transformed to be additive under Lorentz boosts) we expect a particle distribution roughly as sketched in the figure. (There is uncertainty about the central particle density but it probably grows at least as fast as $A^1$.) In the laboratory frame the projectile fireball fragments emerge at very forward angles, $\theta < 5^\circ$. However the above picture may be misleading in several ways. Firstly at SPS energies there is no real separation between the nuclear fragmentation regions and the central region. Even at the ISR, with 2000 GeV/nucleon in pp collisions (lab. equivalent) the nucleon fragmentation regions extend down to $y^* = 0$ and $\sim 1$ unit of $y$ beyond. This has been shown [10] by studying $p$ and $\bar{p}$ distributions in pp and $p\bar{p}$ collisions. Secondly the most interesting (for our purposes) catastrophic collisions are those where the nucleons are really slowed down towards $y^* = 0$, or to negative $y^*$ if $A_{\text{target}} > A_{\text{projectile}}$. Finally Fig. 8 sketches $dN/dy$ averaged over many collisions; the fluctuations may be enormous and it is those that are likely to prove most interesting. In any case even the average multiplicities are very high, two charged particles per unit rapidity in pp leading to $\sim 30$/unit $y$ for $^{16}$O+$^{16}$O on average, if the dependence is $A^1$. One would like the detectors to handle up to $>
100 particles per unit $y$. A calculation by Otterlund [11] for the average rapidity density $\rho(y) = dN/dy$ for $^{16}\text{O} + \text{U}$ at 200 GeV/nucleon is shown in Fig. 9. Note that the maximum density occurs at larger angles than in pp (which of course is symmetric about $y_{\text{nn}} = 0$), because the target is effectively heavier than a single nucleon. This has been observed also in proton-nucleus collisions [12], and was referred to earlier with reference to the E557 results. The effect can be usefully enhanced, triggering on events where the target nucleus has been unusually opaque, by vetoing on projectile spectators. A calorimeter covering the forward $\sim 1$ mrad (say of $\sim 10$ cm transverse dimensions 50 m downstream) detects all the non-interacting /and some of softly interacting projectile nucleons. One can then trigger on the one event in $10^5$ (say) which has the least energy in this calorimeter, and the fact that nuclei are generally "transparent" is then irrelevant. (In the presence of a dipole field the charged projectile fragments are bent to the side, but they can be similarly handled with counters and/or calorimeters.)

Fig. 9

For the high multiplicity events thus selected, traditional "exclusive" analysis where one measures all momenta and identifies all particles is essentially ruled out, although an approach to measuring as much as technically possible in individual events is very important. Rather than an inclusive distribution, e.g. the inclusive $p_T$-spectrum of pions which is averaged over all events, the very high multiplicites allow one to measure a complete $p_T$ spectrum (or $y$-distribution, or $K/\pi$ ratio etc.) for individual events. With this procedure one can extract individual events that deviate from the norm in some way (e.g. the $p_T$-slope is unusual and/or the $\chi^2$ of the fit to a typical $p_T$-distribution is large) and study them for other unusual features. This procedure can already be applied to high multiplicity cosmic ray collisions, two examples [12] being shown in Fig. 10, although the number of such events
and the power of the apparatus (emulsion) is extremely limited in that case. In an SPS experiment one could look for violent fluctuations from uniformity in the γ, Ω plane, in individual high multiplicity events.

Of course selecting catastrophic collisions does not prove the existence of any new forms of matter, but is probably a necessary first step. There is not yet a single indisputable signal (like seeing a Z⁺) that we are sure would prove a phase transition, but there have been several suggestions.

(1) Strangeness

In a quark-gluon plasma formed from nuclei there can be hundreds of u and d quarks present. The high temperature gives rise to prolific q̅q pair production. When a u̅u (d̅d) is created the u(d̅) can rapidly annihilate with an existing u(d) quark and the net number of u(d) quarks is then unchanged...an equilibrium is established. On the other hand when s̅s is created this does not happen and the strange (s and s̅) content of the plasma can rise dramatically and should persist into the final hadrons. Two other possible mechanisms can also increase the strange quark content [14], namely the Pauli exclusion principle and a possible Chiral symmetry restoration which results in the s-quark becoming massless. Signatures, in order of increasing sensitivity, are the ratios K/π and Λ/Σ, $\Lambda/\bar{p}$ and $\Omega/\bar{p}(!)$. One could simply measure those ratios in a small aperture spectrometer and correlate with other features such as multiplicity or $E_T$, but it would be preferable to identify enough hadrons in each event to obtain an event-by-event ratio. An experimental assessment of the possibilities was made at the Bielefeld Workshop [3]. Charged kaons $K^\pm$ can be identified in the target fragmentation region (large lab. angles) with time-of-flight or $dE/dx$ measurements, both of which are difficult (but not impossible) with high track densities. For the central ($5^\circ$) and forward regions the momenta are higher and a large ring-imaging Cerenkov (RICH) counter is the favoured - perhaps the only - approach. $K^0$ and $\Lambda^0$ have topological signatures, which however get progressively more difficult to recognize in the dense forward cone. For the $\Lambda^0 + \bar{p}n^+$ an additional handle on the $\bar{p}$ identity can come from a comparison of momentum with calorimetric energy deposit (kinetic energy + 2 m$_p$ from annihilation), up to \(\gamma 4\) GeV.

(2) Direct photons

Imagine a region of plasma surrounded by relatively cold nuclear matter. Real photons and virtual photons in the form of lepton pairs, can escape from the hot interior, i.e. from the full volume over the full lifetime of the plasma. The more charges there are and the more accelerations they undergo (both being signatures of a hot plasma) the more photons will be emitted. Photons (and lepton pairs) thus provide a thermometric probe of the interior. Pions and other hadrons are, on the other hand, only emitted from the cool surface, or they can form over the full volume when the plasma has expanded and cooled past the hadronization phase transition. Thus one expects the ratio $\gamma/\pi^0$ to be anomalously large in this class of events.
Experimentally it will certainly not be easy to observe such an enhancement, even if an event has say 50 direct photons, in the presence of hundreds of \( \pi^0 \) and \( \eta^0 \) decays. It would certainly require a very fine-grained electromagnetic calorimeter preferably in the form of towers rather than strip readout. This distinction can be seen in Fig. 11, which shows an event in one of the (two) arrays of 600 NaI crystals in use at the ISR (Expt. RB08). So-called strip readout gives only the projections, with self-evident matching problems as the multiplicity increases. It would clearly be expensive to cover the full solid angle with such an array of towers of NaI (or better, BGO) crystals, but such coverage is not of course necessary to establish the effect.

![Fig. 11](image)

(3) **Direct Lepton Pairs**

Similar arguments lead one to expect a relative excess of low mass lepton pairs. Kajantie and Miettinen [15] have noted that \( 1 \gamma \) annihilation of \( q \overline{q} \) pairs in the plasma can give significant yields of lepton pairs even beyond the nucleon-nucleon kinematic limit. Their mass spectrum and any resonance structure in this spectrum is of great interest. What will happen to the \( \Phi, \Psi, \Upsilon \) signals compared with the continuum? From the plasma phase one would expect the continuum to dominate, for the same reason that \( \gamma/\pi \) is enhanced. On the other hand the increased content of heavy quarks may tend to increase heavy quarkonium production when hadronization does occur. To add a "spice of exotica", if chiral symmetry restoration occurs the masses and widths of these states may change ("the melting of the rho"!) [16]. The latter observation would certainly be a dramatic discovery.

Lepton pair physics in nucleus-nucleus collisions is thus well justified. Experimentally one can consider \( e^+e^- \) as best studied in the backward region \( x_F \ll -1 \), the electrons recoiling (in the lab) from a very thin foil or fine wire target, while \( \mu^+\mu^- \) pairs are more naturally studied when produced forward \( x_F \ll +1 \) with a very good hadron-killing dump close to the target. Significant effects can be expected, with e.g. some hundreds of \( \mu^- \)-pairs per day beyond \( x_F = 1 \) in a hypothetical experiment compared with \( \sim 10 \) ordinary Drell-Yan pairs in the same region.
The three signatures discussed, namely strangeness, photons and lepton pairs are those that have so far received most attention, which may merely reflect our lack of imagination. Naturally this new class of collisions should be scrutinized for other weird effects as well as the things we can now imagine but do not really expect (like free quarks). It is also worth noting the special interest in using Bose-Einstein correlations as a tool to study these collisions. Pair distributions of identical bosons e.g. $\pi^+\pi^+$ show interference effects at low pair masses allowing one to measure the size of the emission region (as used with photons for stars in the Hanbury-Brown-Twiss effect). The technique improves in value rapidly with pion multiplicity. Unfortunately many (most?) of the pions come from resonance decay, so the spatial distribution of pion formation is not the same as that of hadronization. If the direct photon multiplicity is high then it would be of great interest to measure their Bose-Einstein interference, which should show a quite different spatial distribution.

I now turn to some considerations of experimental possibilities at the SPS, as considered both at the Bielefeld Workshop [3] and this workshop. Studies were made of the use of already existing detectors, of modifications to these and of new dedicated experiments.

The $\Omega$, an existing facility which will be able to use primary beams, is an example of the former with the planned basic configuration shown in Fig. 12. Important improvements to the present facility are the ring imaging Cerenkov counter, being constructed in the U.K., and a fine-grained (but strip readout, with tubes of liquid scintillator) electromagnetic calorimeter being built by Geneva University. The RICH
detector, Fig. 13, focusses the Cerenkov rings with an array of ~100 spherical mirrors onto planar, drifting photon detectors at the front. With Argon gas $\pi$ are identified from 5-80 GeV, K from 20-80 GeV and p from 20-150 GeV, and two particles which enter with only a few mm separation should be resolved. With the addition of a "beam dump calorimeter" and projectile fragment detector some early studies could be made, including $K/\pi$ and $\Lambda, \bar{\Lambda}, p, \bar{p}$ ratios. The inability of the $\Omega$ detector to handle efficiently very large multiplicity events will certainly be a limiting factor; one group is considering however making a proposal for an experiment with $\alpha$-beams ($\alpha$ to $\Omega$).

