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PHYSICS WITH A 15-30 GeV HIGH INTENSITY
CONTINUOUS BEAM ELECTRON ACCELERATOR :
THE ELFE PROJECT

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ABSTRACT

In order to understand the inner structure of nucleons and nuclei it is proposed to build on an european basis a new 15-30 GeV electron facility : ELFE (Electron Laboratory For Europe). After an historical introduction and a quick survey of QCD, a physics program for the ELFE project is outlined. It centers on the study of exclusive phenomena and semi-inclusive experiments at high energy and high momentum transfers aiming to use well understood perturbative aspects of QCD dominated by asymptotic freedom to study the non-perturbative aspects dominated by confinement and hadron structure. Four detectors which would cover the needs of the outlined scientific program are described. At the end a status of the project is given.

KEYWORDS

MultiGeV electrons, perturbative and non-perturbative QCD, exclusive reactions, spectrometers, 4π -detectors.

1. INTRODUCTION

1.1. Some historical footsteps

By definition particle physics deals with elementary particles and nuclear physics studies nuclei but the definition of an elementary particle has been changing with time. Two thousands and five hundreds years ago, Anaxagoras, Leucippus and Democritus invented the concept of atom which, at that time, was

supposed to be the indivisible particle which made all matter. It was a good insight but more a philosophical one than an experimental one.

In 1911, when Rutherford discovered that α -particles were anomalously scattered at large angles by a gold foil, he invented the nucleus which was considered for some time as an elementary particle. At about the same time J.J. Thompson measured the charge to mass ratio e/m of the particle which produced cathode-rays. This particle, the electron, was also considered as elementary and it has kept its status until now.

Twenty years later the neutron was discovered by Chadwick (1932) and the nucleons became the elementary particles of their time.

Then, in the fifties, Hofstadter and his colleagues [Hofstadter (1956)] from SLAC showed in the first scattering experiments with high energy electrons (which was 500 MeV at that time) that the proton had a definite size (of the order of 0.7×10^{-13} cm) and was not an elementary particle in the sense of an object without size nor structure. But due to the available energy, reactions on the nucleon were essentially restricted to elastic scattering and although they showed that the proton was not a point-like particle, its "elementarity" was still not doubted by anyone.

At the end of the sixties were performed the deep inelastic scattering (DIS) experiments of [Taylor et al. (1991)] which showed that :

- i) as the 4-momentum transfer increased the elastic peak and resonance structures disappeared completely (fig. 1.1),
- ii) the DIS cross-sections were much larger than expected from an extrapolation of data obtained at lower momentum transfers,
- iii) they exhibited a scaling behaviour which had been predicted by [Bjorken (1969)] (fig. 1.2).

These experiments lead to the concept of partons and a few years later, QCD was firmly established : the quarks and the gluons became respectively the elementary particles and carriers of the strong interaction .

This short historical survey should tell us some lessons. First it must teach us some modesty : we believe firmly today that quarks and gluons are elementary particles. But all our great predecessors did believe rightfully the same in their own time. They just did not have the mean (the energy) to prove the contrary. It should then not come as a surprise if in a few years or some decades, more elaborate experiments and theories (some of which being already emerging) show that quarks have themselves an inner structure.

We may even extrapolate further and quote [Kungsun Lun (1992)] who wrote in 300 B.C.

"Take half from a foot-long stick each day ; you will not exhaust it in a million years".

May be in a million years our successors will still find compositeness in the fundamental particles of their time.

Fig. 1.1 - Visual fits to spectra showing the scattering of electrons from hydrogen at a primary energy E of approximately 13.5 GeV, for scattering angles from 1.5° to 18° . The 1.5° curve is taken from MIT-SLAC data used to obtain photo-absorption cross-sections (from [Taylor et al. (1991)]).

The second lesson to be learned is about sociology in physics. Particle physicists are known for their propensity to look for the "elementarity" of things. This is why they have progressed in a continuous move towards higher energies. But as soon as it has been discovered that a given particle had a structure, they have consistently abandoned its study in their search for more fundamental constituents. Although recognizing the interest of this quest, we are seeing new patterns where the nucleus becomes again an object of interest for particle physics, for example in ultra-relativistic heavy ion collisions which are a way to produce a quark-gluon plasma at high nuclear density and temperature or in Deep Inelastic Scattering experiments on nuclei (EMC effect).

This proves that the separation between nuclear and particle physics is just semantic and changes with time. The overlap is presently so large that it is sometime impossible to decide in which journal a paper should be published : articles are distributed, e.g., in Nuclear Physics A and B or Phys. Rev. C and D in a manner which reflects more the background of their authors than the consistency of the physics as emphasized by [Shuryak (1991)]. The project which is presented in this article has attracted until now more attention from the nuclear physics community than from the particle physics one. We hope that this situation will change for the success of the enterprise and that ELFE will become a common playground for the benefit of hadronic physics as a whole.

Fig. 1.2 - Scaling of $F_2 = \nu W_2(\omega)$ vs ω (from [Taylor et al. (1991)]). Here ω is the energy of the virtual photon.

1.2. Presentation of the ELFE project

ELFE is the acronym for the Electron Laboratory For Europe. It is a 15-30 GeV electron accelerator proposed by a community of about 200 european physicists (plus some colleagues from the USA). This project follows a reflection which started in the mid-eighties about what facility will be needed to understand the inner structure of nucleons and nuclei. Experiments at very high energy and high momentum transfer show that hadrons are made of partons with negligible size which behave almost freely : this is the phenomenon of asymptotic freedom. At low energies these partons are fully confined and nuclei appear to be made of nucleons with size of the order of one fermi in which the parton degrees of freedom play no apparent role. One does not understand the dynamics of confinement and deconfinement : are they gradual phenomena ? Is there some sort of phase transition appearing suddenly and in that case under which conditions ? Can we understand nuclear forces at dimension scales of a fraction of a fermi to one fermi ?

This reflection was punctuated by a series of meetings and workshops : although a clear beginning cannot be defined, one could cite as a milestone the workshop held in Courmayeur (Italy) in December 1987 [Courmayeur (1987)] where both the physics and the technical feasibility of superconducting linacs accelerating electrons up to 10 GeV were discussed. This meeting was followed by a series of conference in Seillac [Seillac (1988)], Dourdan [Dourdan (1990)] and Amsterdam [Amsterdam (1991)] and topical workshops in Amsterdam, Clermont-Ferrand, Frascati, Orsay and others. These efforts have culminated in the Mainz European Workshop held in October 1992 which was fully devoted to the new project.

At the Mainz meeting 32 letters of intent were presented (21 experimental, 7 theoretical and 4 technical). Most of them originated from single laboratories or countries and many of them had a strong overlap.

Therefore it has been the task of the European Steering Committee (ESC) which was set-up in fall 1991 to promote the project under the chairmanship of T. Walcher (Mainz) and composed of J. Arvieux (Saclay), E. De Sanctis (Frascati) and P. de Witt-Huberts (Amsterdam), to help merge the different proposals in a collaborative process across national borders. This process took a few months resulting in ten large international experimental proposals which are given in full details in the ELFE Project Report [ELFE (1993)] published at the end of 1993.

In parallel to the development of the physics case a European Electron Machine Committee (EEMC) chaired by M. Promé and comprising some of the most distinguished european accelerator physicists was set-up to define the best technical options obeying the beam characteristics defined by the ESC (Table 1.1). The solution proposed is based on a 5 GeV superconducting linac recirculated twice to reach the energy of 15 GeV. The size of the recirculating arcs has been chosen to allow for a 30 GeV gradual upgrade without changing the structure of the machine. This option did reflect the best economic compromise between costs of superconducting cavities and of recirculating magnets at the time (1992) of the study. Any subsequent improvement of the gradient and Q -value of superconducting cavities may affect this conclusion and make the option of a pure linac economically more viable. The work of the EEMC is summarized in the [ELFE Accelerator Technical Proposal (1993)] which appears fully in the ELFE project report.

On the institutional stage, a Committee of the French Academy of Science chaired in 1989 by G. Charpak fully endorsed in their report about the status of Nuclear Physics in France, the proposal for a continuous beam european accelerator of at least 10 GeV. On the european level the Nuclear Physics European Collaboration Committee (NuPECC) organized in march 1991 a workshop at Ruthin Castle (Great-Britain) on Perspectives for Nuclear Physics in Europe [NuPECC (1991)]. Following this meeting NuPECC proposed "that a major initiative be launched to develop a proposal for a European c.w. electron accelerator in the 15 GeV region which would be a unique facility in the fundamental study of quark properties in extended matter". Since then, NuPECC has examined at two meetings in April and October 1994 the proposal described in the ELFE project report and has given new recommendations endorsing fully the setting-up of a coordinating group which would produce a comprehensive proposal taking into account the latest technical and physics developments. We expect funding agencies in the european countries where physics communities have expressed their interest for the new facility to follow these recommendations which should allow them to take within 2-3 years a sound decision to fund the new facility.

$E \geq 15$ GeV for a first step - Up to 30 GeV later
$I \leq 50$ μ A at 15 GeV after developments of the physics program, from an initial value of 10 μ A
100 % duty-cycle
$\Delta E/E \leq 3 \cdot 10^{-4}$ at 15 GeV Full Width Half Maximum (FWHM)
$\Delta E/E \leq 10^{-3}$ at 30 GeV (FWHM)
$\varepsilon/\pi \leq 10^{-8}$ mrad at 15 GeV (horizontal emittance, 95 % of the beam particles)
$\varepsilon/\pi \leq 3 \cdot 10^{-7}$ mrad at 30 GeV (horizontal emittance, 95 % of the beam particles)
3 beams (time-shared with different energies and intensities)
Beam polarization > 80 %, I maximum

Table 1.1

The first part of the present review aims at introducing the physics of ELFE in a coherent way. The second part is a selection of research proposals appearing in the ELFE project report.

1.3. A short introduction to QCD

The Standard Model of the interactions between elementary particles is based on the gauge symmetry group $SU(3)_C \times SU(2)_L \times U(1)$ where $SU(3)_C$ is the colour group on which QCD is based, $SU(2)_L \times U(1)$ is the unified electroweak group.

There are 3 generations of quarks and leptons :

quarks	u	c	t	charge	2/3
	d	s	b	charge	-1/3
leptons	e	μ	τ	charge	-1
	ν_e	ν_μ	ν_τ	charge	0

Quarks have fractional charges, leptons have unit charges and neutrinos (ν) are neutral as indicated. Each quark and lepton has an anti-particle partner with opposite charge. Evidence for the top quark t , has been recently published [Abe et al. (1994)].

There exist particles which contain three identical valence quarks like the $\Delta^{++}(uuu)$, the $\Delta^-(ddd)$ or the $\Omega^-(sss)$. Due to the Pauli principle their wave-function has to be antisymmetric under the interchange of any two quarks which is clearly impossible if the three quarks are indistinguishable. This lead, together with other findings, to the notion that quarks must carry an extra quantum number which is called colour and comes in three varieties which are sometimes labelled blue, red and green (or yellow). Physical particles only come in colour singlets : the hadrons (qqq) and the mesons ($q\bar{q}$).

QCD has three important properties which are to be exploited in the following [see QCD (1992)].

a) Asymptotic freedom

Quarks interact through the exchange of massless bosons, the gluons which come in 8 different kinds. Due to the structure of the colour field, QCD possesses the property of asymptotic freedom which predicts that the coupling constant α_s becomes smaller at shorter distances or larger transfers (which is the opposite of what happens in QED). To first order :

$$\alpha_s(q^2) = \frac{1}{b \text{Log}(Q^2 / \Lambda_{QCD}^2)}$$

where Q^2 is the momentum transfer squared ; b is a constant which depends on the number of flavors f which are active : $b = \frac{1}{4\pi} \left[11 - \frac{2}{3}f \right]$.

Λ_{QCD} is a scale parameter which can be extracted from the data (see e.g. [Altarelli (1990)]) (see fig. 1.3). It is of the order of $\Lambda_{QCD} \approx 200 \pm 100$ MeV. Due to the leading Q^2 -dependence of the strong coupling constant, perturbation theory can only be applied for $Q^2 \gg \Lambda^2$.

Fig. 1.3 - The running of the QCD coupling constant. The various symbols correspond to different experiments used to measure α_S (from [Altarelli (1990)]).

b) Factorization

In most experiments, hadrons are involved in the initial state (as projectiles and/or targets) or in the final state (e.g. in $e^+e^- \rightarrow$ hadrons). Hadrons have sizes of the order of 1 fm (10^{-13} cm), a scale at which perturbative QCD (pQCD) does not apply. Hadron structure is definitely a non-perturbative problem which cannot be understood yet from first principles. The application of pQCD is nevertheless made possible by factorization theorems [Collins et al. (1988)] whose physical meaning is relatively simple.