Fig. 13

The philosophy of making maximum use of existing facilities brings to mind also the European Hybrid Spectrometer, one arrangement of which is shown in Fig. 14, with the possibilities of using as an active heavy target the rapid cycling bubble chamber or HOLEBC, emulsions, a streamer chamber or an electronic vertex detector. Even the underground experiments UAn could be considered, with internal wire targets intercepting

Fig. 14
the accelerating or coasting $^{0+6}$ beam. If the wires (10 μm C-fibres... 1 μm W-wires) are the spokes of a spinning "target wheel" inside the vacuum pipe, timed to intersect the beam, then every SPS cycle one can do an energy scan and an A-scan! Fig. 15 shows UA1, with three potential target positions covering different angular regions (all in the central to backward target fragmentation region). There has been no technical study of this... it is just an idea... but there are obviously some things one might do at very little cost.

![Diagram of UA1 detector system](image)

**Fig. 15**

Active consideration is however being given to the possibilities of modifying experiments NA3 and NA10 to measure forward $\mu$-pairs with $^{0+6}$ beams with small heavy targets. NA3 is shown in Fig. 16a, and Fig. 16b shows modifications around the target region. They include a special new beam dump and a tiny (solid state detector) forward

![Diagram of NA3 modifications](image)

**Fig. 16**
hodoscope, and can enhance catastrophic collisions by requiring no (or few) projectile
fragments in this hodoscope. Experiment NA10 is shown in Fig. 17 and also considers
some rearrangements and additional detectors for nuclear beam physics. This experiment
aims to measure massive ($M_{\mu\mu} \geq 1.5$ GeV) $\mu$-pairs beyond $x_F = 1$, with an
estimate of several hundred with $M_{\mu\mu} = 2.0 \pm 0.1$ GeV in a 10-day run, if a plasma
is formed in $\approx 10\%$ of the collisions (the background from normal Drell-Yan pairs being
lower by an order of magnitude).

![Fig. 17](image1)

At Bielefeld a set of dedicated multiparticle spectrometers was considered, as
shown very schematically in Fig. 18. Each one can be swung around to scan in angle;
although each has a modest solid angle they intercept several particles and aim to
measure and identify them. They are aimed at particle production studies (including
resonances, K/\pi, \gamma/\pi^0, \bar{\Lambda}/\bar{\pi} etc. ratios, Bose-Einstein correlation measurements
and eventually cross-correlations – for example to search for a correlation between
large $\gamma/\pi^0$ in the NaI spectrometer and large K/\pi ratio in the RICH spectrometers.

![Fig. 18](image2)
It was concluded that while much exploratory physics may be done with such apparatus, there is a strong case for a new "universal" detector to study in as much detail as possible single events which may be very unusual in some triggerable features. Necessary requirements would be $4\pi$ coverage of track detectors and electromagnetic/hadronic calorimetry with special emphasis on the central-backward region, with a designed-in capability of handling very high multiplicity and large $E_T$ (transverse energy) events. The device should be able to identify electrons and muons, direct photons and $\pi^0$, charged and neutral kaons (and $\Lambda^0$), possibly even charmed particles, etc. The conceptual design that emerged, the "Heavy Ion General Spectrometer" is shown in Fig. 19. The target may be a fine wire (diameter $\approx 50\mu\text{m}$)

parallel to the tightly focussed beam, so that large angle photons and electrons emerge with negligible interaction probability. This may be surrounded with very fine grained (solid state) counter hodoscopes (vertex detector) and then a large cylindrical track chamber in a solenoid field. Electromagnetic calorimeter in the form of fine-grained towers precedes the coil, and the return yoke is used as a hadron calorimeter surrounded by muon chambers. Very forward particles (non-interacting projectile fragments) enter beam-dump calorimeters - little energy there can be used to trigger on "catastrophic events". Some (limited) $\pi/K/p$ identification would be achieved through $dE/dx$ measurements - but it is hard to do everything well! Although it would surely be unrealistic to propose such a facility specifically for nucleus-nucleus collisions at this time, the HIGS is so different from all existing SPS experiments that it would surely be a powerful facility also for hadron beam experiments. At the present SPS Workshop a derivative of this concept was presented, see Fig. 20. Known as the Spherical Field Spectrometer, it has an axially symmetric field pulled in by the thin forward "nose-cone". Many of the components (most of the magnet and hadronic calorimeters, some of the central drift chamber, some NaI walls) are presently part of the Axial Field Spectrometer at the ISR. The SFS is presently being studied, with emphasis also on far more detailed studies of lepton (e, $\mu$, $\nu$) production in hadron-hadron collisions than has been possible in the past. It would be a most powerful detector for searching for the effects of quark-gluon plasma formation in nuclear collisions.
To conclude:

(1) The acceleration of nuclei up to (and preferably beyond) \(^{16}\)O in the PS/SPS could, maybe, open up a wide new field of physics of a very fundamental nature. This is not "Nuclear Physics" but may be physics of quarks, gluons, confinement, vacuum properties and symmetry breaking/restoration.

(2) Many powerful existing detectors could be profitably exploited for little cost, at least for an initial exploratory phase, but...

(3) New detectors, optimized for the physics in question are likely to be needed for a thorough study.

Finally, there is of course no guarantee that the phase-transition will occur and can be convincingly observed; such is the nature of research. I omitted the most important discovery, which will be a surprise.

I would like to thank the participants of the Nuclear Beams and Targets session at the Workshop, and especially my colleagues Chris Fabjan and Bill Willis.

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Quark matter formation in high energy nucleus-nucleus collisions - predictions and observations.

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Introduction.

Recent developments of Quantum Chromodynamics provide great confidence in the existence of a new phase of matter - the quark-gluon plasma - which could be reached at high energy densities or temperatures [1-9].

The most realistic possibility within the next five years for creating conditions in which evidence for quark-gluon plasma may be found is by acceleration of medium heavy nuclei in the CERN SPS to an energy of ~200 A GeV. Valuable steps in this direction may be achieved already by the Plastic ball and streamer-chamber experiments if approved at CERN [10].

In this talk I give a short summary of the recent discussion around predictions and possible observations of quark-gluon plasma and fireballs in ultrarelativistic nucleus-nucleus collisions. In particular this talk is focused on heavy ion reactions at 200 A GeV.

The quark-gluon fireball and plasma - a new state of matter.

Three phases

Recent studies have indicated that there may be three phases: the hadron gas, an intermediate phase with quarks and gluons but also pions and their resonances, and the high temperature quark-gluon phase. The transition from a system of hadrons to a deconfined plasma of quarks and gluons is expected to take place somewhere between 0.5 and 1.5 GeV/fm³.

Production of a target fireball

Estimates of energy densities at very high energies i.e. more than 20 GeV/nucleon colliding beams, have been given e.g. refs. [1,3,6,8,9]. At these energies the beam and target fragmentation regions start to separate and a central region then appears in between.

Energy densities, ε, and quark number densities, n_q - n_u, are of importance in comparing hadronic and quark matter. The values of these parameters are crucial for the attainment of quark gluon plasma. Let us see how these numbers were estimated by Anishetty et al. [1].

The hit target nucleons, behind the passing through nucleus, are recoiling in the forward direction towards the nucleons at rest. This is schematically illustrated in Fig. 1. When the last nucleon in the target is passed by the projectile nucleus the first hit nucleon has moved a distance v(2R_A/c). The target fireball, moving with a velocity \( v_{FB} \), is therefore compressed to a thickness in the lab system which is

\[
2R_A \left(1 - \frac{v_{FB}}{c}\right),
\]

(1)

In the rest system of the fireball the compression (CF-compression factor) is
Fig. 1. Production of a quark-gluon plasma in ultrarelativistic nucleus-nucleus collisions.

\[
\gamma_{FB} \cdot \frac{2R_A}{c} \left(1 - \frac{v_{FB}}{c}\right) = \frac{2R_A}{CF} \tag{2}
\]

\[
CF = \gamma_{FB} \sqrt{\gamma_{FB}^2 - 1} = e^{\gamma_{FB}} \tag{3}
\]

From pp collisions we know that the recoiling nucleon is slow (p_\perp \sim 1 \text{ GeV/c}, \, \gamma \sim 1.5). However, the pions are moving faster (\gamma \sim 10) [8]. Therefore if they are moving forward and trapped in the fireball they accelerate it.

Some of the virtual fragments produced in the collision are materialized inside the target nucleus. These slow particles have a chance to becoming trapped in the hadronic fireball. If we assume that pions with \gamma < 2 are trapped then about 3 pions are added to the fireball for every colliding target nucleon. From pp collisions we know the energy of these slow pions. Using this information the energy trapped per hit target nucleon is found to be \mu_{FB} \approx 3.6 \text{ GeV} [1]. The energy density in the fireball, \varepsilon, is:
\[ \varepsilon = \frac{A}{V} M_{FP} \cdot CF = 0.15 \cdot 3.6 \cdot 3.6 \approx 2 \text{ GeV/fm}^3 \] (4)

and far beyond the density in nuclear matter and in nucleons:

\[ \varepsilon = 0.17 \text{ GeV/fm}^3 \] (5)

\[ \varepsilon = 0.44 \text{ GeV/fm}^3 \] (5)

Nuclear Matter

For the quark density we obtain:

\[ n_q - n_{\bar{q}} = 0.15 \cdot 3 \cdot CF = 1.6 \text{ fm}^{-3} \] (6)

Production of a quark-gluon plasma in the central region.