They factorize the scattering process into 3 steps :

- i) the probability to find some partons inside hadrons. This is expressed by parton distribution functions in inclusive reactions or by hadron wave-function distribution amplitudes in exclusive reactions.
- ii) a hard collision process of elementary fields (quarks, gluons, photons...) occurring at short distances which can be calculated within pQCD.
- iii) the probability that partons produced in the hard sub-process will find their way into final hadrons. This is described by fragmentation functions in inclusive reactions, by distribution amplitudes in exclusive reactions.

The factorization formula has been checked experimentally in many inclusive processes against leading order QCD predictions (see for instance [Huth and Mangano (1993)]), within an accuracy of 10-20 % for transfers typically greater than a few $(\text{GeV}/c)^2$.

c) Confinement

Confinement is the property by which quarks and gluons are confined into colour neutral hadrons (baryons and mesons). It is presently outside the realm of pQCD. There are some indications that QCD can produce confinement in some limited cases, for example in lattice calculations of the structure of hadrons [Parisi (1994) ; Butter *et al.* (1993)]. There are also theoretical explanations of confinement such as the analogy with superconductors [Huang (1992) ; Seiberg and Witten (1994)] where magnetic flux tubes would be replaced by electric ones, or string theories [Polyakov (1988)].

But one can safely state that quark confinement is not understood yet from basic principles and it is one of the most interesting problem in contemporary physics. It is the aim of the proposed multiGev electron accelerator, ELFE, to uncover some of its aspects by a comprehensive study of quark correlations in hadrons.

1.4. Non-perturbative QCD and the ELFE project

The ELFE facility will be a 15-30 GeV electron accelerator with large intensity, high duty-factor and good energy resolution. It must be made clear that such an accelerator is not intended to test pQCD. The minimal Standard Model has had impressive successes in describing quarks and leptons and their unified interactions in many experiments. Still these cases do represent only a small part of the hadron world. Even at very large Q^2 , the region of very small x (x is the Bjorken variable which is defined in the next section), which is now attainable at HERA [Bernardi (1993)], may have strong non-pQCD aspects due to the high density of partons (up to 50 gluons can be found packed into a proton at $x = 10^{-4}$) [Laenen and Levin (1994)]. Another case where pQCD does not apply readily is the world of hadrons and nuclei. Simple estimates explain this situation [Jaffe (1991)]. The mass difference between a Δ and a nucleon is $300 \text{ MeV}/c^2$, so this is what it costs just to flip the spin of one quark in a nucleon. Thus Δ resonances play a minor role in a nucleus although this role can be enhanced in some special reactions and kinematical conditions [Hennino *et al.* (1993)]. Coming to quark effects in nuclei it costs about one GeV to separate by one additional fermi a quark from its two companions in a baryon (the string tension in QCD is of the order of $1 \text{ GeV}/\text{fm}$). Therefore it is not surprising that quark effects in nuclei are not showing up easily. This problem is related to a special feature of the nucleon-nucleon (NN) interaction which exhibits a strong hard core repulsion [Barnes *et al.* (1993)] at short distances and then prevent quarks from coming at distances small enough to allow pQCD concepts to be applied. This repulsion is attributed in the meson-nucleon picture to rho- and omega-exchanges. But this explanation raises many questions [Jaffe (1988)] which can be summarized in the cartoon of fig. 1.4. It shows intuitively that, if the concept of π -exchange may be correct in describing the long-range part of the NN force, the exchange of a rho- or omega-meson between 2 nucleons makes little sense when plotted to scale [Gross (1989)]. An attractive alternative which has been

demonstrated in a simple, non-relativistic ("toy") model is quark-quark repulsion through Pauli-principle [Lenz et al. (1986)], but it has not yet been incorporated in a full theory.

Fig. 1.4 - Cartoon showing finite sizes of two nucleons (shaded) with finite sized meson (unshaded) being exchanged. The figures are roughly to "scale" and in each case the nucleons are separated by the effective range of the force due to that meson. (a) Pion exchange with an effective range of roughly 6 fm. (b) Rho or omega exchange with an effective range of roughly 1 fm (from [Gross (1989)]).

A primary goal of nuclear and particle physics will be then to understand the structure of hadrons and their interactions in terms of their fundamental quark and gluon degrees of freedom. Lattice QCD gauge calculations describe hadron spectra [Hamber and Parisi (1983) ; Weingarten (1983)]. The next important step will be to derive from first principles the structure functions which enter in inclusive reactions, the hadron form-factors which control elastic scattering and the fragmentation functions which parametrize the partition of quarks and gluon jets into hadrons. This knowledge is crucial both for high energy physics and for nuclear physics, taken in their traditional acception.

In situations where factorization is supposed to apply, the hadron structure becomes the main source of uncertainty like, e.g., in the computation of hadronic matrix elements in weak decay amplitudes or in the calculation of heavy meson decays into hadronic channels [Brodsky and Lepage (1989)].

As far as nuclei are concerned, one would like to incorporate our new knowledge on hadrons to understand the strong interaction which is a residual effect of colour forces.

The accelerator which is proposed here will concentrate on non-pQCD aspects of the strong interaction. It will use electrons since the electroweak field generated during lepton-scattering is well known and it allows to probe the unknown structure of target hadrons by means of well defined current operators. Furthermore its strength is weak enough to allow for a perturbative treatment in powers of α , and strong enough to permit accurate measurements at large energy and momentum transfer [Drell (1992)].

Other lepton beams include muons and neutrinos. Muon beams reach higher energies than electron beams and muon experiments require less radiative corrections due to the large mass of the muon, but since they come only as secondary beams their intensity is limited : up to 10^7 - 10^8 muons per second at best compared to micro-amperes (in fixed target experiments) or milli-amperes (in storage rings) of electrons. Neutrinos have unique features to test the flavor content of a nucleus and in particular to separate quark and anti-quark distribution functions [Sloan et al. (1988)] but their use is limited by a very small cross-sections. Both muon and neutrino beams have been so far essentially restricted to the study of inclusive reactions.

Concerning the choice of energy there are different opinions about the onset of scaling. The earlier historical DIS experiments at SLAC indicated an approximate scaling occurring already at $Q^2 \geq 1$ (GeV/c)² and $W \geq 2.6$ GeV (W is the square-root of the invariant mass) [Bloom et al. (1969) ; Breidenbach et al. (1969)].

Dimensional counting rules in exclusive reactions show also scaling starting at $Q^2 = 2 \text{ (GeV/c)}^2$ [Brodsky and Lepage (1981)] (see section 2.1). On the other extreme a global analysis of DIS results from EMC and BCDMS experiments and Drell-Yan reactions sets conservative perturbative cuts at $Q^2 > 10 \text{ (GeV/c)}^2$ and $W > 4 \text{ GeV}$ [Morfin (1990)]. Whatever the true case, the chosen energy of 15-30 GeV for the ELFE accelerator will allow to reach momentum transfers of 15-30 (GeV/c)^2 well into the scaling region.

Exclusive reactions, being coherent quark processes, have low cross-sections. It will be possible to study them at very high momentum transfers, thanks to a large luminosity (many orders of magnitude larger than presently available) through the use of high intensity beams on external targets.

The study of quarks in nuclei will result in many-body final states in exclusive or semi-inclusive reactions which will be resolved in energy and in time with an excellent beam energy resolution ($\Delta E/E \sim 10^{-4}$ at 15 GeV) and a high duty cycle (hopefully 100 %).

Some of the physics topics which will be discussed in the following can (and will be) also addressed at existing accelerators. Existing machines are useful but they are much limited in duty cycle and in luminosity.

Fig. 1.5 - Electron facilities for hadronic studies. The area of the square is proportional to the beam intensity.

* For the Hermes experiment (fixed target in storage ring) the area of the circle has been taken proportional to the luminosity which is similar to the one obtained at SLAC and the duty cycle takes into account the time resolution of the detector (from [ELFE (1993)]).

For semi-inclusive reactions the only detector which is expected to take precise enough data within a reasonable time is the Hermes internal target experiment which will use the 30 GeV electron beam from HERA [HERMES (1990),(1993) ; Stock *et al.* (1994)]. It will show the way, but due to its limitations in duty cycle (1 per cent) and luminosity ($10^{32} \text{ cm}^{-2} \cdot \text{s}^{-1}$ at most for an internal target experiment compared to up to 10^{38} at ELFE with external targets), it will certainly not exhaust the program we are outlining in what follows. An extension of the SMC experiment at CERN is also under study (HMC project). If and when realized, the ELFE facility will be the first one of its kind having a large energy and 100 % duty cycle as can be seen in fig. 1.5.

1.5. Kinematics

When comparing reactions induced by hadrons and by electrons at intermediate energies, electrons have properties which make them unique. Hadrons interact via the strong force : the interaction is being driven by effective strong coupling constants g (e.g. $\frac{g_{\pi NN}^2}{4\pi} \sim 14$) therefore the cross-sections, which are proportional to g^2 are generally very large [Brown and Jackson (1976)]. But due to the size of g there is no way to use perturbation theory. In short, hadron reactions are very efficient at uncovering the gross structures of new phenomena, less at doing precision physics. This has been verified many times in the history of particle physics although one can always find exceptions. At the quark level a simple hadron-hadron interaction like NN scattering is a 6 valence quarks plus sea quarks and gluons rather messy interplay. Moreover, if we assume that about half of the momentum is shared by the quarks and the other half by the gluons, it means that the average energy available per parton-parton interaction is less than one-tenth of the center-of-mass total energy.

The most significant feature of electrons is that, to a high accuracy, they interact essentially through one photon exchange. At the energies we are dealing with (a few tens of GeV at most), the weak interaction has a negligible effect except when its interference with the electromagnetic interaction can be measured as in parity violating processes.

Fig. 1.6 shows a typical exclusive reaction in electron scattering. The target (initial hadron) is often a proton. Even when it will be a nucleus we will assume here that the primary interaction is between the incident electron and one of the nucleons (a proton or a neutron) of the target or, at a deeper level, with one of the partons belonging to these nucleons. The final hadron may be a nucleon or an hyperon or a nucleon resonance. The produced particle may be a photon, or any meson associated to the final hadron.

The kinematical variables are defined (in the laboratory system) in Table 1.2.

Earlier deep-inelastic scattering experiments have shown that DIS cross-sections scale with the Bjorken variable x_{Bj} [Bjorken (1969)] which will be abbreviated as x in what follows. In deep inelastic scattering, x is the fraction of the nucleon momentum carried by the struck parton. Elastic scattering corresponds to the limit $x = 1$ for a proton target, $x = A$ for a target of mass number A . Values of x larger than one require that one parton carries more than the momentum of a single nucleon. They then need a cooperative action of more than 3 quarks and are a tool of choice for studying quark correlations.

Fig. 1.6 - Typical exclusive reaction induced by electrons on a hadron (from [ELFE (1993)]).

Four-momentum of incident electron :	$\mathbf{k} = (E, \vec{k})$
Four-momentum of scattered electron :	$\mathbf{k}' = (E', \vec{k}')$
Four-momentum of virtual photon :	$\mathbf{q} = \mathbf{k} - \mathbf{k}' = (\nu, \vec{q})$
Initial hadron :	$\mathbf{p} = (m, 0)$
Final hadron :	$\mathbf{p}' = (E_{p'}, \vec{p}'); E_{p'} = (m_{p'}^2 + p'^2)^{1/2} = m_{p'} + T_{p'}$
Recoil system :	$\mathbf{q}' = (E_{q'}, \vec{q}'); E_{q'} = (m_{q'}^{*2} + q'^2)^{1/2} = m_{q'}^* + T_{q'}$
Invariant mass squared of the virtual photon :	$Q^2 = -\mathbf{q}^2 = 4EE' \sin^2 \frac{\theta}{2} = \vec{q}^2 - \nu^2$
Invariant mass squared of the hadronic final system :	$W^2 = (m + \nu)^2 - \mathbf{q}^2 = m^2 + 2m\nu - Q^2 = s$
Missing energy :	$E_M = m_{p'} + m_{q'}^* - m$
Center of mass energy :	$E_{cm} = W - (m_{p'} + m_{q'}^*)$ $E_M + m = W - E_{cm}$
Bjorken variable :	$x_{Bj} = \frac{Q^2}{2m\nu} \approx \frac{Q^2}{W^2 + Q^2}$
Energy transferred to hadron :	$t = (\mathbf{p} - \mathbf{p}')^2$
Transverse momentum of the produced hadron with respect to the direction of the virtual photon :	$ p_T' = \sin \theta_{qp'} (s - m^2 + m_{p'}^2) / 2\sqrt{s}$
Scaled energy transfer (in the lab) :	$y = \nu/E$
Scaled hadron energy = fraction of the virtual photon energy carried by the produced hadron	$z = E_{p'} / \nu$

Table 1.2

The electron scattering plane is defined by the 3-momenta $\vec{k}$ and $\vec{k}'$ and it also contains $\vec{q}$.

The hadron plane is defined by the 3-momenta $\vec{p}'$ and $\vec{q}'$ and it also contains $\vec{q}$.

The invariant mass of the virtual photon q^2 is always negative in electron scattering (the virtual photons are said to be space-like).

2. EXCLUSIVE PROCESSES

2.1. Definitions

Exclusive reactions are reactions in which the final state is completely resolved. They are important since at high momentum transfers, they are very sensitive to the quark composition of the hadron themselves as expressed by quark distribution amplitudes.

Infinite momentum frame

To probe hadronic structure at very small distances λ we must transfer to the target a large momentum transfer $Q \sim 1/\lambda$. The recoil kinetic energy being usually larger than the rest mass of the hadron, one is lead to use a relativistic framework. As first suggested by Feynman [unpublished but cited by Bjorken and Paschos (1969)] we can gain an intuitive understanding of relativistic reactions if we look at the hadron from an infinite momentum frame. This leads to view hadrons as collections of quasi-free objects, the partons, sharing each a fraction $0 < x_i < 1$ of the infinite momentum and moving closely parallel to it. They are bound by the strong colour force but their binding energy being small compared to their momentum, they behave almost freely. The parton model is for the photon-hadron interaction what the impulse approximation is for nuclei except that due to confinement, partons are not observed directly.

In exclusive reactions, one first writes the wave-function of a composite state as a simple expansion of Fock states [Fock (1932)] with a fixed number of quarks and gluons [Brodsky (1985)] :

$$|\pi\rangle = \psi_V |q\bar{q}\rangle + \psi_g |q\bar{q}, g\rangle + \psi_{q\bar{q}} |q\bar{q}, q\bar{q}\rangle + \dots$$

$$|N\rangle = \psi_V |qqq\rangle + \psi_g |qqq, g\rangle + \psi_{q\bar{q}} |qqq, q\bar{q}\rangle + \dots,$$

where the valence parts ψ_V will turn out to be contributing most to exclusive reactions.

Here the quarks are really "current" quarks and not "constituent" ones (constituent quarks are a complicated mixture of quarks and gluons which can only be approximately defined in non-relativistic models and are therefore of little usefulness in relativistic quantum field theories).

The valence wave-functions ψ_V are functions of momentum fraction x_i , transverse momenta p_T and helicities. They contain much information on the confinement dynamics. After integration over transverse momenta, they are known as distribution amplitude $\phi(x)$.

The analysis of leading QCD corrections to any exclusive amplitude has shown [Lepage and Brodsky (1980)] that these distribution amplitudes obey a renormalization group equation, leading to a well understood Q^2 -evolution in terms of pQCD. At asymptotic Q^2 , the distribution amplitudes simplify, e.g. for the proton :

$$\phi(x_1, x_2, x_3, Q^2) \rightarrow x_1 x_2 x_3 \delta(1 - x_1 - x_2 - x_3)$$

Fig. 2.1 - (a) Factorization of the nucleon form factor at large Q^2 in QCD. (b) The leading order diagrams for the hard scattering amplitude T_H . The dots indicate insertions which enter the renormalization of the coupling constant. (c) The leading order diagrams which determine the Q^2 dependence of the distribution amplitude $\phi(x, Q)$ (from [Brodsky and Lepage (1989)]).

This same analysis derived the factorization property of exclusive amplitudes, which may be schematically written as :

$$\mathcal{M} = \phi(x_i, Q^2) \otimes T_H(x_i, y_j, Q^2) \otimes \phi^*(y_j, Q^2)$$

where integrals over momentum fractions x_i and y_j are understood and where T_H is calculable perturbatively as an expansion in $\alpha_s(Q^2)$ free of large logarithmic corrections (see fig. 2.1).

Helicity conservation

An important consequence of pQCD is helicity conservation [Brodsky and Lepage (1981)] : at high momentum transfer, the total helicity of hadrons in the initial state must be equal to the total helicity of hadrons in the final state. This selection rule is independent of any photon or lepton spin appearing in the reaction and it is valid to any order of α_s in perturbation theory. It follows from :

- a) neglecting the quark masses
- b) the vector coupling of gauge particles
- c) the dominance of valence Fock states with zero angular momentum projection.

A corollary of hadron helicity conservation is that transverse polarization quantities (polarizations of outgoing particles or analyzing powers) will be zero at high momentum transfers [Carlson and Chachkhunashvili (1992)]. Deviations from these predictions at sufficiently high momentum transfers would put stringent tests on the factorization hypothesis or the dominance of short transverse distances. They would be a signature of genuine non pQCD effects such as quark-quark correlations (diquarks).

Dimensional scaling

The applicability of a partonic description to the hard process entails the existence of dimensional counting rules which apply to the amplitudes and cross-sections of exclusive processes [Brodsky and Farrar (1973), (1975) ; Matveev *et al.* (1973) ; Brodsky (1985)]. At high s and t the hard scattering amplitude should scale as $M \sim (\sqrt{s})^{4-n}$ where n is the total number of elementary lepton, photon or quark fields entering or leaving the hard scattering subprocess.

Combining with the phase-space dependence

$$\frac{d\sigma}{dt} \sim \frac{1}{s^2} |M|^2$$

one deduces the following dimensional counting rule for the cross-section

$$\frac{d\sigma}{dt} = \frac{1}{s^{n-2}} f(\theta_{cm})$$

Fig. 2.2 - Comparison of experiment with the QCD dimensional counting rule $(Q^2)^{n-1} F(Q^2) \sim \text{"const."}$ for form-factors (from [Brodsky and Lepage (1989)]).

where $f(\theta_{\text{cm}})$ is a functional form at θ_{cm} (or t/s) fixed. In elastic lepton scattering the target partons must share the momentum of the incident virtual photon in order to stay grouped together in the final state as shown in fig. 2.1. From the scaling behavior of the amplitude one can derive dimensional counting rules for helicity conserving elastic form-factors :

$$F(Q^2) = \left(\frac{1}{Q^2} \right)^{n-1}$$

where n is the number of partons in the hadron. In the asymptotic limit the simplest quark configurations will be dominant, therefore $n = 2$ for mesons, $n = 3$ for baryons, $n = 6$ for deuterons...

$$F_\pi(Q^2) \sim \frac{1}{Q^2} \quad F_1^N(Q^2) \sim \frac{1}{Q^4} \quad F_d(Q^2) \sim \frac{1}{Q^{10}}$$

A controlled logarithmic deviation to these Q^2 dependence is obtained from the analysis of gluon radiation including the running of the coupling constant [Lepage and Brodsky (1980)]. As can be seen in fig. 2.2, dimensional counting rule is surprisingly well verified for Q^2 as low as $2(\text{GeV}/c)^2$ for pions and $3-4(\text{GeV}/c)^2$ for nucleons. Its empirical success for the power law fall-off of form-factors and other reaction mechanisms such as hadron-hadron scattering (not discussed here) has given important evidence for scale invariant quark and gluon interactions at short distances.

In high luminosity, high duty cycle experiments made possible by the ELFE accelerator, dimensional scaling could be checked at much higher transfers (up to $10-15 (\text{GeV}/c)^2$) and for many reactions.

A new description of electromagnetic form-factors has been given [Li and Sterman (1992)] which includes suppression of diagrams where quarks scatter elastically on-shell (Sudakov effect). In particular it is shown that, by taking this effect into account, the applicability of pQCD can be pushed down to smaller energies.

In summary the dynamics of exclusive reactions reflect not only the behavior of quark-gluon scattering processes at the amplitude level, but also the fundamental structure of the hadron wave-functions themselves. In a relativistic quantum field theory a bound state cannot be described in terms of a fixed number of constituents but in the case of exclusive reactions at large momentum transfer only the lowest valence-quark Fock state $|q\bar{q}\rangle$ or $|qqq\rangle$ contribute. Higher Fock state contributions such as $|qqqg\rangle$ are suppressed by a power of the momentum transfer Q for each additional constituent ensuring a strong simplification.

Experiments which will exploit the unique capabilities of the ELFE project, in terms of luminosity and duty cycle, for exclusive experiments and which are fully described in the ELFE report [ELFE (1993)] include :

- a) Virtual Compton scattering from nucleons
- b) Elastic and transition form-factors of baryons (proton, excited baryons, deuteron)
- c) Parity-violating experiments

Other experiments such as real Compton scattering and meson photo- and electro-production at fixed angle should also be envisaged.

2.2. Compton scattering from nucleons

Exclusive reactions involving two real or virtual photons provide a particularly interesting testing ground for QCD because of the relative simplicity of the couplings of the photons to the underlying quark currents and the absence of significant initial state interactions.

Among these, Compton scattering is one of the simplest and, at the same time, most fundamental process in physics. It can be divided in the scattering of real photons by nucleons (elastic scattering) and virtual Compton scattering (VCS). In VCS the target absorbs a virtual photon and emits a single real photon. Compton scattering is a pure electromagnetic process whose underlying theory, QED, is well understood and in which all the Feynman graphs contributing to lowest order can be calculated.

2.2.1. Compton Scattering with real photons

Real Compton Scattering $\gamma p \rightarrow \gamma p$ has been studied experimentally at energies up to $s = 12 \text{ GeV}^2$ and $t = -4 \text{ GeV}^2$ [Deutsch et al. (1973) ; Schupe (1979) ; Duda et al. (1983)]. The angular distributions are shown in fig. 2.3. An optimistic observer might guess a convergence with the s^{-6} scaling law expected from the dimensional rule (at least viewed on a log plot).

The data are compared to two types of calculations. The dashed curve is a pQCD calculation [Farrar and Zhang (1990)]. The solid and dotted curves are diquark calculations [Anselmino et al. (1993) ; Kroll et al. (1991a)].

Fig. 2.3 - Scaled unpolarized proton Compton scattering differential cross-section $s^6 d\sigma/dt$. For explanations of the theoretical curves, see text (from [Fonvieille et al. (1993)]).

The pQCD calculations are rather technically complicated since they involve several thousands of Feynmann diagrams of order α_s^2 due to the combinatorial rules in connecting three quark lines by two gluons.

The cross-sections have been computed with different relativistic proton wave-functions [Zhitnitskii et al. (1988) ; Dziembowski (1988) ; King and Sachrajda (1987) ; Chernyak and Zhitnitskii (1984a) (1984b)] but only the one giving the "best" agreement (the COZ wave-function of [Zhitnitskii et al. (1988)]) is shown here (dashed curve in fig. 2.3).

Another pQCD calculation by [Kronfeld and Nizic (1991)] gives results in better agreement with experiments as shown in fig. 2.4 and very different from [Farrar and Zhang (1990)]. It seems that the difference comes from the treatment of the Sudakov effect. The large variation of the calculations with the choice of wave-function indicates a strong sensivity of the data to the hadronic structure (see also [Farrar et al. (1989)]). Interestingly, being integrable this singularity leads to a calculable phase for the VCS process which could be checked in polarization experiments.

The fact that the data do not scale as s^{-6} indicates that the data available are at too low an energy for pQCD to apply. More precise real Compton scattering data at higher energies would ensure that the asymptotic region is indeed reached and they would shed light on the baryonic structure at high momentum transfer.

2.2.2. Compton Scattering with Virtual Photons [Fonvieille et al. (1993)]

Virtual Compton Scattering is schematically pictured in fig. 2.5a. It corresponds to bremsstrahlung by the proton (or, at high momentum transfer, by the parton inside the proton). It must be distinguished from the Bethe-Heitler (BH) process which is bremsstrahlung emission from the scattered electron (fig. 2.5b).

Fig. 2.4 - Comparison of the QCD predictions from [Kronfeld and Nizic (1991)] for different QCD sum rule distribution amplitudes.

VCS is of special interest as compared to elastic scattering. First the photon being virtual, it provides information on the Q^2 -dependence as well as the s - and t -dependence. Furthermore it allows to determine unambiguously the VCS phase by measuring its interference with the Bethe-Heitler mechanism whose amplitude is purely real. This phase originates from intermediate on-shell quarks and gluons and it is a sensitive test of almost on-shell parton propagation in hadronic matter. As such VCS should also be studied in nuclei.