To estimate the energy density in the fireball we will consider the particle density in the central region of rapidity \( \rho(y) \):

\[ \frac{1}{\sigma} \frac{d\sigma}{dy} = \frac{dn}{dy} = \rho(y) \] (7)

The average separation in rapidity between the pions is

\[ \Delta y = \frac{1}{\rho} \] (Fig. 2).

\[ \begin{array}{c}
\text{TARGET} \\
\text{FIREBALL}
\end{array} \quad \begin{array}{c}
\text{PRODUCED WITH} \\
\gamma = \cosh y
\end{array} \quad \begin{array}{c}
\text{RICH IN} \\
\text{STRANGE PARTICLES} \\
\text{AND BARYONS}
\end{array} \quad \begin{array}{c}
\text{ONE PION}
\end{array} \quad \begin{array}{c}
\text{FIREBALL} \\
\text{RICH IN MESON AND} \\
\text{POOR IN BARYONS}
\end{array}
\]

\[ \Delta y = \frac{1}{\rho} \]

Fig. 2. Production of a quark-gluon plasma in the central region of rapidity.

\[ z = (\text{life-time}) \cdot \text{velocity} = (\gamma \cdot 1) v = \]

\[ = (\cosh y' \cdot 1) \cdot \tanh y' = \sinh y' = \sinh \frac{1}{\rho} \approx \frac{1}{\rho} \text{ fm} \] (9)

from the pion at rest (at \( z = 0 \)).

The average volume occupied by one pion is \( V = \text{area} \cdot z = \pi A_B^{2/3} \rho^{-1} \).

The energy in this volume is \( <m_\perp> \) and the energy density is

\[ \varepsilon = \frac{<m_\perp>}{V} = \frac{<m_\perp>}{\pi A_B^{2/3}} \cdot \rho = \frac{<m_\perp>}{\pi A_B^{2/3}} \frac{dn}{dy} \] (10)
To produce a quark-gluon plasma the density of particles, neglecting any sideways leakage, have to be larger than a critical value \( \rho_c \):

\[
\frac{dn}{dy} > \rho_c = \frac{\pi A_B^{2/3}}{\langle m_1 \rangle} \cdot \varepsilon_c
\]  

(11)

\( \varepsilon_c \) is the energy density needed to produce quark matter. The transition from a system of hadrons to a deconfined plasma of quarks and gluons should take place somewhere between 0.5 and 1.5 GeV/fm\(^3\) i.e. three to ten times normal nuclear density. The relevant temperature are in the 200 MeV range [11].

\( \rho_c \) depends on the size of the beam nucleus. From a \(^{238}\text{U} \) to a \(^{16}\text{O} \) projectile, the critical particle density differs with a factor of 6 for the same value of \( \varepsilon_c \) and neglecting sideways leakage. For illustration we consider \(^{238}\text{U} + {^{238}\text{U}} \) collisions at ISR energies.

Inserting for example the values \( \varepsilon_c = 1.5 \text{ GeV/fm}^3 \); \( A_B^{2/3} = 38.4 \ (^{238}\text{U}) \) and \( \frac{\langle m_1 \rangle}{\pi} \approx 10 \text{ MeV} \) we obtain \( \rho_c \approx 600 \) i.e. \( \frac{dn}{dy} > 600 \). We obtain the same energy density in a central reaction \(^{16}\text{O} \) on \(^{238}\text{U} \) when \( \rho_c = 100 \). For the target dependence we have:

\[
\frac{dn}{dy} = \rho = \rho_0 A_T^{2+3p/3} \]

(12)

\[
A_T^{2+3p/3} > \frac{\rho_c}{\rho_0} \quad \text{(condition for } \varepsilon > \varepsilon_c \text{)}
\]

(13)

At ISR energies \( \rho_0 = 2.1 \) and therefore, if \( A_B = A_T \),

\[
\frac{p/3}{A_T} > \frac{\pi}{\langle m_1 \rangle} \frac{\varepsilon_c}{\rho_0} = 6.3
\]

i.e. the conditions for reaching \( \varepsilon > 1.5 \text{ GeV/fm}^3 \) is \( p > 1 \) [9].

**Heavy flavour production.**

In the target and beam fireballs a large number of \( u \) and \( \bar{d} \) quarks are present already in the initial stage of the reaction. If they are thermalized in the plasma they occupy the lowest lying levels (Fig. 3). This means that the \( u \) and \( \bar{d} \) production may be suppressed because they are fermions and can not populate the lowest \( u \) and \( \bar{d} \) levels which already are occupied (the Pauli Exclusion Principle). It may therefore be more energetically favourable to produce quarks with heavier flavour i.e. \( s \bar{s} \) pairs (Fig. 3). One may thus even populate more \( s \) quarks than \( u \) and \( \bar{d} \) in the plasma. Especially in the fireball regions this may increase the \( K/\pi, \Lambda/\pi, \Xi/\pi \) etc. ratios [13,14].

Fig. 3. \( u \bar{u} \) and \( \bar{d}d \) production is suppressed while heavy flavour production may be favoured [12].
Lepton pair production.

Kajantie and Miettinen [16] have studied the $q\bar{q}$ annihilation to a massive virtual photon in a hot plasma. These virtual photons give rise to significant ratios of $e^+e^-$ pairs at large rapidity, even beyond the kinematic limit for nucleon-nucleon collisions (Fig. 4). It has been suggested that experimentally one should look for electron pairs produced backwards from a thin target and muon pairs in the very forward direction after a hadron absorber close to the target [17].

Melting of vector mesons.

If a plasma of only quarks and gluons are produced of such a size that its surface could be neglected we would not expect to see any vector mesons because they do not exist. If they existed in an earlier phase they have been "melted". The disappearance of vector mesons would be observed by weakly interacting probes, i.e. in the lepton pair spectrum [18,19].

Direct photons.

Prompt photons are radiated by the thermalized plasma. They measure the temperature of the quark gluon plasma. Correlations can reflect the space-time structure of the photon production process, the time during which the production occur, as well as the onset of any coherence.

Nucleus-nucleus collisions at $\sim 200$ A GeV.

Guided by observations in hadron-nucleus (hA) reactions some general properties of nucleus-nucleus collisions can be worked out. The purpose of such an extrapolation is mainly to present figures useful for the design of experimental set ups [20].

Multiplicities.

We assume that pion production in high energy heavy ion reactions only depends on the projectile energy per nucleon, on the number of participating nucleons, $P$, and that the multiplicity can be factorized into one energy-dependent, $n_0(E)$, and one energy-independent contribution, $P(\Lambda_1, \Lambda_2, \beta)$. The latter depends on the mass of the beam nucleus $\Lambda_B$, on the target nucleus $\Lambda_T$, and on the impact parameter, $b$:

$$n(\Lambda_B, \Lambda_T, b, E) = n_0(E) P(\Lambda_B, \Lambda_T, b)$$ (14)

$P=\Lambda_B \Lambda_T$ is simply the number of nucleons in the overlapping volumes of the two nuclei (Fig. 5). For pA reactions we have
\[ n(1,A_T,b,E) = n_o(E) P(1,A_T,b) = n_o(E)(<\nu>+1) \]  \hspace{1cm} (15)

We assume that all participant nucleons contribute with equal efficiency to the pion production and that the average contribution per participant nucleon is the same as in \( pA \) reaction i.e.

\[ n_o(E) = \frac{<n>_{pA}}{<\nu>+1} \]  \hspace{1cm} (16)

At present only a few cosmic (CR)-reactions at energies \( \gtrsim 100 \text{ A GeV} \) are described in the literature \([20,21]\). In Fig. 6 some central CR-reactions in the energy range 300-500 A GeV are shown. They are all in fairly good agreement with eqs. (14) and (16).

**Rapidity distribution**

To estimate rapidity distributions in AA reactions, we assume that their shapes in central AA reactions are determined by scaling of the ratio \( k \) where

\[ k = \frac{p_T}{p_B} \]  \hspace{1cm} (17)

Fig. 5. The clean cut participant-spectator picture of a nucleus-nucleus reaction.

Fig. 6. Shower particle multiplicities in cosmic ray events as a function of the number of participating nucleons \([20,21]\).
i.e., by the number of participant target nucleons, \( P_T \), to the number of participating projectile nucleons, \( P_B \). This assumption is justified by observations in pA-reactions. Here it is found that \((v+1)\) participant nucleons give rapidity distributions with shapes relatively independent of the target mass. For pA reactions we have

\[
\frac{dn}{dy} = \rho(y) = \rho_0(y) P_B + \rho_0(y) \beta(y) (P_T - P_B) \\
P_B = 1; \quad P_T = <v> \tag{18}
\]

\[
\rho(y) = \rho_0(y) [1 + \beta(y) (<v>-1)], \quad \text{(pA reactions)} \tag{19}
\]

Fig. 7 shows \( \beta(y) \) for 200 GeV pA reactions detected in streamer chamber \([22,23]\). \( \beta(y) \) is given by the equation:

\[
\beta(y) = 4.48 e^{-1.91y} - 0.155y + 0.874 \tag{20}
\]

In the range \( 0 < y < 7 \) we obtain \( <\beta> = 0.48 \). For AA collisions we have:

\[
\rho(y) = \rho_0(y) P_B + \rho_0(y) \beta(y)(P_T - P_B) \tag{21}
\]

and

\[
\rho(y) = P_B \rho_0(y) [1 + \beta(y)(k-1)], \quad \text{(AA reactions)} \tag{22}
\]

pA and AA reactions with the same \( k (=<v>) \) -values are assumed to exhibit y-distributions with similar shapes.

Fig. 8 gives \( P = P_B + P_T \) for average pA and central \(^{16}\)O+A reactions. In Fig. 9 distributions extrapolated from pEm reactions are compared with CR-events and in Fig. 10 rapidity distributions estimated for \(^{16}\)O + \(^{238}\)U at 200 A GeV using eqs. (22) and (20) are shown.

**Multiplicity fluctuations.**

Figs. 9 and 10 show the average behaviour. Large fluctuations may occur (c.f. Fig. 9).

The rapidity distribution for produced charged particles (solid curve) estimated for \(^{16}\)O+\(^{238}\)U collisions at 200 A GeV from eqs. (19) and (22) is compared with the rapidity distribution of singly charged projectile spectator fragments (dotted curve) in Fig. 11.