Fig. 2.5 - Virtual Compton Scattering (a) and Bethe-Heitler process (b) (from [Fonvieille et al. (1993)]).

The BH process can be calculated exactly provided the electromagnetic form-factors of the nucleon are known. The VCS amplitude can be calculated from the diagram of fig. 2.6. Changing the azimuthal angle between the hadronic plane and the leptonic plane allows to tune the interference between the VCS and BH processes. This requires a large acceptance detector.

Fig. 2.6 - Virtual Compton Scattering in the parton picture (from [Fonvieille et al. (1993)]).

Detailed predictions of virtual Compton amplitudes are available [Farrar and Zhang (1990)] but no data exist yet. A feasibility study including two experimental options has been done up to $Q^2 = 15 \text{ GeV}^2$. The physical background is essentially due to π^0 electroproduction $ep \rightarrow ep\pi^0$ followed by $\pi^0 \rightarrow \gamma\gamma$ which has a cross-section 50 times larger than VCS and which may be kinematically very close to it when the decay is strongly asymmetric. In both options the signal (S) to noise background (B) was calculated in the absence of photon detection. It was found to be of the order of $S/B \sim 1/50$ which is unacceptably large, requiring therefore the detection of all three particles (in which case the signal to background rate becomes of the order of 1/3).

In the first option the scattered electron and the recoil proton are detected in a set of two high resolution, low acceptance spectrometers and the photon is detected in a calorimeter. The second option considered a 4π -detector with a large acceptance but reduced luminosity.

a) Two-spectrometer option

The two spectrometers are described in section 7.2. The luminosity is $L = 10^{38} \text{ cm}^{-2} \cdot \text{s}^{-1}$ corresponding e.g. to a 20 μA electron beam on a 20 cm long liquid hydrogen target. The spectrometers being in the same plane (coplanar kinematics), the azimuthal angle of the photon is limited to $\phi_\gamma = 0^\circ$ or $\phi_\gamma = 180^\circ$.

Cross-sections have been calculated by fixing several kinematical variables in order to study a few important physics variables at a time e.g. Q^2 or t or θ^* (the angle of the emitted photon with respect to $\vec{q} = \vec{k} - \vec{k}'$) or ϵ (the polarization parameter of the virtual photon). The counting rates calculated at $s = 10 \text{ GeV}^2$ are of the order of a couple of counts per hour for the most interesting kinematics.

b) 4π -detector option

This option is particularly well suited for 3 body kinematics with out-of-plane detection. This is particularly important in the case of VCS since the BH amplitude is strongly peaked at 0° and decreases sharply as ϕ_γ increases up to 180° (the BH cross-section is 10 000 times larger at 0° than at 180°). The VCS amplitude behaves in a much smoother way, the interference with the BH amplitude being optimum when the two amplitudes are of the same order.

The characteristics of the 4π -detector are given in section 7.5. The cross-section at $Q^2 = 2 \text{ GeV}^2$, $s = 8 \text{ GeV}^2$ and $t = -2 \text{ GeV}^2$ where the interference is large, is shown in fig. 2.7 for a 15 GeV incident beam. At $t = -4 \text{ GeV}^2$ and with a luminosity $L = 10^{36} \text{ cm}^{-2} \cdot \text{s}^{-1}$, a minimum counting rate of the order of 800 events per 90 days (3.5 % statistical uncertainty) in a bin with $\Delta Q^2 = 1 \text{ (GeV/c)}^2$, $\Delta s = \Delta t = 1 \text{ GeV}^2$ and $\Delta\phi_\gamma = 0.1 \text{ rad}$ can be obtained corresponding to a cross-section of $10^{-3} \text{ pb/GeV}^6/\text{rad}$.

To conclude this section it may be pointed out that the so-called background events from the reaction $ep \rightarrow e'p\pi^0$ have their own physics interest since they can also be calculated by pQCD using the same framework as the one used for VCS calculations with the benefit of a much higher cross-section.

Fig. 2.7 - ϕ -dependence of the virtual Compton scattering cross-section on the proton for $Q^2 = 2 \text{ (GeV/c)}^2$, $s = 8 \text{ (GeV/c)}^2$ and $t = -2 \text{ (GeV/c)}^2$ (from [Fonvieille et al. (1993)]).

2.3. Meson form-factors

2.3.1. Theoretical considerations

Understanding quark confinement in mesons is particularly interesting. Due to their simpler $q\bar{q}$ structure and smaller intrinsic sizes there is a greater probability for two valence quarks to act coherently than for baryons which require the three quarks exchanging at least two gluons. Therefore, for mesons, the on-set of pQCD is expected and seems to arise at lower Q^2 (see fig. 2.2).

The elastic pion form-factors have been calculated within asymptotic QCD [Chernyak and Zhitnitsky (1977); Chernyak et al. (1977); Radyushkin (1977); Brodsky and Lepage (1979)] but to fit the available data up to $Q^2 = 2 \text{ GeV}$ an unreasonably large value of the strong coupling-constant $\alpha_s \approx 0.7$ (instead of $\alpha_s \approx 0.3 - 0.4$ expected at this value of Q^2) seemed first to be required. A wave-function [Chernyak and Zhitnitsky (1982)], derived from QCD sum-rules (CZ) with a double asymmetric hump, fit well the data with $\alpha_s = 0.3$ but it was shown that only 1.5 % of the momentum fraction of the CZ wave-function contributes to the region where pQCD is supposed to be applicable [Isgur and Llewellyn-Smith (1989)]. These two facts lead to advocate large nPQCD effects in the pion wave-function and large effects of soft terms [Radyushkin (1992)]. Recent studies of Sudakov effects [Li and Sterman (1992)] have however enforced the applicability of an "improved" pQCD analysis of meson form-factors in the Q^2 -range of a few $(\text{GeV/c})^2$ (see also [Gousset and Pire (1995)]). Lattice gauge calculations have also been performed [Kronfeld and Photiadis (1985); Martinelli and Sachrajda (1987); Hecht and Debrand (1992)].

The charge form-factor of the pion and the kaon have been investigated in the light cone formalism and their sensitivity to hard constituents in the wave-functions has been studied [Cardarelli et al. (1994)].

2.3.2. Experimental considerations and analysis of existing data

Kinematical variables are defined in section 1.5. The most general (unpolarized) six fold differential cross-section depends on 4 four structure functions W_{ij} :

$$\frac{d^6\sigma}{dE' d\Omega dE_h d\Omega_h} = |\vec{p}_h| \sigma_M \frac{Q^2}{2\vec{q}^2} \frac{1}{\epsilon} \left[W_T + \epsilon W_L + \epsilon W_{TT} \cos(2\phi_h) \right. \\ \left. + (\epsilon(\epsilon+1)/2)^{1/2} W_{LT} \cos(\phi_h) \right]$$

where E_h , Ω_h and p_h are the hadron energy, solid angle and momentum respectively ; σ_M is the Mott cross-section and ϵ is the virtual photon polarization :

$$\frac{1}{\epsilon} = 1 + \frac{2\vec{q}^2}{Q^2} \tan^2\left(\frac{\theta}{2}\right)$$

where θ is the angle between the incoming and outgoing electrons.

The cross-section for reactions induced by polarized electrons contains a 5th structure function [Picklesimer and van Orden, (1987)].

The longitudinal structure function W_L is related to the form-factor F . Close to the pole at $t = m_h^2$, W_L is dominated by the pole term [Gourdin (1974)]

Pions :

$$W_L^\pi(\nu, Q^2, t) \sim \frac{-t F_\pi^2(Q^2, t) g_{\pi NN}^2(t)}{(t - m_\pi^2)^2}$$

Kaons :

$$W_L^K(\nu, Q^2, t) \sim \frac{(-t + (m_p - m_\Lambda)^2) F_K^2(Q^2, t) g_{KN\Lambda}^2(t)}{(t - m_K^2)^2}$$

where $g_{\pi NN}$ and $g_{KN\Lambda}$ are the form-factors at the πNN and $KN\Lambda$ vertices respectively. The πNN vertex is usually parametrized as

$$g_{\pi NN}(t) = g_{\pi NN}(0) \frac{1}{1 - \frac{t}{\Lambda_{\pi N}^2}}$$

where $\Lambda_{\pi N} \sim 1$ GeV.

To summarize the experimental problems in determining the meson structure functions one needs to do experiments at fixed Q^2 for different values of ϵ (separation of W_T and W_L) and of ϕ_h (separation of W_{TT} and W_{LT}). This means that experiments have to be carried at different energies with an out-of-plane detection system going at very small angles to minimize the interference term contributions.

Fig. 2.8 - Existing data for the pion form-factor (left) and kaon electroproduction cross-sections divided by the virtual photon flux (right) (from [Bebek et al. (1977,1978)]).

For pions, only one longitudinal-transverse separation has been done at fixed relatively small values of $Q^2 = 0.7 \text{ (GeV/c)}^2$ and $W = 2.2 \text{ GeV}$ [P. Brauel et al. (1977)]. The other data shown on fig. 2.8 (left side) from $Q^2 = 0.2 \text{ (GeV/c)}^2$ up to 9.8 (GeV/c)^2 relied on empirical arguments to extract F_π [Bebek et al. (1978) ; Brown et al. (1973) ; Driver et al. (1971) ; Sofair et al. (1972)]. As stated by the authors this procedure is not reliable at $Q^2 > 4 \text{ (GeV/c)}^2$ which is reflected in the large error bars of the data.

For kaons no form-factor has ever been extracted and the data are usually presented as photoproduction cross-sections for the reaction $ep \rightarrow e'K\Lambda$. Data obtained up to $Q^2 = 4 \text{ (GeV/c)}^2$ are shown in fig. 2.8 (right side).

2.3.3. Proposed experiment [Blok et al. (1993)]

It is proposed to obtain high quality data on the form-factors of the pion up to $Q^2 = 8 \text{ (GeV/c)}^2$ well into the scaling region and of the kaon up to $Q^2 = 4 \text{ (GeV/c)}^2$. The structure functions W_L , W_T , W_{TT} and W_{LT} will be measured as a function of Q^2 and t by detecting the hadron out-of-plane ($\theta_h = \pm 10^\circ$) and by working at least at two (high and low) different energies to vary, in a large range, the virtual photon polarization ϵ at fixed Q^2 , then ensuring a precise longitudinal-transverse separation.

The reactions to be studied include :

proton target

$$H(e, e' \pi^+) n$$

$$H(e, e' K^+) \Lambda$$

neutron (deuteron) target

$$n(e, e' \pi) p$$

neutral channels (using an electromagnetic calorimeter) $H(e, e' \pi^0) p$
 $H(e, e' K^0) \Sigma^+$

excited baryon channels $H(e, e' \pi^+) \Delta^0$
 $H(e, e' K^+) \Sigma^0$
 $n(e, e' K^-) \Sigma^+$
 $n(e, e' K^+) \Sigma^-$

The reactions $ep \rightarrow e' p \pi^0$ and $ep \rightarrow e' K^0 \Sigma^+$ are particularly interesting since they are pure "background" terms having no contribution from the pole term. They allow to evaluate the corrections to the Born term approximation. They can also be directly compared (at high Q^2) to QCD predictions [Carlson and Milana (1990)].

The use of nuclear targets would allow to test the concept of nuclear transparency [see section 3] in meson production where, due to the smaller size of $q\bar{q}$ configurations (as compared to 3 quark systems), it has a better chance to be observed at lower Q^2 .

The cross-sections for π^+ and K^+ electroproduction calculated in the t -pole approximation [Gavin and Mulders (1992)] are shown in fig. 2.9. The counting rates have been estimated with a luminosity of $10^{35} \text{ cm}^{-2} \text{ s}^{-1}$ assuming a $1 \mu\text{A}$ electron beam on a 2.5 mm liquid hydrogen target. At the largest (and most interesting) value of $Q^2 = 8 \text{ (GeV/c)}^2$, about 900 counts per day can be obtained for the $H(e, e' \pi^+)$ reaction. Cross-sections for K^+ -production are about a factor of 20 smaller but they may have been underestimated in the pole term approximation [Bebek et al. (1978)].

The proposed apparatus is a forward spectrometer (FAST) described in section 7.3.

Fig. 2.9 - Comparison of π^+ and K^+ electro-production cross-sections at $W = 3 \text{ GeV}$ as a function of Q^2 (from [Blok et al. (1993)]). θ_h is the hadron angle.