Projectile spectator fragments are expected in a narrow forward cone and with near beam velocity.
Fig. 8. The number of participants, $P$, for average pA and central $^{16}O+A$ reactions.

Fig. 9. Pseudo-rapidity distributions in CR-events detected in emulsion. The solid curve is an extrapolation from proton-emulsion nucleus collisions at corresponding energies [20,21].
Fig. 10.
a) Rapidity distributions estimated for $^{16}\text{O}+^{238}\text{U}$ collisions at 200 A GeV using pA streamer chamber data [22]. Two estimates are shown: the solid curve when $\rho_o = \rho_o^+$ the density of all charged particles and the dotted curve when $\rho_o = 2\rho_o^-$ the density of negative particles.

b) Comparison between the $\rho_o$ values estimated from linear fits to pA data and the actually measured $\rho_o^-$ values in pp-collisions.

Fig. 11. The rapidity distribution for produced charged particles (solid curve) estimated using streamer chamber data (c.f. Fig. 10). The dotted curve shows the pseudo rapidity distribution for singly charged projectile spectator fragments estimated for 200 A GeV $^{16}\text{O}+^{238}\text{U}$ collisions.
in the laboratory system [24]. At high energy the spectator protons are expected to be distributed around a pseudo-rapidity value \( \eta_s \) where [21]

\[
\eta_s = \ln p_{\text{inc}} + 3
\]

\( p_{\text{inc}} \) is the momentum per nucleon in GeV/c of the incident nucleus. The rapidity distribution of spectator protons is narrow. Outside \( \eta = \eta_s \pm 1 \) only a small number appears. A selection of events with low densities in the nuclear fragmentation region (say \( \eta_s - 2 \), at 200 GeV this corresponds to \( \theta_{\text{lab}} \approx 0.3 \)) and large multiplicities at say \( 1 < \eta < 3 \) (correspond to \( 40^\circ \), \( \eta_{\text{lab}} < 50^\circ \)) may select reactions with high particle and energy densities [13].

**Estimated energy densities.**

It has been pointed out by Gyulassy [25] that energy densities extracted from some central ultrarelativistic CR-events are high. Here I give a similar estimate of the energy densities as given by Gyulassy [25]. The Ca-Pb reaction in Fig. 9 has \( (dn/d\eta)_{\text{max}} \approx 150 \) at \( \eta = 3 \). If we assume that the number of produced pions are \( 3/2 \eta_s \) we obtain (c.f. eq. 10)

\[
\epsilon = 0.1 \cdot \frac{1}{\left(A_B^{2/3}\right)^2} \cdot \frac{dn}{d\eta} = 0.1 \frac{1}{\left(40^{2/3}\right)^2} 150 \frac{3}{2} = 1.9 \text{ GeV/fm}^3
\]

---

**Fig. 12.** The ratio of densities in \(^{16}\text{O}+\text{A}\) collisions to that of \(p\bar{p}\)-collisions versus \(A\) and for different rapidity bins.
So the event shown in Fig. 9 may indicate that already at 200 A GeV high energy densities are produced for a transition to quark gluon matter.

In \(^{16}O + ^{238}U\) reactions, extrapolated from pA reactions at 200 GeV, we have \(\rho^*(\eta)_{\text{max}} \approx 65\) at \(\eta = 2\) (Fig. 10). If we include neutral particles \(\rho(\eta)_{\text{max}} \approx 100\). The energy density is then:

\[
\epsilon = 0.1 \frac{1}{(A_{B})^{2/3}} \rho = 0.1 \frac{1}{(16)^{2/3}} 100 = 1.5 \text{ GeV/fm}^3
\]  

(24)

Imagine that large fluctuation may occur. Therefore much higher values could be reached.

We estimate the value of \(\rho\) defined in eq. (12) for \(^{16}O + A\) reactions:

\[
\frac{p}{3} > \left(\frac{A_{B}}{A_{T}}\right)^{2/3} \frac{\pi \epsilon_c}{\epsilon_{\text{c}} - \epsilon_{\text{m}}} \frac{1}{\rho_o}
\]  

(25)

For \(\epsilon_c = 1.5 \text{ GeV/fm}^3\), \(\rho_o = 2.4 \text{ fm}^3\), \(A_{B} = 16\) and \(A_{T} = 238\) we obtain \(p > 0\).

We can expect to be in this regime already at 200°A GeV (Fig. 12).

A final comment.

In this talk I have shown a few speculations about the physics which may meet us if ultrarelativistic heavy ions would become a reality. Let us hope that in the near future physicists can probe this field with experiments and not only on paper.

References.


THE STATES OF MATTER IN QCD

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Abstract: We survey the thermodynamics of strongly interacting matter, as predict-
ed by quantum chromodynamics. At low values of temperature and density, we
find hadronic matter, while at high values the system becomes a primordial
plasma of non-interacting massless quarks and gluons. Separating the two
regimes is a transition region in which colour deconfinement and chiral symme-
try restoration take place. We obtain preliminary values for the transition
parameters and discuss the possibility of observing plasma formation in high
energy heavy ion collisions.

I. Introduction

Changes of state are among the most familiar and yet most striking instances
of collective behaviour. Do they also occur in nuclear matter? Will a sufficient
increase in density lead us out of the realm of normal nuclear matter, made up of
nucleon constituents, into a new world, in which quarks and gluons form a plasma
of primordial matter?

Such a transition has been discussed ever since the advent of the quark model
of hadrons. Today the pursuit of these ideas, the physics of strongly interacting
matter at very high density, is emerging more and more as an autonomous field of
research\(^1\). It brings together problems and features from nuclear physics, partic-
le physics, and statistical physics. In cosmology, it is essential for an under-
standing of the early stages of our universe.

The rapid recent rise of interest in this field has two main origins: quantum
chromodynamics (QCD) and heavy ion physics.

With QCD, we have today a serious and so far "uncontradicted" candidate for
the theory of strong interactions. This provides us in principle with the possibili-
ity of deriving strong interaction thermodynamics. Phenomenological models of
various types have been employed for many years to discuss a possible transition
from nuclear to quark matter; they always have two phases as input and obtain the
transition by construction. The lattice formulation of QCD\(^2\) now for the first
time allows us to deduce the phases of strongly interacting matter and the transi-
tion behaviour from one basic theory. QCD thermodynamics predicts the existence of
a quark-gluon plasma at high temperature as well as that of hadronic matter at low
temperature; between these regimes lies a transition region, in which - coming
from low $T$ - colour is deconfined and chiral symmetry restored. That is one side
of the picture.
Obviously, we would like to test these ideas experimentally. Their relevance for cosmology and neutron star physics was realized immediately; now it is becoming apparent that heavy ion collisions may allow us to study high density strong interaction physics in the laboratory. Several estimates today suggest that the conditions in energy and density needed for plasma formation could be reached through heavy ion collisions using existing particle accelerations—provided these are adapted to accommodate heavy ions. Moreover, specific machines dedicated to this field of physics have been proposed. Arguments have been given that collective systems produced in such collisions may exist long enough to attain equilibrium, both thermal and "chemical". The study of the observable consequences of plasma formation is at present in full swing.

It is these two aspects then:
- the chance to study the high density limit of the fundamental theory of strong interactions, and
- the chance to produce in the laboratory the primordial states of matter, which presently make ultrarelativistic heavy ion physics a subject of such principal importance and of such great fascination. In the next chapter, we shall study the states of matter predicted by QCD; in chapter III, we shall then see to what extent these states can be formed in relativistic heavy ion collisions.

II. The thermodynamics of quarks and gluons
A. PHENOMENOLOGY

Quantum chromodynamics describes the interaction of quarks and gluons—the strong interaction. Quarks and gluons are not observed as free objects in the physical vacuum: in non-interacting form, as free particle states, we only see hadrons. The low density limit of QCD thermodynamics must therefore lead to a system of non-interacting hadrons. On the other hand, sufficiently energetic "hard" hadron-hadron or hadron-lepton scattering processes indicate independent interactions of quarks and gluons with each other or with leptons: strong interactions become weak at high energies. This novel feature, "asymptotic freedom", is in fact provided by QCD. To obtain such a behaviour, quarks and gluons must have an additional intrinsic degree of freedom, "colour", which makes gluon-gluon interactions possible in a gauge-invariant framework. In potential language, the confining force between quarks rises linearly with increasing separation; at short distances, however, the potential becomes Coulomb-like. For the high-density limit of QCD, we therefore expect a plasma of non-interacting, "Debye-screened" quarks and gluons; here, in addition, an overall shift in energy between vacuum and plasma ground state has to be taken into account.

Let us use these limiting forms to construct a simple two-phase picture of strongly interacting matter. Our thermodynamic variables are the temperature $T$,
the baryonic chemical potential $\mu$, and the volume $V$; $\mu$ specifies the baryon number density. Here and in the following we shall for simplicity always restrict ourselves to non-strange hadrons (pions and nucleons) and quarks ($u$ and $d$).