2.4. Nucleon form-factors

2.4.1. Physics interest

Quark distribution amplitudes describing the fractional longitudinal momentum distribution of the three valence quarks in a nucleon are, like meson distribution amplitudes, non perturbative objects. Some approximated lattice results [Martinelli and Sachrajda (1989) ; Hecht and Debrand (1992)] or some model estimates like QCD sum-rules [Chernyak and Zhitnitsky (1984b) ; Radyushkin (1977), (1992)] are available. Hybrid models incorporating Vector Meson Dominance (VMD) constraints at low Q^2 [Gari and Stefanis (1986), (1987)] have also been used to calculate nucleon form-factors.

More phenomenological models like the diquark model [Kroll et al. (1991b) ; Anselmino et al. (1993)] or the constituent quark model on the light cone [Schlumpf (1993), (1994)] fit a large spectrum of data in the intermediate Q^2 -range with a limited number of free parameters. Even in QCD-inspired models, the distribution amplitudes are far from being unique [Schaefer (1989)].

A remarkable prediction of QCD sum rule calculations is that the momentum distribution of the 3 quarks in a hadron is very flavour-asymmetric as can be seen in fig. 2.10 [Chernyak et al. (1977)]. These distributions, which have been confirmed in an independent analysis [King and Sachrajda (1987)], indicate that 65 % of the proton momentum is carried by the valence u -quark with helicity parallel to the proton helicity. They provide a reasonable description of the proton form-factor and the $J/\psi \rightarrow p\bar{p}$ decay rate [Brodsky (1993)]. They agree qualitatively with quark-diquark models which too, suggest large asymmetries and strong spin-correlations in the baryon wave-functions [Kroll et al. (1991b)].

These predictions are completely at variance with the lattice results obtained in the quench approximation [Martinelli and Sachrajda (1989)] which favor a symmetric distribution where the 3 quarks share the same fraction of the total proton momentum but these calculations underestimate by two orders of magnitude the proton magnetic form-factor.

The striking difference between QCD sum rules and lattice calculations of the proton form-factor is difficult to understand since both methods agree for the pion distribution amplitudes (see preceding section). Either the model used for the proton in QCD sum rule calculations is incorrect (although it agrees with the quark-diquark picture) or there is a computational problem in the lattice QCD result. Other explanations involve contributions of gluons and non valence quarks such as strange quarks which are indicated by recent polarized DIS experiments (see Brodsky and Lepage (1989) for a comprehensive discussion).

In any case form-factor data at large Q^2 ($Q^2 > 10$ (GeV/c) 2) would insure that factorization is correct and would allow to deduce distribution amplitudes which could then be compared to baryon models at a fundamental level.

The differential cross-section for elastic ep scattering can be written

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega} \right)_{Mott} \left[F_1^2(Q^2) + \frac{\kappa}{4m_p^2} Q^2 F_2^2(Q^2) + \frac{Q^2}{2m_p^2} (F_1(Q^2) + \kappa_p F_2(Q^2))^2 \tan^2 \theta / 2 \right]$$

Fig. 2.10 - The COZ proton distribution amplitude $\phi_P(x, y, 1-x-y; \mu)$ determined from QCD sum-rules at the resolution scale $\mu \sim 1 \text{ GeV}$ (from [Zhitnitsky et al. (1988)]).

where $\kappa = 1.7928$ is the proton anomalous moment in nuclear magneton units and $\left(\frac{d\sigma}{d\Omega}\right)_{Mott}$ is the no-structure cross-section. $F_1(Q^2)$ and $F_2(Q^2)$ are the so-called Dirac and Pauli form-factors respectively which are functions of Q^2 only. They parametrize the internal structure of the proton. They are normalized in such a way that for $Q^2 \rightarrow 0$, the photon coupling reduces to that of a point charge

$$F_1(0) = 1 \quad \text{and} \quad F_2(0) = 1.$$

Cross-sections are often written in terms of the Sachs form-factors $G_E(Q^2)$ and $G_M(Q^2)$, which parametrize the electric and magnetic charge distributions respectively [Ernst et al. (1960)] :

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \left[\frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1 + \tau} + 2\tau G_M^2(Q^2) \tan^2 \theta / 2 \right]$$

where $\tau = Q^2 / 4m_p^2$.

They are related to the Dirac and Pauli form-factors by

$$G_E(Q^2) = F_1(Q^2) - \tau \kappa F_2(Q^2)$$

$$G_M(Q^2) = F_1(Q^2) + \kappa F_2(Q^2)$$

This form of the cross-section allows to perform a Rosenbluth separation [Rosenbluth (1950)] of G_E and G_M by varying the angle θ . This appears more clearly if one uses the following reduced cross-section

$$\sigma_R = \left[\frac{d\sigma}{d\Omega} / \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \right] \frac{1 + \tau}{\tau} = \frac{\epsilon}{\tau} G_E^2(Q^2) + G_M^2(Q^2).$$

The quantity ϵ is a measure of the longitudinal polarization of the photon defined in section 2.3.2. σ_R being linear in ϵ for fixed Q^2 , the form-factor can be extracted from a linear fit of σ_R at constant Q^2 but varying ϵ . The slope yields G_E^2 / τ and the intercept gives G_M^2 . Since τ is proportional to Q^2 , as Q^2 increases the cross-section becomes dominated by G_M , making precise measurements of G_E more and more difficult.

Fig. 2.11 - The magnetic form-factor of the proton. Data are from [Hoehler et al. (1976)] and [Arnold et al. (1986)].

2.4.3. Analysis of existing data

Until recently, both proton form-factors G_{E_p} and G_{M_p} had been measured independently up to $Q^2 \approx 4$ (GeV/c)² [Bartel et al. (1973) ; Berger et al. (1971) ; Litt et al. (1970) ; Walker et al. (1989) ; Bosted et al. (1990)]. For neutrons, G_{E_n} and G_{M_n} have been separated up to $Q^2 \approx 2.6$ (GeV/c)² but with much larger errors [Bartel et al. (1973) ; Arnold et al. (1988a) ; Esaulov et al. (1987); Lung et al. (1993)].

If one assumes the following simple relations between form-factors :

$$G_{E_p}(Q^2) \sim G_{M_p}(Q^2) / \mu_p \sim G_{M_n}(Q^2) / \mu_n \sim G_D(Q^2)$$

$$G_{E_n}(Q^2) \sim 0,$$

where the subscripts p and n stand for proton and neutron respectively and where G_D is a dipole form-factor, then one can extract the magnetic form-factors of the proton up to 31(GeV/c)² (see fig. 2.11) and of

the neutron up to $(10 \text{ GeV}/c)^2$ using forward angle elastic cross-section data [Hoehler *et al.* (1976); Arnold *et al.* (1986) ; Sill *et al.* (1993) ; Rock *et al.* (1982)]. The result of the fit gives a dipole Q^2 -dependence :

$$G_D(Q^2) = \left(1 + \frac{Q^2}{0.71}\right)^{-2}$$

with deviations from a dipole form at low momentum transfer of the order of 5 % for G_M and reaching 20 % for G_E which is more poorly measured.

A recent experiment [Andivahis *et al.* (1994)] has pushed the Rosenbluth separation method for the proton up to $8.83 \text{ (GeV}/c)^2$ by measuring elastic ep cross-sections in the angular range from 13° to 90° . At low Q^2 the new data overlap with the old ones but with much reduced uncertainties : $< 11 \%$ in G_{E_p} and $< 1 \%$ in G_{M_p} .

Fig. 2.12 - Experimental values of G_{E_p} / G_D compared with different models and predictions [from Andivahis *et al.* (1994)] as explained in the text.

Fig. 2.13 - Experimental values of $G_{M_p} / \mu_p G_D$ compared with different models and predictions [from Andivahis *et al.* (1994)] as explained in the text.

Within these uncertainties results for G_{E_p} are now consistent with a dipole fit (fig. 2.12). One observes however a continuous decrease of $G_{M_p}(Q^2) / \mu_p G_D(Q^2)$ from 1.05 to 0.92 from 2 to 9 (GeV/c)² (fig. 2.13).

The data are compared with different models: Vector Dominance Model (VMD) [Hoelher et al. (1976); Iachello et al. (1973)], hybrid models which try to reconcile a mesonic model at low Q^2 and pQCD at high Q^2 [Gari and Krümpelmann (1984), (1985)], QCD sum-rules [Radyushkin (1984)], diquark model [Kroll et al. (1991b)] and relativistic constituent quark model [Chung and Coester (1991)]. None of these models characterize fully the data over the whole Q^2 -range.

As shown in section 2.1, the helicity conserving form factor $F_1(Q^2)$ should vary as Q^{-4} . For the helicity non-conserving form-factor $F_2(Q^2)$, dimensional scaling predicts an additional factor of Q^{-2} due to the extra quark helicity flip thereby $F_2(Q^2) \sim Q^{-6}$. Then the ratio $Q^2 F_2(Q^2)/F_1(Q^2)$ should approach a constant which is the case starting at $Q^2 \sim 3-4$ (GeV/c)² (fig. 2.14) and up to 6 (GeV/c)² (data at higher Q^2 are not significant due to large error bars).

Fig. 2.14 - Dimensional scaling rule for $Q^2 F_2/F_1$ as a function of Q^2 (from Andivahis et al. (1994)).

The same experiment [Andivahis et al. (1994)] has measured G_{M_n} and G_{E_n} up to 4 (GeV/c)² in $e-d$ scattering.

2.4.4. Proposed experiment [Bauer et al. (1993)]

The fact that the electric contribution tends to become negligible compared to the magnetic one sets a limit for the use of the Rosenbluth separation at large Q^2 . It is then proposed to measure directly the ratio F_2/F_1 or G_E/G_M by using a polarization method [Dombey (1969) ; Scofield (1966)]. Using polarization the interference between the electric and magnetic form-factors (and hence their sign) can be directly measured. The systematic errors are different than in a Rosenbluth separation and they may be much lower since they require only measuring relative cross-sections and not absolute ones.

There are two possible methods : the recoil polarimeter option and the polarized target option.

Fig. 2.15 - Definition of the electron scattering and second scattering angles (from [Bauer et al. (1993)]).

a) Recoil polarimeter

The double differential cross-section for elastic scattering of longitudinally polarized electrons from unpolarized protons is, in the one-photon approximation :

$$\frac{d^2\sigma}{d\Omega_e d\Omega_p} = \left(\frac{d^2\sigma}{d\Omega_e d\Omega_p} \right)_0 \left[1 + hp_x A_y(\theta') \sin \phi' + hp_z \sin \chi A_y(\theta') \cos \phi' \right]$$

where h is the beam helicity, $A_y(\theta')$ the analyzing power depending on the angle θ' of the recoil proton scattering (see fig. 2.15). The angle χ is the precession angle of the proton through the magnetic spectrometer. The sideways and longitudinal polarizations are respectively

$$p_x = -[2\tau\epsilon(1-\epsilon)]^{1/2} \frac{G_E G_M}{\epsilon G_E^2 + \tau G_M^2}$$

$$p_z = \tau(1-\epsilon^2)^{1/2} \frac{G_M^2}{\epsilon G_E^2 + \tau G_M^2}$$

where τ and ϵ have been defined above ($\epsilon = 1$ for $\theta = 0^\circ$ and 0 for $\theta = 180^\circ$).

From the Fourier analysis of the ϕ' distribution of the proton asymmetry

$$A_s(\theta', \phi') = \frac{\sigma^+(\theta', \phi') - \sigma^-(\theta', \phi')}{\sigma^+(\theta', \phi') + \sigma^-(\theta', \phi')} = a(\theta') \sin \phi' + b(\theta') \cos \phi'$$

where $\sigma^\pm$ are cross-section with electrons helicities $\pm h$, one gets the amplitudes :

$$a(\theta') = p_b p_x A_y(\theta'),$$

$$b(\theta') = p_b p_z \sin \chi A_y(\theta'),$$

from which one can extract :

$$r = \frac{G_E}{G_M} = -\frac{a}{b} \tau^{1/2} \left(\frac{1+\epsilon}{2\epsilon} \right)^{1/2} \sin \chi.$$

This ratio has the remarkable property that it is independent of the beam polarization and the analyzing power A_y .

b) Polarized target

In the case of a polarized target experiment, it is not necessary to measure the recoil proton but one has to take into account the fact that the polarized nucleons are diluted by a factor f in the target. The formula are very similar except that the ratio $r = \frac{G_E}{G_M}$ depends now on the analyzing power A_x measured in the x direction :

$$\frac{G_E}{G_M} = -\frac{1}{A_x} \left[\frac{\tau(1-\epsilon)}{2\epsilon} \right]^{1/2} \left[1 - \left(1 - \frac{2A_x^2}{1-\epsilon} \right) \right]$$

which reduces to

$$\frac{G_E}{G_M} \sim -A_x \left(\frac{\tau}{2\epsilon(1-\epsilon)} \right)$$

in the $G_E^2 \ll \tau G_M^2$ limit.