For zero baryon number ($\mu = 0$), we have at low temperatures basically a gas of pions. For a non-interacting system of massless pions, the pressure is given by

$$P_H(T, \mu = 0) = \frac{\pi^2}{90} \times 3 \times T^4$$

(2.1)

taking into account the three charge states of the pion. The corresponding energy density is

$$\varepsilon_H(T, \mu = 0) = \frac{\pi^2}{30} \times 3 \times T^4$$

(2.2)

At sufficiently high temperatures, we expect a plasma of non-interacting quarks and gluons, with the pressure

$$P_Q(T, \mu = 0) = \frac{\pi^2}{90} \left[ 2 \times 8 + \frac{7}{8} \times 2 \times 2 \times 2 \times 3 \right] T^4 - B$$

(2.3)

Here both gluons (first term in square brackets) and quarks (second term) have two spin degrees of freedom; in accord with the SU(3) gauge structure of QCD, gluons have eight and quarks three colour degrees of freedom. There are, for $\mu = 0$, both quarks and antiquarks present, and we include, as mentioned, two flavours. Finally, the (positive) bag constant $B$ accounts for the ground state shift in the plasma; to provide confinement at low density, the physical vacuum exerts a pressure on the system. The corresponding energy density becomes

$$\varepsilon_Q(T, \mu = 0) = \frac{\pi^2}{30} \left[ 2 \times 8 + \frac{7}{8} \times 2 \times 2 \times 2 \times 3 \right] T^4 + B$$

(2.4)

To satisfy the thermodynamic requirement of minimal free energy, the system must be in the state of higher pressure. For low $T$, this is the pion gas, for high $T$, the plasma; see fig. 1. From $P_H(T_C, 0) = P_Q(T_C, 0)$ we find

$$T_C = \left[ \frac{(45/17\pi^2)}{B} \right]^{1/4} \approx 0.72 \ B^{1/4}$$

(2.5)

for the transition temperature at $\mu = 0$. From the description of hadronic spectra, we have $145 \text{ MeV} \leq B^{1/4} \leq 235 \text{ MeV}$; using $B^{1/4} \approx 190 \text{ MeV}$, we obtain $T_C \approx 140 \text{ MeV}$. The transition arrived at in this way is by construction of first order, with

$$\varepsilon_Q(T_C, 0) - \varepsilon_H(T_C, 0) = 4B$$

(2.6)

as the latent heat per unit volume. The resulting energy density is also shown in fig. 1.

Let us now apply the same simple model to the case of cold strongly interacting matter ($T = 0$). In the hadronic phase, we now have a completely degenerate Fermi gas of nucleons, whose pressure and energy density are given by
\[ P_H(T=0, \mu) = \frac{1}{2\pi^2} \times 2 \times 2 \times \mu^+ , \]  
\[ \epsilon_H(T=0, \mu) = \frac{1}{6\pi^2} \times 2 \times 2 \times \mu^- , \]  
(2.7)  
(2.8)

with protons and neutrons of two possible spin orientations. The baryon number density is given by

\[ n_B = 2\mu^3/3\pi^2 . \]  
(2.9)

At high baryon number density, we expect a cold plasma, whose pressure is given by

\[ P_Q(T=0, \mu) = \frac{1}{2\pi^2} \times 2 \times 2 \times 3 \times \mu_Q^+ - B \]  
(2.10)

including two flavour and three colour degrees of freedom for the quarks; \( B \) again denotes the vacuum pressure on the system. The quark density is given by

\[ n_Q = 2\mu_Q^3/\pi^2 \]  
(2.11)

in terms of the quark chemical potential \( \mu_Q \); from \( n_B = n_Q/3 \), we obtain

\[ \mu_Q = \mu \]  
(2.12)

so that the subscript \( Q \) on the chemical potential in eq. (2.10) can be dropped. The energy density of the plasma is

\[ \epsilon_Q(0, \mu) = \frac{1}{6\pi^2} \times 2 \times 2 \times 3 \times \mu^+ + B . \]  
(2.13)

We obtain the critical point by requiring minimal thermodynamic potential, which again means highest pressure. From \( P_H(0, \mu_C) = P_Q(0, \mu_C) \) we get

\[ \mu_C = (3\pi^2 B)^{1/4} \approx 2.33 B^{1/4} \]  
(2.14)

which implies

\[ n_C = 2(3\pi^2)^{-1/4} B^{3/4} \approx .85 B^{3/4} \]  
(2.15)

for the critical density. Using as above \( B^{1/4} \approx 200 \text{ MeV} \), this yields

\[ n_C \approx 5n_0 \]  
(2.16)

with \( n_0 = 0.17 \text{ fm}^{-3} \) denoting standard nuclear density. In comparison, the baryon number density of a inside a nucleon is about \( 3n_0 \), so that the value (2.16) seems not unreasonable. Finally, we obtain, as in eq. (2.6),

\[ \epsilon_Q(0, \mu_C) - \epsilon_H(0, \mu_C) = 4B \]  
(2.17)

for the latent heat of the transition at \( T = 0 \).

Extrapolating these results to intermediate temperatures and chemical potentials, we obtain the phase diagram shown in fig. 2. It clearly presents only the rudiments of the picture: the inclusion of internuclear forces and/or resonances in the hadronic phase, and the inclusion of perturbative terms in the plasma would
Figure 1: Pressure (a) and energy density (b) in a two-phase ideal gas model for strongly interacting matter.

Figure 2: Phase diagram in a two-phase ideal gas model for strongly interacting matter; \( n_B \) is a baryon number density in units of standard nuclear density \( n_0 \).
certainly modify the values of the transition parameters. Nevertheless, the basic reason for the transition would be expected to remain: we have more degrees of freedom in the plasma phase, causing it to dominate at high temperatures and pressures. Because of $B$, we have a higher pressure "normalization" in the hadronic phase, leading it dominate at low temperatures and pressures.

In any phenomenological model, such as the one considered here, the transition is of course obtained by construction. The basic question for QCD therefore is: can we derive both critical behaviour and limiting phases from one fundamental description? In the following section, we shall see that this is indeed the case.

B. THE PHASE STRUCTURE OF QCD

The Lagrangian density of quantum chromodynamics is given by

$$\mathcal{L}(A, \psi, \overline{\psi}) = -\frac{1}{4} \left[A^a_\mu A^a_\mu - g f^{abc} A^b_\mu A^c_\nu \right] \psi_k \overline{\psi}_k \psi_k + \frac{1}{2} \mu^2 (A^a_\mu A^a_\mu)^{\frac{1}{4}} + \overline{\psi}_f (i \gamma^\mu - g A^a_\mu \lambda^a) \psi_f$$  \hspace{1cm} (2.18)

in terms of the gluon fields $A^a_\mu$ and the quark spinors $\psi^k_f$. Here the $f^{abc}$ are the structure constants of the colour gauge group, whose generators $\lambda^a$ satisfy $[\lambda^a, \lambda^b] = i f^{abc} \lambda^c$. The gluonic colour indices $a,b,c$ run from one to eight for colour $SU(3)$, those for the quarks $(k)$ from one to three ("red, white and blue").

As we shall here consider only $u$ and $d$ quarks, the flavour index $f$ only takes on two values.

If we would set the structure constants $f^{abc}$ equal to zero, we would recover quantum electrodynamics; it is the non-abelian nature, with the gluon-gluon interaction in eq. (2.18), which distinguishes QCD. In contrast to electrodynamics, we thus have in chromodynamics an interacting theory even if we leave out quarks altogether. The resulting Yang-Mills theory in fact already exhibits many of the essential features of the full theory and can therefore be taken as a model to introduce both formalism and evaluation techniques of QCD thermodynamics. We shall make use of this and first consider purely gluonic matter; subsequently, we shall go on to full QCD with quarks.

The theory introduced with the Lagrangian (2.18) is an interacting relativistic quantum field theory; so far, the only general non-perturbative way to solve such a theory, is provided by the lattice regularization approach of K. Wilson\(^2\). Together with the Monte Carlo evaluation technique pioneered by M. Creutz\(^3\), it will form the basis for our treatment of QCD thermodynamics.

The partition function for a quantum system described in terms of fields $A(x)$ by a Hamiltonian $H(A)$ is defined as

$$Z = \text{Tr} \{ \exp \ - \beta H \} \hspace{1cm} (2.19)$$

where $\beta^{-1} = T$ is the physical temperature. The conventional lattice formulation is obtained from this in three steps, which we shall now briefly sketch for the Yang-Mills system.
\[ (A) = -\frac{1}{2} \left[ \partial_{\mu} A_{\nu}^a - \partial_{\nu} A_{\mu}^a - g f_{bc}^a A_{\mu}^b A_{\nu}^c \right]^2. \]  
(2.20)

First, the partition function \( Z \) is rewritten in form of a path integral:\(^4\)

\[ Z(\beta, V) = \int [dA] \exp \left\{ -\frac{B}{\beta} \int_0^\beta \int d^3x \mathcal{L}[A(x, \tau)] \right\}, \]
(2.21)

where \( \mathcal{L}[A(x, \tau)] \) is the Euclidean density, with \( \tau = i\tau \), periodic in \( \tau \). The three-dimensional integral of the Hamiltonian formulation \( \langle H \sim \int d^3x \mathcal{H}(x) \rangle \) thus becomes an asymmetric four-dimensional integral, with the "special" dimension measuring the temperature.

In the next step, we replace the Euclidean \( x-\tau \) continuum by a finite lattice, with \( N_\sigma \) sites and spacing \( a_\sigma \) in the spatial part, \( N_\beta \) sites and spacing \( a_\beta \) in the temperature direction. The integrals in the exponent of eq. (2.21) now become sums, and we have \( V = (N_\sigma a_\sigma)^3 \), \( B = N_\beta a_\beta \). The thermodynamic limit requires \( N_\sigma \to \infty \) at fixed \( a_\sigma \); the continuum limit is obtained by \( a_\sigma, \ a_\beta \to 0 \) with fixed \( N_\beta a_\beta \), which forces also \( N_\beta \to \infty \). The success of the approach rests on the (lucky) facts that already rather small lattices \((N_\sigma \sim 5-10, \ N_\beta \sim 3-5)\) seem to be asymptotic, and such that scale changes (changes in lattice spacings) can be connected to changes in the coupling strength \( g \) by the renormalization group relation, indicating continuum behaviour.

In the last step, we replace the gauge field 'variable' \( A_{\mu}(x_i + x_j/2) \) associated to the link between two adjacent sites \( i \) and \( j \) by the gauge group element

\[ U_{ij} = \exp \left\{ -i(x_i - x_j)^{\mu} A_{\mu}^{\frac{x_i + x_j}{2}} \right\}, \]
(2.22)

where \( A_{\mu}(x) = \lambda_a \eta_{\mu}(x) \). With this transformation, the partition function becomes

\[ Z(\beta, V) = \int \prod_{\text{links}} \{dU_{ij}\} \exp(-S(U)), \]
(2.23)

where the lattice action is, for colour \( SU(N) \), given by

\[ S(U) = \frac{2N}{g^2} \left\{ \sum_{P_\sigma}^{a_\sigma} \left[ 1 - \frac{1}{N} \text{Re} \text{Tr} U_{ij} U_{jk} U_{kl} U_{ij} \right] \right. \]
\[ + \sum_{P_\beta}^{a_\beta} \left[ 1 - \frac{1}{N} \text{Re} \text{Tr} U_{ij} U_{jk} U_{kl} U_{ij} \right] \right\}. \]
(2.24)

Here the sum \( \{P_\sigma\} \) runs over all purely spacelike lattice plaquettes \( (ijkl) \), while \( \{P_\beta\} \) runs over all those with two spacelike and two "temperature-like" links. - If we insert eq. (2.22) in eq. (2.23/2.24) and expand for small lattice spacings \((|x_i - x_j| \to 0)\), then we recover in leading order the starting form
(2.21). In eq. (2.24), we have kept the colour gauge group general, since the behaviour of the SU(2) Yang-Mills system is presently known with greater precision than that for the SU(3) system. We shall therefore generally consider both; they appear to provide basically the same thermodynamics.

From eq. (2.23/2.24), the energy density
\[ \epsilon = -\frac{1}{V} \left( \frac{\partial \ln Z}{\partial \beta} \right)_V = \frac{\partial}{\partial \beta} \left( \frac{\partial}{\partial \beta} \right)_{\beta} \right]_{\beta} (2.25) \]
is found to be
\[ \epsilon = 2N_{\sigma B} a_\sigma a_B g^2 \left( \begin{array}{c} a_B \Sigma \left( 1 - \frac{1}{N} \Re \Tr UUUU \right) \\ a_\sigma \Sigma \left( 1 - \frac{1}{N} \Re \Tr UUUU \right) \end{array} \right) \]
with <> denoting the usual thermodynamic average
\[ \langle X \rangle = \left\{ \int \Pi dU \ e^{-S(U)} X(U) \right\} / \left\{ \int \Pi dU \ e^{-S(U)} \right\} \]. \hspace{1cm} (2.26)

Eq. (2.26) is our starting point for the Monte Carlo evaluation of gluon thermodynamics.

The evaluation is now carried out as follows. The computer simulates an \( N_{\sigma} x N_{B} \) lattice; for convenience we choose \( a_\sigma = a_B = a \). Starting from a given ordered (all \( U = 1 \), "cold start") or disordered (all \( U \) random, "hot start") initial configuration, successively each link is assigned a new element \( U' \), chosen randomly with the weight \( \exp \left( -S(U) \right) \). One traverse of this procedure through the entire lattice is called one iteration. In general, it is found that five hundred or so iterations provide reasonable first indications about the behaviour of the energy density (2.26), but for some precision one should have more. The results shown here for colour SU(2) are obtained with typically around three thousand iterations, after which we observe quite stable behaviour; the SU(3) results are generally based on a few hundred iterations. The work was done with \( N_{\sigma} = 7,9,10 \) for \( N_{B} = 2,3,4,5 \); apart from expected finite lattice size effects there was no striking \( N_{\sigma} \) dependence of \( \epsilon \), suggesting that in general the thermodynamic limit is reached. To give at least some intuitive grounds for this, note that a \( 10^3 \times 3 \) lattice has about 12,000 link degrees of freedom.

As result of the Monte Carlo evaluation, we obtain for a lattice of given size \( (N_{\sigma}, N_{B}) \) the energy density \( \epsilon \) as function of \( g \). In the continuum limit, \( g \) and the lattice spacing \( a \) are for colour SU(N) related through
\[ a \Delta L = (11 Ng^2/48n^2)^{-51/121} \exp \left( -24n^2/11 Ng^2 \right) \]; \hspace{1cm} (2.28)
this relation is found by requiring a dimensional parameter \( \Delta L \) to remain constant under scale changes accompanied by corresponding changes in coupling
strength. Hence once we are in the region of validity of the continuum limit, eq. (2.28) gives us the connection between $g$ and $A$. Since $(N_c a)^{-1}$ is the temperature in units of $A_L$, we then have the desired continuum form of $\varepsilon(\beta)$.

In fig. 3, we show the resulting energy density $\varepsilon$ as function of the temperature $T$, for both SU(2)$^5$ and SU(3)$^6$. We first note that at high temperatures, the results of the Monte Carlo evaluation agree quite well with the anticipated Stefan-Boltzmann form

$$\frac{\varepsilon}{T^4} = \begin{cases} \pi^2/3 & \text{SU(2)} \\ 8\pi^2/15 & \text{SU(3)} \end{cases}$$

Let us now go to lower $T$, concentrating on the SU(2) case. At about $T = 50 A_L$, $\varepsilon$ drops sharply. The derivative of $\varepsilon$ gives us the specific heat, shown in fig. 4a. At $T \approx 43 A_L$, it has a singularity-like peak, which signals the transition from bound to free gluons. With $A_L$ taken in physical units, this gives us $T_C \approx 180 - 200$ MeV; for SU(3), we find similarly $T_C \approx 160 - 180$ MeV. How do we know that it is deconfinement which occurs here? One can study the behaviour of a static $q\bar{q}$ pair immersed in a gluon system of temperature $T$. The free energy $F$ of an isolated quark then serves to define the thermal Wilson loop $<L> = \exp (-\beta F)$ as order parameter. It is found that $<L>$ is essentially zero below and non-zero above $T_C$ (see fig. 4b). Since $<L> = 0$ corresponds to an infinite free energy of an isolated colour source, we have confinement below $T_C$.

In accord with this, it can also be shown that for $T < T_C$ the system behaves essentially as a gas of gluonium states$^{10}$.

All lattice results presented here were obtained with the Wilson form (2.24) of the action, which provides the correct continuum limit. There are, however, other lattice actions which also do this, and we may therefore ask if deconfinement, both qualitatively and quantitatively, is independent of the choice of action. It was recently shown that this is indeed the case$^{11}$.

For the Yang-Mills system, we have thus seen that the lattice formulation together with Monte Carlo techniques allow us to evaluate gluon thermodynamics over the whole temperature range. The resulting behaviour shows the expected two-phase nature: at low temperatures, we have a hadronic resonance gas of gluonium states; heating brings us to a deconfinement transition and beyond that to an ideal gluon gas.

We now want to extend our considerations to include quarks and antiquarks. We shall see that this brings in a basically new feature - the question of chiral symmetry restoration at high temperature. The lattice formulation encounters as a result the problem of species doubling$^{2,12}$, and in addition the Monte Carlo evaluation becomes considerably more complex. Nevertheless, first results both on the full QCD energy density$^{13}$ and on chiral symmetry restoration$^{13,14}$ have now appeared; we shall first consider the former and then return to chiral symmetry
Figure 3: Energy density of the Yang-Mills system, normalized to the ideal gas value $\varepsilon_{SB}$, (a) for SU(2) colour group, from ref. 5, and (b) for SU(3) colour group, from ref. 6.
Figure 4: Specific heat (a) and squared order parameter (b) for the SU(2) Yang-Mills system, from ref. 5.
questions.

For the full Lagrange density (2.18), the Euclidean form of the partition function on the lattice is now given by

$$Z = \int \prod_{\text{links}} dU \prod_{\text{sites}} d\psi d\bar{\psi} e^{-S^G(U) - S^F(U, \psi, \bar{\psi})}$$  \hspace{1cm} (2.30)

with the $dU$ integration to be carried out for all links, the $d\psi d\bar{\psi}$ integrations for all sites of the lattice. The fermion action $S^F$ is taken in the form

$$S^F = \bar{\psi}(1-K\Lambda)\psi$$  \hspace{1cm} (2.31)

$$M^\mu_\nu = (1-\gamma^\mu) U^\mu m_n \gamma^m \gamma^\mu + (1+\gamma^\mu) U^\mu n_m \gamma^m \gamma^\mu$$  \hspace{1cm} (2.32)

while the gluon part $S^G$ is given by eq. (2.24); the coupling between quarks and gluons is given by the "hopping parameter" $K(g^2)$. The integration over the anti-commuting spinor fields can be carried out\(^\text{15}\) to give an effective boson form

$$Z = \int \prod_{\text{links}} dU e^{-S^G(U)} \det(1-K\Lambda)$$  \hspace{1cm} (2.33)

The energy density $\varepsilon$ is obtained from this $Z$; it becomes the sum $\varepsilon = \varepsilon^G + \varepsilon^F$ of a pure gluon part and a quark-gluon part\(^\text{13}\)

$$\varepsilon^F = -\varepsilon^2 (N^3 N a^4 Z)^{-1} \int \prod_{\text{links}} dU e^{-S^G(U)} \det Q \times$$

$$\times \left\{ \frac{3K(q^2)}{4} \text{Tr}(M^\mu_\nu Q^{-1}) - \frac{K(q^2)}{4} \sum_{\mu=1}^3 \text{Tr}(M^\mu_\nu Q^{-1}) \right\}$$  \hspace{1cm} (2.34)

with $Q = 1-K\Lambda(U)$.

The computational problem beyond what is encountered in the pure Yang-Mills case lies in the evaluation of $\det Q$ and of $Q^{-1}$. We shall here use the expansion of these quantities in powers of the fermionic coupling $K$ ("hopping parameter expansion"),\(^\text{16}\) and retain in both cases only the leading term. For $\det Q$ the leading term is

$$\det Q = \det(1-K\Lambda) \approx 1$$  \hspace{1cm} (2.35)

("quenched approximation"), while in the expansion

$$Q^{-1} = [1-K\Lambda]^{-1} = \sum_{\epsilon=0}^\infty K^\epsilon M(U)$$  \hspace{1cm} (2.36)

because of gauge invariance, the first contribution to $\text{Tr}(Q^{-1}M)$ arises for the shortest non-vanishing closed loop obtained from $M(U) \sim U$. For $N_B = 2$ and 3, this is a thermal loop, i.e., one closed in the temperature direction; hence in that case, the first term is $\epsilon = N_B - 1$, and we obtain
\[ e^F a^4 \sim \frac{3}{4} [K(g^2)]^{N_B \over 2} N_B^{N_B + 2} \langle L \rangle \]  
(2.37)

with \( \langle L \rangle \) for the expectation value of the thermal Wilson loop, and \( a \) for the lattice spacing. Comparing this with the leading term of the hopping parameter expansion for an ideal gas of massless fermions, \( e_{SB}^F \), we get

\[ e^F / e_{SB}^F = [8K(g^2)]^{N_B \over N} \langle L \rangle / N \]  
(2.38)

since for the ideal gas \( K = 1/8 \) , \( \langle L \rangle = N \).