The experimental apparatus would use the electron and hadron spectrometers (see section 7.2) with a proton recoil polarimeter in the focal plane (fig. 2.16) or a 4π -detector (MEMUS) described in section 7.5 in the polarized target option.

Side view

Fig. 2.16 - Schematic view of the polarimeter (from [Bauer et al. (1993)]).

The figure of merits of the two methods are compared in table 2.1. At the highest Q^2 (around 15 (GeV/c)²) the polarized target option is more efficient since it depends less on the momentum transfer (the analyzing power of the polarimeter decreases with Q^2 whereas the target polarization is constant).

In conclusion the overall experimental time to measure F_2/F_1 (or G_E/G_M) with a 20 % accuracy or better (set by the highest momentum transfer) up to about 15 (GeV/c)² is 165 days at 15 GeV. The main limitation is the electron intensity on target (0.2 μ A) for the polarized target option. Increasing the energy of the electron beam up to 21 GeV would decrease the time needed to 93 days.

	Polarimeter	Polarized Target
length(cm)	10	1.5
density (g.cm ⁻³)	.0708	0.9
intensity (μ A)	50	0.2
luminosity (cm ⁻² .s ⁻¹)	1.3 10 ³⁸	$\frac{3}{17} 5 \cdot 10^{35} = 8.8 \cdot 10^{34}$
$\epsilon \bar{A}_y^2, f_{dil} \cdot P_t^2$	2.5 10 ⁻⁴	(0.9) x (0.9) ² =0.73
FOM	1.6 10 ³⁴	1.3 10 ³⁵

Table 2.1 - Global figure of merit (FOM) of the two options. With the polarized target it is independent of Q^2 . For the polarimeter option, it depends on the proton energy and then on Q^2 . A value of $0.25 \cdot 10^{-3}$ corresponds to $T_p = 7.5$ GeV and $Q^2 = 14$ GeV².

Besides the measurement of elastic nucleon form-factors, ELFE will be the ideal machine to study excited nucleons by means of exclusive single meson production reactions on the proton : $p(e,e'p)\pi^0$ and $p(e,e'p)\eta$ [Adams et al. (1993) ; Stoler (1993)] up to $Q^2 \sim 10$ (GeV/c)².

2.5. Deuteron form-factors

The deuteron is one of the simplest object in nuclear physics. It is the only known bound state of two nucleons and its static properties are known with a high precision [Arvieux and Cameron (1987)]. At very low Q^2 , the two nucleons are treated as point-like objects and the deuteron data can be fitted by standard nucleon-nucleon potentials within the impulse approximation [Haftel et al. (1980) ; Lacombe et al. (1980)]. At medium momentum transfer ($Q^2 = 0.5-1$ (GeV/c)²), meson-exchange currents become sizeable and they are needed to fit the deuteron form-factors [Gari and Hyuga (1976), (1977); Nyman and Riska (1986) (1987); Hummel and Tjon (1989)]. Above 1(GeV/c)² relativistic effects cannot be neglected any more and the Schrödinger equation is no more appropriate [Friar (1973) (1975) ; Gross (1966) ; Zuilhof and Tjon (1980); Buck and Gross (1979) ; Bhalerao and Gurvitz (1981) ; Bhalerao (1982) ; Arnold et al. (1981)]. For very high Q^2 , the deuteron form-factors are expected to reach some simple scaling limits which can be predicted by pQCD calculations as shown in section 2.1.

The value of Q^2 at which the scaling limit will appear is matter of debate. [Brodsky and Chertok (1976)] propose a very early scaling. A recent analysis [Farrar et al. (1995)] shows however that if this is the case then the deuteron distribution amplitude is very different from a proton-neutron bound state, for instance that it contains, and even is dominated by, non nucleonic components. The measure of the Q^2 dependence

of the deuteron form factors at high energy is thus of utmost importance for the understanding of the structure of light nuclei.

At some intermediate $Q^2 \sim (5-10 \text{ (GeV/c)}^2)$, deuteron observables may also be sensitive to hidden color 6 quark-components of the wave-function which can be taken into account in rather phenomenological hybrid models [Kisslinger (1982) ; Dijk and Bakker (1989)].

In the range of Q^2 (up to 4 (GeV/c)^2) presently explored no breakdown of the meson-nucleon picture has yet been observed (see fig. 2.2) and it is proposed to measure $A(Q^2)$ up to 10 (GeV/c)^2 in an attempt to reach the asymptotic regime.

2.5.1. Separation of the charge and quadrupole form-factors

The unpolarized cross for the elastic scattering of an electron by a deuteron is given by:

$$\frac{d\sigma}{d\Omega}(\theta, Q^2) = \left(\frac{d\sigma}{d\Omega} \right)_{Mott} \left[A(Q^2) + B(Q^2) \tan^2(\theta/2) \right],$$

where $A(Q^2)$ and $B(Q^2)$ are combinations of the deuteron charge, magnetic and quadrupole form-factors $G_C(Q^2)$, $G_M(Q^2)$ and $G_Q(Q^2)$ respectively :

$$A(Q^2) = G_C^2 + \frac{8}{9} \tau^2 G_Q^2 + \frac{2}{3} \tau G_M^2$$

$$B(Q^2) = \frac{4}{3} \tau(1 + \tau) G_M^2$$

$$\tau = Q^2 / 4m_d^2$$

A variation of θ at fixed Q^2 or a variation of Q^2 (variable incident energy) at fixed θ allows to separate the relativistically invariant structure functions $A(Q^2)$ and $B(Q^2)$ and hence to determine the magnetic form-factor.

To separate G_C and G_Q one must measure polarization observables. The simplest way (in principle) is to measure the tensor-polarization components $t_{\lambda\mu}$ of the recoiling deuteron [Arvieux and Cameron (1987)]

$$\frac{d\sigma}{d\Omega}(\theta) t_{20}(\theta) = -\frac{1}{\sqrt{2}} \left\{ \frac{8}{3} \tau G_C G_Q + \frac{8}{9} \tau^2 G_Q^2 + \frac{4}{3} \tau [1 + 2(1 + \tau) \tan^2(\theta/2) G_M^2] \right\}$$

$$\frac{d\sigma}{d\Omega}(\theta) t_{21}(\theta) = \frac{4}{\sqrt{3}} \left[\tau + \tau^2 \sin^2(\theta/2) \right]^{1/2} G_M G_Q \sec(\theta/2)$$

$$\frac{d\sigma}{d\Omega}(\theta) t_{22}(\theta) = -\frac{1}{2\sqrt{3}} G_M^2$$

where the Q^2 -dependence of the form-factors has been omitted throughout.

A measurement of t_{20} has been done between 0.6 and 0.8 (GeV/c)² at the MIT-Bates Laboratory, using a recoil polarimeter (AHEAD) developed at University of Alberta and Saturne. The results are shown in fig. 2.17 together with the resulting $|G_C|$ and G_Q distributions [Garçon *et al.* (1994)]. They are compared with conventional meson-nucleon calculations using the Paris potential [Mosconi and Ricci (1989)], the Argonne ν_{14} potential [Schiavilla and Riska (1991)] or the full Bonn-E potential [Pauschenwein *et al.* (1992)]. As can be seen the simplest NN potentials give a reasonable account of the data.

Fig. 2.17 - $t_{20}(\theta_e = 70^\circ)$, G_C and G_Q calculated in the non-relativistic impulse approximation using the Paris Potential (solid line), the Argonne ν_{14} potential (dotted line) or the full Bonn-E potential (dashed line) (from [Garçon *et al.* (1994)]).

In terms of helicity cross-sections σ_λ where λ is the final deuteron polarization ($\lambda = \pm 1$ or 0), t_{20} is given by:

$$t_{20} = \frac{1}{\sqrt{2}} \frac{\sigma_+ + \sigma_- - 2\sigma_0}{\sigma_+ + \sigma_- + \sigma_0}$$

In the helicity representation, the three deuteron form-factors are [Carlson (1990)] :

$$G_{00}^L = G_C + \frac{4}{3} \tau G_Q$$

$$G_{+-}^L = G_C - \frac{2}{3} \tau G_Q$$

$$G_{0+}^T = \tau^{1/2} G_M$$

where L and T refer to photons with helicity 0 and +1 respectively. The subscripts on the G 's are the helicities of the incoming, λ_i , and outgoing, λ_f , deuterons respectively. Angular momentum conservation requires that

$$\begin{array}{lll} \lambda_i + \lambda_f = 0 & \text{for} & \text{longitudinal photons} \\ \lambda_i + \lambda_f = +1 & \text{for} & \text{transverse photons.} \end{array}$$

Fig. 2.18 - Resonance electroproduction, drawn in the Breit frame, for differing photon helicity. The double arrows represent spin direction, and λ is helicity (from [Carlson (1990)]).

However hadron helicity conservation requires that the helicity of the incoming deuteron equals the helicity of the outgoing one. This only happens for G_{00}^2 (shown in fig. 2.18) which is the dominant pQCD amplitude. Hence the helicity zero cross-section σ_0 will dominate over the helicity changing amplitudes $\sigma_\pm$ and hence in pQCD

$$t_{20} \rightarrow -\sqrt{2}.$$

As can be seen in fig. 2.17 at 4.6 fm^{-1} (which corresponds to about 1 (GeV/c)^2), t_{20} is far from its asymptotic value. It has been argued recently [Kobushkin and Syamtomov (1994)] that in the range of a few $(\text{GeV/c})^2$, the light-cone helicity-flip amplitudes could not be omitted which pushes up the pQCD limit close to the experimental value at the largest momentum transfer (fig. 2.19).

The extension of the t_{20} measurement to higher Q^2 -values is a natural topic for the ELFE accelerator but a detailed proposal has yet to be made.

Fig. 2.19 - The predictions for T_{20} in the approach of [Kobuskin and Syamtonov (1994)] (full line) as compared with QCD calculations by [Brodsky and Hiller (1992)] (dotted line).

2.5.2. Measurement of $A(Q^2)$ at medium Q^2 [Garçon et al. (1993)]

Existing $A(Q^2)$ data are shown on fig. 2.20 and compared to some meson-exchange calculations [Hummel and Tjon (1989)] including the $\rho\pi\gamma$ and $\omega\sigma\gamma$ vertex corrections (fig. 2.21). Above 2 (GeV/c)^2 , meson-exchange contributions completely dominate the Impulse Approximation term.

For very high Q^2 , $A(Q^2)$ is supposed to reach an asymptotic limit which can be calculated within pQCD [Brodsky et al. (1983)] in a way similar to the one described in section 2.1 for the factorization of the nucleon form-factor. One can define a reduced form-factor [Brodsky and Chertok (1976)]

$$f_d(Q^2) \equiv \frac{F_d(Q^2)}{F_{1N}^2(Q^2/4)}$$

where $F_{1N}(Q^2)$ is the nucleon form-factor defined in section 2.4 and $F_d(Q^2)$ is the following combination of $A(Q^2)$ and $B(Q^2)$

$$F_d(Q^2) = \left[A(Q^2) + B(Q^2) \tan^2(\theta/2) \right]^{1/2}.$$

In the asymptotic limit, $F_d(Q^2)$ is dominated by the non spin-flip helicity amplitude and then $F_d(Q^2) \sim \sqrt{A(Q^2)}$. Applying the dimensional counting rule, $F_d(Q^2)$ should scale like Q^{-10} and $F_{1N}(Q^2)$ like Q^{-4} then $f_d(Q^2)$ should scale like Q^{-2} . The data are shown on fig. 2.22 and one can see that dimensional scaling sets at the surprisingly low value of $Q^2 \sim 2(\text{GeV}/c)^2$.

Fig. 2.20 - Deuteron $A(Q^2)$ structure function as calculated by [Hummel and Tjon (1989)]. The dotted line is the impulse approximation, while the dashed and solid lines contain $\rho\pi\gamma$ and $\omega\gamma\epsilon$ meson exchanges. The dash-dotted line was computed using a different choice for the nucleon form-factors.

It is proposed to extend measurements of $A(Q^2)$ which exist up to $4(\text{GeV}/c)^2$ with reasonable accuracies [Benaksas et al. (1966) ; Buchanan and Yearian (1965) ; Galster et al. (1971) ; Arnold et al. (1975) ; Simon et al. (1981) ; Platchkov et al. (1990)] up to $8-10(\text{GeV}/c)^2$. In order to separate the elastic scattering from the deuteron break-up channel ($E_B = 2.2 \text{ MeV}$) the experiment would use the two spectrometers described in section 7.2.