Taking \( K(g^2) \) from a numerical evaluation\(^{17}\) and using the Monte Carlo data\(^6\) for \( \langle L \rangle \), we obtain for the SU(3) case the ratio \( e^F / e_{SB}^F \) shown in fig. 5.

We note that the energy density takes on its asymptotic value for \( T \gtrsim 100 \Lambda_L \); around \( T \sim 80 \Lambda_L \) (\( \sim 160 \text{ MeV} \)), there is a sharp drop, corresponding to the onset of confinement.

For the SU(2) case, the restriction to the leading term of the hopping parameter expansion (2.36) has been removed\(^{18}\); including all terms up to order 50 results in the energy density shown in fig. 5b. We note that the qualitative features of fig. 5a persist.

In fig. 6, we show finally the overall energy density \( e/T^4 \) for full QCD with colour SU(3), obtained by combining the results for \( e^F \) with those for the pure Yang-Mills system. We conclude that full quantum chromodynamics with fermions indeed appears to lead to the deconfinement behaviour observed in the study of Yang-Mills systems alone. In particular, we note that at temperatures \( T \gtrsim 2T_C \) essentially all constituent degrees of freedom have been "thawed".

Quantum chromodynamics, for massless quarks a priori free of dimensional scales, contains the intrinsic potential for the spontaneous generation of two scales: one for the confinement force coupling quarks to form hadrons, and one for the chiral force binding the collective excitations to Goldstone bosons. These two lead in thermodynamics to two possible phase transitions, characterized by two critical temperatures, \( T_C \) and \( T_{ch} \). Above \( T_C \), the density is high enough to render confinement unimportant: hadrons dissolve into quarks and gluons. Above \( T_{ch} \), chiral symmetry is restored, so that quarks must be massless. For \( T \) below both \( T_C \) and \( T_{ch} \), we have a gas of massive hadrons; for \( T \) above both \( T_C \) and \( T_{ch} \), we have a plasma of massless quarks and gluons. Conceptually simplest would be \( T_C = T_{ch} \); the possibility \( T_C > T_{ch} \) appears rather unlikely\(^{19}\). On the other hand, \( T_C < T_{ch} \) would correspond to a regime of unbound massive "constituent" quarks, as they appear in the additive quark model for hadron-hadron and hadron-lepton interactions\(^{20}\). The question of deconfinement vs. chiral symmetry restoration thus confronts us with one of the most intriguing aspects of quark-gluon thermodynamics.

The fermionic action of Wilson used in the last section avoids species
Figure 5a: Energy density of the fermion sector, normalized to the ideal gas value $\epsilon_{SB}^F$, for SU(3) Wilson fermions, leading term hopping parameter expansion, from ref. 13).

Figure 5b: Energy density for SU(2) Wilson fermions, hopping parameter expansion up to order 50, from ref. 18).
Figure 6: Energy density of full QCD, compared to that of the SU(3) Yang-Mills system, from ref. 13.)
doubling at the cost of chiral invariance. Even an ideal gas of massless quarks in this formulation is not chirally invariant, since the expectation value \(<\bar{u}u>\) is always different from zero. It has therefore been suggested\(^{21}\) to use the difference between this "Stefan-Boltzmann" value and the corresponding QCD value for Wilson fermions as the physically meaningful order parameter: it would vanish when the behaviour of a non-interacting system of massless fermions is reached.

In fig. 7 we show this order parameter as calculated for colour SU(2)\(^{22}\) and SU(3)\(^{13}\), in leading power of the hopping parameter expansion. It is non-zero up to

\[
T_{\text{ch}} \propto \begin{cases} 
60 \Lambda_L & \text{SU(2)} \\
100 \Lambda_L & \text{SU(3)}
\end{cases} \tag{2.39}
\]

and vanishes for higher temperatures. This suggests chiral symmetry restoration slightly above deconfinement, with

\[
T_{\text{ch}} / T_c \simeq 1.3 \tag{2.40}
\]

It remains open at present to what extent this will be modified by the inclusion of virtual quark loops, or if there are any significant finite lattice effects. Using for the SU(2) case a chirally invariant action with the resulting species doubling, it was found in ref. 14) that chiral symmetry restoration occurs at

\[
T_{\text{ch}} = (0.55 \pm 0.07) \sqrt{s} \tag{2.41}
\]

this leads to similar conclusions on \(T_{\text{ch}} / T_c\). It should be emphasized, however, that in view of possible finite size effects, both presently available calculations do not exclude the possibility \(T_{\text{ch}} = T_c\).

In the lattice evaluation of QCD thermodynamics, we have calculated all physical quantities in terms of the dimensional lattice scale \(\Lambda_L\). To convert \(\Lambda_L\) into physical units, we just have to measure one of these physical observables. String tension considerations give for Yang-Mills systems

\[
\Lambda_L = \begin{cases} 
(1.1 \pm 0.2) \times 10^{-3} \sqrt{s} = (4.4 \pm 0.8) \text{ MeV}^{22} \\
(1.3 \pm 0.2) \times 10^{-2} \sqrt{s} = (5.2 \pm 0.8) \text{ MeV}^{23}
\end{cases} \tag{2.42}
\]

in case of colour SU(2) and

\[
\Lambda_L = (5.0 \pm 1.5) \times 10^{-3} \sqrt{s} = (2.0 \pm 0.6) \text{ MeV}^{24} \tag{2.43}
\]

for colour SU(3). The deconfinement temperature is found to be

\[
T_c = (38^{8} - 43^{5}) \Lambda_L \tag{2.44}
\]

for SU(2) and

\[
T_c = (75^{25} - 83^{6}) \Lambda_L \tag{2.45}
\]

for SU(3). Taking the average of eq. (2.42), we have
Figure 7: Chiral symmetry order parameter, (a) for SU(3) Wilson fermions, from ref. 13), and (b) for SU(2) Wilson fermions, from ref. 18).
\[
T_c = \begin{cases} 
[(170 - 210) \pm 30] \text{ MeV} & \text{SU(2)} \\
[(150 - 170) \pm 50] \text{ MeV} & \text{SU(3)}
\end{cases}
\] (2.46)

and thus little or no dependence of \( T_c \) on the colour group. The temperature for chiral symmetry restoration is accordingly given by relation (2.40).

From eq. (2.46) and the form of fig. 7, we can now estimate the energy density values at the two transition points. For the SU(3) Yang-Mills case, we obtain
\[
\epsilon(T_c) = 200 - 300 \text{ MeV/fm}^3 
\] (2.47)

where we have assumed that the turver over in \( \epsilon \) occurs at about half the Stefan-Boltzmann value. This range, corresponding roughly to hadronic energy density, seems physically quite reasonable. It is not known at present if and how much it would be increased by the introduction of quarks; a shift proportional to that of the Stefan-Boltzmann limit would double the value of eq. (2.47). This suggests twice standard nuclear density \( (n_0 = 150 \text{ MeV/fm}^3) \) as lower and four times nuclear density as upper bound for the deconfinement transition. Chiral symmetry restoration, if it occurs at only slightly higher temperatures, requires considerably higher energy densities. Just a small increase beyond \( T_c \) brings us to the top of the Stefan-Boltzmann "shelf", where the energy density is above 2 GeV/fm³.

Our basic conclusion in this chapter is certainly that the lattice formulation of quantum chromodynamics appears to be an extremely fruitful approach to the thermodynamics of strongly interacting matter. It is so far the only way to describe within one theory the whole temperature range from hadronic matter to the quark-gluon plasma. It leads to deconfinement and provides first hints on chiral symmetry restoration.

We are still at the beginning. It is not really clear if \( T_c \neq T_{ch} \), finite size scaling near the phase transitions has not been studied at all for \( T \neq 0 \), and the lattice thermodynamics of systems with non-zero baryon number has not been touched. Nevertheless, there seems to emerge today from QCD ever growing evidence for a two or three state picture of strongly interacting matter such as we have presented here.

III. Thermodynamics and nuclear collisions

In this chapter, we want to check if nuclear collisions lead to strongly interacting matter of the form just discussed. Expectations for this are based on the following hypothetical picture:
- the collision first provides compression and heating of nuclear matter;
- then thermal and constituent species ("chemical") equilibrium is attained;
- the system expands and cools off;
- finally, once the density has fallen below same critical value, there is break-up and hadronization.

Before we can apply the thermodynamics of QCD, we therefore have to answer some essential questions. What are the possible energy densities attainable in nuclear collisions? Are the relevant space and time scales sufficiently large to expect equilibrium? What features of the primordial stages survive the final hadronization and thus serve as signals for the plasma?

Here we want take up these questions; let us first note, however, that nuclear transparency, as observed primarily in nucleon-nucleus interactions, will restrict the formation of matter in equilibrium in any case to local regions of coordinate or momentum space. It is certainly not expected that e.g. a relativistic Uranium-Uranium collision will lead to one big system in overall equilibrium; only by considering the excited target or projectile, or by looking at slow secondaries in the overall CMS, does one hope to find suitable conditions.

A. PARAMETERS IN NUCLEAR COLLISIONS

Let us now consider a central collision between two energetic nuclei of equal mass A, observed in the overall CMS. If each nucleon experiences a collision with one other nucleon, we have in total A interactions, distributed over the nuclear cross-section of \( \pi R_A^2 \), with \( R_A \approx A^{1/3} \). At sufficiently high energy, the nuclei are Lorentz-contracted along the collision axis to a thickness of about one fermi \( \text{fm} \). Many collisions will therefore take place in the same space-time region. In a transverse area of the size of one nucleon, we will in fact have

\[
\nu = A(R_p^2/R_A^2) \approx 5 A^{1/3}/6
\]  
(3.1)

collisions, with the proton radius \( R_p \approx 0.85 \text{ fm} \). Nucleon-nucleus collisions provide evidence that hadrons interact in nuclear matter more strongly than in nucleon-nucleon collisions. Using an additive quark picture \( \text{fm} \), one naively expects all quarks to interact in a sufficiently large nuclear target \( \text{fm} \), whereas only one quark of the projectile and one of the target interact in a hadron-hadron collision. This gives us a nuclear enhancement factor of three, and hence for A-A interactions \( \text{fm} \)

\[
\nu_A \approx 15 A^{1/3}/6
\]  
(3.2)

collisions per nucleon cross-section, instead of one in a proton-proton collision. In a pp or e\(^+\)e\(^-\) interaction, we have an energy deposit of about 200 MeV/fm\(^3\), corresponding to about one secondary of 1/2 GeV per fermi emitted in the cascade following the collision \( \text{fm} \). This, together with eq. (3.2), leads us to expect an energy deposit of about

\[
\varepsilon \approx (A^{1/3}/2) \text{ GeV/fm}^3
\]  
(3.3)
in nucleus-nucleus collisions. This result (implying about 3 GeV/fm$^3$ for a U-U collision) agrees quite well with more detailed studies in both the fragmentation and the central region. It should be noted that violations of Feynman scaling, as observed at very high energies, will increase the value (3.3).

Have such high energy densities ever been observed? It seems that in newer cosmic ray data there are in fact examples of such extreme conditions. The JACEE collaboration observes an event with approximately 300 secondaries per unit rapidity interval around zero in the overall CMS; the primary collision here is Si+Ag Br at about 80-100 GeV/A CMS energy. Writing the energy density as

$$\epsilon \approx E_{\text{CMS}} \times (dN/dy)^{AA}_{y=0} / V_A$$

we have, with $E_{\text{CMS}} \approx 1/2$ GeV, for this event

$$\epsilon \approx 150 \text{ GeV}/V_A$$

The effective nuclear volume, with a longitudinal thickness of one fermi and an effective transverse radius of 3-5 fm (from $^{28}$Si and $^{109}$Ag), becomes about 50 fm$^3$. The initial energy density in this event must thus have been about 3 GeV/fm$^3$!

In general, we expect for heavy nuclei from the additive quark picture

$$(dN/dy)^{AA}_{y=0} \approx 3A(dN/dy)^{PP}_{y=0}$$

where $(dN/dy)^{PP}_{y=0}$ denotes the CMS rate of a proton-proton collision. Together with

$$V_A \approx 3A^{2/3}$$

as the effective volume of the Lorentz-contracted nucleus, this gives

$$\epsilon \approx (A^{1/3}/2) (dN/dy)^{PP}_{y=0}$$

for the typical central energy density in an A-A collision. With the Feynman-scaling form $(dN/dy)^{PP}_{y=0} \approx 1-2$, this agrees with the previous estimate (3.3); moreover, it indicates that the quoted JACEE event is not at all unusual.

In fig. 8, we plot eq. (3.8), assuming a logarithmic breaking of Feynman scaling

$$(dN/dy)^{PP}_{y=0} \propto 1 + \log \sqrt{s}$$

Also shown are the JACEE event and some further cosmic ray data; to allow a direct comparison of results from different primaries, all data have been converted to equivalent U-U values. We thus conclude from fig. 8 that cosmic ray data do seem to provide instances of sufficient energy density for plasma formation.
Figure 8: Energy density in cosmic ray collisions, compared to $\varepsilon = 1 + \ln \sqrt{s}$. 
B. EQUILIBRIUM FORMATION\textsuperscript{32}

As hadronization in proton-proton collisions typically provides secondaries of about 1/2 GeV total energy in an "isotropic" rest-frame, we assume the freeze-out to occur at an energy density of about 200 MeV/fm\textsuperscript{3}, roughly that of cold nuclear matter. This means that the local collision system of energy density \( \varepsilon \) must expand by a volume factor 5e, or a linear factor of \((5eA)^{1/3}\), to reach break-up. The mean free path of a hadron in nuclear matter, \( \lambda_n \), is about 1.5 fm\textsuperscript{29}, so that the linear size of the system at break-up is a factor

\[
(5eA)^{1/3} / 1.5 \tag{3.10}
\]

larger than the hadronic mean free path. Eq.(3.10) implies about 12 \( \lambda_n \) for U-U collisions yielding \( \varepsilon \approx 3 \) GeV/fm\textsuperscript{3}; equivalently, we expect on the average twelve collisions per constituent. This seems adequate to provide thermal equilibrium. Requiring at least five collisions leads to the empirical equilibrium condition

\[
\varepsilon A \gtrsim 85 \tag{3.11}
\]

The life time of the expanding thermodynamic system has as lower bound the time it takes a shock wave to reach the boundary of the break-up volume. For a speed of sound \( c_s^2 = 1/3 \), this means a life time of at least

\[
t \gtrsim \sqrt[3]{5eA^{1/3}} \tag{3.12}
\]

or about 32 fm for the mentioned U-U example, to be compared with the typical hadronic time scale of one fermi. Both space and time scales in energetic collisions of heavy nuclei thus seem to permit equilibrium formation.

C. SIGNALS FOR NEW STATES

The "little angular"\textsuperscript{36}, expected to occur in a heavy ion collision at sufficiently high energies, shares with its cosmological big brother the feature of being gone when observations are made. It is therefore of great importance to find features of the primordial states of matter which survive the subsequent hadronization and can provide us with information about possible new phases. The quest for such signatures has triggered much work; for a recent survey, see ref. 37). We shall here only mention what at present seem to be the two most important lines of approach.

Real or virtual photons, formed either by quark-antiquark annihilation or through quark bremsstrahlung, will interact only electromagnetically with our system and thus in general escape "freely". We can therefore use energetic photons or dileptons
- to study thermalization\textsuperscript{36,38} (Planck distribution; collective energy effects);
- to measure the primordial temperature\textsuperscript{36,38});
- to look for discontinuities caused by critical behaviour in the strongly interacting system\textsuperscript{39}).

The rate of emission of photons should itself provide some information: in contrast to hadron emission, it should be a volume, not a surface effect, and thus be much enhanced\textsuperscript{40,41}).

If in the primordial plasma the different constituent species are in thermal equilibrium, then the resulting particle ratios at break-up should be effected. In the target or projectile fragmentation region, we have a high density of $u$ and $d$ quarks, from the incident nuclei. In the case newly formed $\bar{u}u$ or $d\bar{d}$ pair, this means a high annihilation probability for the antiquark. For an $s\bar{s}$ pair, this is not the case, and as a result, e.g., the $\Lambda/\bar{\Lambda}$ ratio should be much enhanced in the corresponding kinematic regions\textsuperscript{42}). Quantum number information transfer can thus also serve as indicator for an initial plasma phase.

**IV. Conclusions**

The thermodynamics based on QCD as interaction dynamics was shown to provide hadronic matter at low temperatures and predict a primordial quark-gluon plasma at high temperatures. Around $T \sim 200$ MeV, colour deconfinement and chiral symmetry restoration should occur.

High energy nuclear collisions are expected to provide locally sufficient energy density for plasma formation. Space and time scales make equilibrium formation likely. Indicative signals have been discussed, though none are so far unambiguous.

The physics of high energy nuclear collisions may well open up a fascinating new field of research: a field with many exploratory - rather than confirmatory - aspects also for experimental physics, and a field in which nuclear and particle physics come together again.

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THEORETICAL ASPECTS OF NUCLEUS-NUCLEUS COLLISIONS

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Most of the talk covered the same material as Ref. 1, and will not be repeated here. The following points were made in addition.

1. The usual estimates of thermalization times in terms of mean free path estimates may not be entirely relevant for hadron production processes. What is needed for the application of statistical methods to (partially) inclusive processes is that the distribution of the relevant degrees of freedom over many collisions be well approximated by a microcanonical distribution. When the latter holds for many degrees of freedom, it is equivalent to a canonical distribution, i.e., a thermal distribution, and a thermodynamical description can be applied.

For example, a cylindrical phase space distribution for the secondaries in a narrow interval of longitudinal rapidity ($\delta y \leq 1$) should be very similar to a microcanonical distribution in the co-moving frame, i.e., the average rest frame of the secondaries considered. The same should hold for the hadron distributions obtained in the fragmentation of quark or gluon jets, with the exception of a few leading hadrons in these jets.

2. If a group of secondaries of a soft collision originates from a blob of thermalized hadronic matter, its $p_T$ distribution should be related to the blob temperature $T$ at emission time of the secondaries, and its multiplicity $N$ to the entropy $S$ of the blob (which is approximately constant throughout expansion). A correlation between $p_T$ distribution and $N$ can therefore be related to the equation of state of hadronic matter. Such correlations exist in cosmic ray events$^2$, in minimum bias collisions at the $p\bar{p}$ collider$^3$ and in large $E_T$ events at lower energy$^4$. They may provide a new signal for quark-gluon plasma formation$^5$.

3. Gyulassi$^6$ proposed still another signal, stronger-than-Poissonian fluctuations of the rapidity distribution $dN/dy$ on an event-by-event basis. He suggests that such fluctuations, which have been seen in high multiplicity cosmic ray events$^7$, might be related to the first order phase transition from the plasma state to the hadronic state.

4. Theoretical considerations on ultra-relativistic nucleus-nucleus collisions will remain very crude and uncertain until systematic data become available, including data at energies likely to be too low for plasma formation. Much useful data could be obtained with nuclear beams at the SPS. Among machines under construction, ISABELLE with nuclear beams of up to 100-200 GeV per nucleon would cover an energy region which, according to present estimates, is of greatest interest for plasma formation.
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