Fig. 2.21 - Meson exchange diagrams : (a) pair term, (b) recoil, (c) reorthonormalization, (d) $\rho\pi\gamma$, (e) $\omega\sigma\gamma$ (from [Hummel and Tjon (1989)]).

Fig. 2.22 - (a) Reduced deuteron form-factors f_d as compared to the asymptotic QCD prediction of [Brodsky (1985)] using several values for the QCD parameter Λ . The prediction is normalized at $Q^2 = 4 \text{ (GeV/c)}^2$. (b) Comparison of the quantity $(1 + Q^2/m_0^2)f_d$ with the data. Here the dashed curve is the calculation of [Hummel and Tjon (1989)], transformed into a scaling curve (from [Brodsky (1985)]).

3. COLOUR TRANSPARENCY

3.1. Theoretical considerations

We have seen in section 2.1 that the nuclear wave-function of a nucleon $|N\rangle$ can be expanded schematically (forgetting helicity and colour indices) in different configurations involving 3 quarks and an infinite number of $q\bar{q}$ pairs and gluons.

At high momentum transfer, QCD makes a set of predictions which have led to the concept of "colour transparency" and "colour neutrality" [Bertsch *et al.* (1981) ; Mueller (1982) ; Brodsky (1982)]. For recent reviews see also [Frankfurt and Strikman (1988) ; Frankfurt *et al.* (1992), (1994)] and for a more didactic approach [Pire and Ralston (1991)].

1. Small objects are produced in exclusive reactions at high momentum transfer. These objects can be identified with the minimum Fock configuration $|qqq\rangle$ (in the case of a nucleon) or $|q\bar{q}\rangle$ (in the case of a meson). The question of the size of the ejectile is discussed in detail in [Nikolaev (1992a)] and in [Greenberg and Miller (1993)].

2. Small objects have reduced interactions. The observation that the interaction of a small size hadronic system with a target is largely suppressed, was made a long time ago by [Gunion and Soper (1975)] within a two gluon exchange-model, the Low-Nussinov "bare" pomeron [Low (1975) ; Nussinov (1975), (1976)]. An example of colour transparency is the quasi-elastic production at high momentum transfer of protons by energetic electrons. At the time of the interaction the "minihadrons" [Ralston and Pire (1990)] can propagate through the nucleus with little attenuation. Instead of showing the normal exponential flux decrease, the rate of protons produced is decreasing much more slowly than predicted by normal (e.g. Glauber) nuclear theories : the nucleus is becoming transparent.

Fig. 3.1 - Interaction (ionization) probability vs. distance from the origin of the $e^+ e^-$ pair (from [Frankfurt *et al.* (1992)]).

Colour transparency is specific of gauge theories. It is not unique to QCD and a similar phenomenon of charge transparency is observed in QED. It is well known that the ionizing power of a e^+e^- pair in an emulsion is smaller near the point of its origin. This has been found in the observation of ultra high energy cosmic ray photons converted in the nuclear Coulomb field of a nucleus $\gamma + A \rightarrow e^+e^- + A$ [Chudakov (1955)] or in the decay of fast pions in nuclear emulsion : $\pi^0 \rightarrow e^+e^- \gamma$ [Perkins (1955)] as seen in fig. 3.1. The explanation of this phenomenon is the following : near its point of creation the electron and positron are separated by a distance r of the order of the inverse $r \sim 1/m_\pi$ of the pion mass. This separation is much less than a typical atomic radius and the e^+e^- pair acts as a neutral object having then very little interaction with the surrounding medium. This can be expressed in terms of an electric dipole moment being proportional to the transverse distance between the two charges. As the charges propagate they separate from each other, the dipole moment increases and ionization does occur.

The notion of electric dipole interaction is also valid for the quark-quark interaction in QCD except that charges are replaced by colours and that being a non-Abelian theory, the self interaction of gluons must also be taken into account.

3.2. Colour Transparency in $(p,2p)$ reactions

The first hint for colour transparency was observed in $(p,2p)$ reactions at Brookhaven [Carroll *et al.* (1988), Heppelmann *et al.* (1990)]. The experiment was done on several nuclear targets (Li, C, Al, Cu and Pb) at incident proton momenta of 6, 10 and 12 GeV/c. The transparency T was defined as the ratio of the $(p,2p)$ cross-section in nuclei to the elastic pp scattering in hydrogen taken at the same four-momentum transfer t . The results shown in fig. 3.2, were indeed showing an increase in transparency by a factor of two from 6 to 9.5 GeV/c followed by a significant fall between 9.5 and 12.5 GeV. They have been fitted by a combination of a colour-transparency mechanism explaining the rise of T and other mechanisms to explain the subsequent decrease, such as an interference between two p QCD subprocesses : a multiple scattering process ("à la Landshoff") [Landshoff (1974)] and a hard amplitude resulting from quark counting rules [Ralston and Pire (1988)]. This theory explains also the oscillating behaviour of the pp elastic cross-section at fixed angle (fig. 3.3) when the regular quark counting rule dependence in s^{-10} has been divided out [Pire and Ralston (1982)].

Another hypothesis advocates the opening of the charm production threshold at about 3 GeV above the pp mass [Brodsky and de Terramond (1988)] to explain the change in transparency behaviour at 10 GeV/c.

Colour transparency has been initially investigated in a time-dependent approach and a Fock state decomposition but a time-independent approach with physical states leads to the same conclusions [Jennings and Miller (1991) (1992)]. In this case the condition that the escape time of the mini-hadron has to be small is replaced by a closure approximation on the nucleon excitation energies which have to remain low. The closure approximation sets a minimum energy in the c.m. system $E \gg 2 A^{1/3}$ GeV or $E_L \gg 12$ GeV for ^{27}Al in the laboratory. From these arguments it is not clear whether the BNL data are related to colour transparency and in a fully nucleonic Glauber approach, [Frankel and Frati (1992)] claim that the A -dependence of the BNL data shows no evidence for the enhancement expected from "colour screening".

Fig. 3.2 - (a) The transparency vs beam momentum for various nuclear targets selected for $-0.2 \text{ GeV/c} < p_z < 0.1 \text{ GeV/c}$. (b) Transparency for ^{27}Al for different beam momenta vs effective incident momentum (from [Heppelman (1990)]).

Fig. 3.3 - (a) The energy dependence of $R_1(s) \sim s^{10} d\sigma/dt (pp)|_{90^\circ}$ for high energy pp elastic scattering at 90° cm angle. (b) Prediction of oscillating transparency $T(s)$ for $A=27$ (from [Pire and Ralston (1991)]).

A lively debate [Jennings and Kopeliovich (1993) ; Bianconi et al. (1993) ; Nikolaev et al. (1993)] has emphasized the eventual importance of Fermi motion effects.

A consensus emerges to say that the interpretation of the $(p,2p)$ data, in terms of colour transparency is still elusive ; data at higher Q^2 are expected to come from the EVA experiment at BNL.

Two experimental results have been published recently : the $(e,e'p)$ reaction was studied at high momentum transfer (up to $Q^2 = 6.8 \text{ (GeV/c)}^2$) on several targets at SLAC (NE18 Collaboration) and it does not show large transparency effects. The other experiment done at FNAL (E665 Collaboration) on the exclusive virtual photoproduction of the ρ^0 meson on nuclei shows a strong colour transparency effect as a function of Q^2 from $Q^2 = 0$ to $Q^2 = 7 \text{ (GeV/c)}^2$ [Guang (1993)].

3.3. Colour Transparency in $(e,e'p)$ reactions

The advantage of quasi-free nucleon production by the $(e,e'p)$ reaction is many-fold :

- the electromagnetic probe samples the complete volume of the nucleus
- the elementary electron-nucleon interaction is well known and it varies smoothly over the

kinematical range of interest

- momentum distribution of nucleons inside a nucleus have been measured with the same probe
- the relatively high energy resolution (as compared to typical high energy experiments) allows a clean detection of quasi-elastic scattered recoiling nucleons over a large kinematical range.

The NE 18 experiment was performed at SLAC and used the Nuclear Physics Injector. The beam energy resolution ranged from 1. to $2 \cdot 10^{-3}$ and the beam current was 2 to 10 μA . The duty factor was rather low ($D.F = 2 \times 10^{-4}$). The targets studied were hydrogen, deuterium, ^{12}C , ^{56}Fe and ^{197}Au . The scattered electrons were detected using the 1.6 GeV/c spectrometer and the recoiling protons were detected in the 8 GeV/c spectrometer. Both spectrometers gave a resolution of the order of 1.5×10^{-3} resulting in a missing energy resolution (FWHM) ranging from 8 MeV at $Q^2 = 1 \text{ (GeV/c)}^2$ to 20 MeV at $Q^2 = 6.8 \text{ (GeV/c)}^2$, ensuring the rejection of inelastic events with pion production.

The elastic hydrogen data are well explained with a dipole form for the proton electric form-factor, and the parametrization of the magnetic form-factor by [Gari and Krümpelman (1985)]. The shapes of spectral functions and missing momentum spectra extracted from the deuterium and ^{12}C data are in excellent agreement with PWIA calculations showing that no significant rescattering of the knocked-out proton did occur. It has been estimated that the uncertainty brought by this assumption on the transparency factor is of the order of 2 % for moderate missing momentum up to $p_m \approx 250 \text{ MeV/c}$ [Nemchik *et al.* (1994a)].

Fig. 3.4 - Measured transparencies for various targets versus Q^2 (from [Makins *et al.* (1993)]). The inner error bars are the statistical uncertainty, and the outer error bars are the statistical and systematic uncertainties added in quadrature. The points at $Q^2=0.33 \text{ (GeV/c)}^2$ are from [Geesaman *et al.* (1989)] and [Garino *et al.* (1992)].

In this experiment, the transparency T is defined as the ratio of the number of actual events at a fixed value of Q^2 to the number of counts predicted by the PWIA :

$$T(Q^2) = \frac{\sum_{\mathfrak{R}} N_{data}}{\sum_{\mathfrak{R}} N_{PWIA}}$$

where $\mathfrak{R}$ represents a region covering the range of missing energy $-25 < E_m < 100$ MeV and missing momentum $0 < p_m < 250$ MeV/c. The results are shown in fig. 3.4 [Makins *et al.* (1993), Makins and Milner (1994)]. They exhibit very little colour transparency : the variation with Q^2 is almost monotonic with a slight decrease around 5 (GeV/c)² contrary to crude colour-transparency expectations which would predict a rise of T as a function of Q^2 .

This trend is followed by many Glauber calculations in ¹²C and ⁵⁶Fe as shown in fig. 3.5 and 3.6 [Kohama *et al.* (1993) ; Nikolaev *et al.* (1993) ; Benhar *et al.* (1992) ; Farrar *et al.* (1988) ; Jennings and Miller (1991)], although the absolute value of $T(Q^2)$ may be underestimated by the theory. This was not totally unexpected since the most recent calculations show a very slow on-set of colour-transparency as a function of Q^2 [Frankfurt *et al.* (1994); Nikolaev *et al.* (1994) ; Nemchik *et al.* (1994b); Jennings and Miller (1992)]. In this respect the NE 18 data can only rule out clearly the naive parton model of [Farrar *et al.* (1988)]. A recent calculation [Nemchik *et al.* (1994a)] of transparency on ²H, ¹²C, ⁵⁶Fe and ¹⁹⁷Au ($e, e'p$) reactions shows that the final state interactions (FSI) of the recoiling proton broaden the $p_{\perp}$ distribution and do not allow to factorize any more the spectral function as it is done in the PWIA. The resulting calculations fit almost perfectly the data as shown in fig. 3.7. Other theoretical aspects of colour transparency using a QCD oriented approach [Nikolaev and Speth (1993)] and hadronic dynamics [Bianconi *et al.* (1993b)] can be found in the full ELFE report.

Fig. 3.5 - Experimental transparency for ⁵⁶Fe compared with several Glauber calculations (from [Makins and Milner (1994)], see references of theoretical calculations in the text.

Fig. 3.6 - Measured experimental transparency for ^{12}C compared with several calculations including colour transparency from [Makins and Milner (1994)].

Fig. 3.7 - Predictions for the Q^2 dependence of nuclear transparency are compared with the NE18 data. The dashed curve denotes the $p_{\perp}$ -integrated nuclear transparency T_A ; the dotted curve gives the nuclear transparency measured in parallel kinematics at $p_{\perp} = 0$; the solid curve represents the nuclear transparency T_A (NE18) including the NE18 acceptance cuts (from [Nemchik et al. (1994a)]).

In conclusion the interpretation of the $(p,2p)$ data in terms of colour transparency is ambiguous and in the range of Q^2 explored, the $(e,e'p)$ data show experimentally little transparency. To sign colour transparency as a true QCD feature one must go to different reactions, as for example in vector-meson production, or reach higher momentum transfers and better energy resolutions in the $(e,e'p)$ reaction.

3.4. Colour Transparency in vector meson production

The exclusive production of vector mesons $\gamma^* p \rightarrow Vp$ is a hard scattering process in which the transverse size r_Q of the quark configurations which dominate at large momentum transfer is given by

$$r_Q = \frac{2}{\sqrt{m_V^2 + Q^2}},$$

where m_V is the mass of the vector meson, making this reaction a laboratory for the controlled study of colour transparency [Kopeliovich et al. (1994)]. The data on exclusive electroproduction of ρ^0 mesons from the E 665 experiment at FNAL show indeed a strong variation with increasing Q^2 of the transparency ratio $T_A = \sigma_A/A\sigma_N$, where σ_A and σ_N are the incoherent exclusive production on a nucleus with atomic number A and on a nucleon respectively, in rough agreement with some colour transparency model calculations as shown in fig. 3.8.

Fig. 3.8 - Predictions of nuclear transparency $T_A = \sigma_A/A\sigma_N$ for the incoherent exclusive production of ρ^0 mesons versus the E665 data (from [Nikolaev and Zakharov (1993)]).

Fig. 3.9 - The qualitative pattern of the Q^2 -dependent scanning of the wave functions of the ground state $V(1S)$ and the radial excitation $V'(2S)$ of the vector meson. The wave-function and radius r in arbitrary units (from [Nemchik et al. (1994a)]).

Photoproduction of J/ψ should be an even better case due to the small intrinsic radius of the J/ψ (of the order of 0.15 fm). In particular scaling laws for the production of ρ^0 and J/ψ mesons can be inferred from dimensional arguments which are verified by existing but not very precise data [Brodsky and Hoyer (1989) ; Farrar et al. (1990)]. Finally due to the presence of a node in the radial wave-function of the radial excitation V' of vector mesons as shown in fig. 3.9, the cross-sections for producing a vector meson V and a radially excited meson V' are very different as shown in fig. 3.10 for the case of a $\rho^0(1S)$ and a $\rho'(2S)$. As a consequence radially excited vector mesons may display colour opacity instead of colour transparency as shown in fig. 3.11 where the transparency for the ρ' is predicted to increase with the size of the nucleus. The same effects should be observed with the $\phi(1020)$ and $\phi'(1680)$ or with the J/ψ and ψ' as shown in fig. 3.12. The electroproduction of nucleon resonances : $\Delta(1232)$, $N^*(1440)$, $N^*(1710)$ at high momentum transfer would help to disentangle the modification of the struck ejectile in the hard process from the diffractive excitation of the proton and to understand better colour transparency in $(e,e'p)$ reactions [Gardner (1992)].

Fig. 3.10 - The Q^2 dependence of the $\rho' (2S)/\rho^0 (1S)$ ratio of forward production cross-sections (from [Nemchik et al. (1994a)]).

Fig. 3.11 - The Q^2 and A dependence of nuclear transparency for the $\rho^0 (1S)$ and $\rho' (2S)$ electroproduction on nuclei (from [Nemchik et al. (1994a)]).

Fig. 3.12 - Predicted Q^2 and ν -dependence of the J/ψ and ψ' electroproduction (from [N.N. Nikolaev (1992b)]).

3.4. Proposed experiment at ELFE

It is proposed [Anklin et al. (1993)] to measure the quasi-free ($e, e'p$) cross-section and normal component P_n of the polarization of the recoiling proton on ^2H , C, Fe and Au targets. The data will cover the range $Q^2 = 6\text{--}21 \text{ (GeV/c)}^2$, ensuring an overlap with the NE18 data from SLAC.

The spectrometers are described in detail in section 7.2. The resolution in missing energy will be 12-13 MeV FWHM which is adequate to discriminate against 2-nucleon knockout and allows for a limited study of shell effects even at the highest momentum transfer.

Counting rates have been calculated using the elementary cross-sections shown in fig. 3.13.

With luminosities varying from $3.7 \times 10^{35} \text{ cm}^{-2} \cdot \text{s}^{-1}$ for Au up to 1.6×10^{38} for liquid hydrogen and a total time of about 1000 h, a statistical accuracy better than 12 % over the full Q^2 range for C, Al and Cu targets and up to 18 $(\text{GeV/c})^2$ for Pb, could be obtained.

In the absence of any nuclear medium effect the normal component of the recoiling proton polarization should be zero to first order in PWIA [Gomez et al. (1991)]. This effect can be used to filter out cleanly FSI effects : it is a straightforward consequence of the foundations of colour transparency and it is, therefore, largely model- independent [Bianconi et al. (1994)].

To measure the recoil polarization P_n a polarimeter will be needed at the focal plane of the hadron spectrometer. At low energy (up to 2.4 GeV [Cheung et al. (1994)]), carbon can be used as analyzer. Above 2.4 GeV, where no calibration data exist, other schemes will have to be used. The methods to be investigated are the elastic scattering by liquid hydrogen (to improve the efficiency) or a switching to a self-calibration scheme as described in [Gomez et al. (1991)] and [Perdrisat and Punjabi (1989)]. Counting rate estimates and uncertainties ΔP_n on P_n assuming efficiency of $\varepsilon = 3 \times 10^{-3}$, have been made. They indicate that a precision of 0.20 on ΔP_n can be obtained in 500 hours at $Q^2 = 12 \text{ (GeV/c)}^2$ for a Fe target and $Q^2 = 9 \text{ (GeV/c)}^2$ for a Au target.

Fig. 3.13 - Predictions for the Q^2 -dependence of nuclear transparency in $(e,e'p)$ reactions on various targets (from [Nikolaev and Zakharov (1993)]).

The feasibility of the P_n measurement will therefore be severely limited by the counting rate if no breakthrough is achieved in proton polarimetry at high energy.

A second experiment is proposed by a russian group [Degtyarenko et al. (1993a)]. It would use the 4π -detector MEMUS described in section 7.5 to measure the transverse size of the interaction region r_Q by measuring Bose-Einstein correlations between two hadrons $(e,e'2p)$ or $(e,e'2\pi)$ and the azimuthal asymmetry β (which is also connected to r_Q) up to $Q^2 = 16$ (GeV/c)². The same apparatus can also be used to measure cumulative particle production in hadronization processes as proposed by [Degtaryenko et al. (1993b)].

4. HEAVY QUARKS : STRANGENESS AND CHARM

4.1. Physics Case

Understanding heavy quark production requires the disentangling of the 3 following steps :

i) the structure of the struck nucleon : in the case of heavy flavour production it is, in particular, important to know how much intrinsic strangeness $s\bar{s}$ or charm $c\bar{c}$ components exist in the nucleon wave function,

ii) the elementary production mechanism,

iii) the formation and propagation of the final state.

Elementary production mechanisms are different for elastic and inelastic reactions :

a) elastic vector meson production proceeds, in the limit of high energy (compared to the rest mass) mostly through a diffractive mechanism, with a cross-section which is strongly forward peaked at $z \approx 1$ and small transverse momentum. In this picture, the photon fluctuates as a virtual meson ($\rho, \phi, J/\psi$) with a lifetime given by the coherence length

$$\tau_c = \frac{2\nu}{m_V^2 + Q^2},$$

where m_V is the mass of the vector meson. Then scattering proceeds through a soft process involving the exchange of a "soft" Pomeron. This is often expressed as the Vector Meson Dominance (VMD) model.

Near threshold (ν small) or for large m_V^2 or Q^2 , this mechanism has no time to fully develop and the Pomeron exchange reduces to its first order contribution which is dominated by two-gluon exchange diagrams which can be estimated perturbatively : this is the hard Pomeron of fig. 4.1.

Fig. 4.1. Schematic two-gluon exchange for vector-meson production.

Since τ_c can be made of the order of a few fm/c, the use of a nucleus as a target allows to study the formation of heavy mesons in the dense nuclear medium and study their interaction with the surrounding nucleons. This mechanism can be, in particular, used to induce colour rearrangement between quark clusters in nuclei in order to study "hidden" colour components of light nuclei [Laget (1993)].

b) Open charm production shown in fig. 4.2 is well under control theoretically through the photon-gluon fusion mechanism [Babcock et al. (1978); Fritzsche (1977)].

Fig. 4.2. Photon-gluon fusion mechanism for open charm production..

c) Inelastic production of vector mesons is usually described through the colour singlet model of fig. 4.3 (here in the case of J/ψ production) but it deserves further theoretical studies [Berger and Jones (1981)].

Fig. 4.3. The colour singlet model mechanism (from [Benhar et al. (1993)]).

By comparing the production of light (ρ and ω), intermediate (ϕ) and heavy (J/ψ) vector mesons one can disentangle quark interchange mechanisms from gluon exchange (with colour rearrangement) : Light (u and d) quarks can be produced at the vertex of the interaction with the photon or produced subsequently in the hadronization process whereas heavy quarks do not preexist in the struck nucleon (except for a small $s\bar{s}$ or $c\bar{c}$ component which may exist in the nucleon wave-function).

Another tool for understanding the dynamics of the reaction is the use of spin degrees of freedom. By using a polarized electron beam and polarized target or by measuring the polarization of the produced vector mesons (through the polar and azimuthal angular distribution of their decay products) one can determine the various helicity amplitudes and test different reaction models. The same technique can be used in open heavy flavour production with strange (Λ , Σ) or charmed baryons whose polarization can be self-analyzed through their weak decays.

In order to compare ϕ and J/ψ production one often relies on the notion of transverse quark mass $\sqrt{m_q^2 + p_T^2}$ where p_T is the transverse momentum of the heavy quark. Due to the large mass of the charmed quark ($m_c \approx 1.5$ GeV) perturbative calculations are expected to be applicable to J/ψ production almost at threshold since the running coupling constant α_s is of the order of 0.3. To get the same transverse mass, the transverse momentum P_T of a ϕ -meson which is about twice the transverse momentum of each quark, has to be of the order of 2.8 GeV/c or $Q^2 \approx 8$ (GeV/c)², a value easily achieved with ELFE at 15 GeV.

Due to the low threshold of strangeness production : 0.9 GeV for $\gamma p \rightarrow K\Lambda$ or 1.54 GeV for $\gamma p \rightarrow p\phi$ as compared to 8.2 GeV for J/ψ production, the cross-section for strangeness production are much larger than for charm production : 400 nb for the reaction $ep \rightarrow e'p\phi$ in the range $3 < E_\gamma < 10$ GeV as compared to 5 nb for $ep \rightarrow e'p J/\psi$ at 20 GeV [Cassel et al. (1981)].

Four proposals dealing with heavy quark production have been submitted in the ELFE project report.

1. Electroproduction of polarized lambdas
2. Photo-production and electro-production of ϕ -mesons at large p_T
3. Charmonium production
4. Open and associated charm production

4.2. Electro-production of polarized lambdas

4.2.1. Measurement of the Λ polarization at large p_T [Kunne et al. (1993); Anton et al. (1993)]

There are many reasons why spin effects should be small at high energies. Since in perturbative QCD helicity is conserved at the quark-gluon vertices in the zero quark mass limit, an unpolarized initial state cannot produce a polarized final state and, as a result, single spin effects (analyzing powers or particle polarizations) must become negligible at asymptotic energies.

Another, more practical reason, is that polarization results from the interference of at least two amplitudes which characterize the interaction :

$$P \sim \frac{\text{Im}(f^*g)}{f^2 + g^2},$$

where f is the sum of all the spin-independent amplitudes and g the sum of all spin-dependent amplitudes. Let's take, as an example, the inclusive production of a Λ hyperon in a p - p collision at hundreds of GeV. At the time of the collision several other particles are created which are not measured. The amplitudes f and g will be therefore a sum of all possible distributions of these particles each with a different phase. The phases then are expected to average out and very little polarization should be measured.

These are the reasons why spin has, for a long time, not attracted the attention of many high energy physicists. The situation has changed in the last few years due to two experimental discoveries.

First it has been observed at Fermilab that lambdas produced in the $pp \rightarrow \Lambda X$ reaction induced by 400 GeV protons have large polarizations when they carry a significant fraction x_F of the incident proton momentum. The polarization increases linearly with the transverse momentum p_T and with x_F until reaching negative values of the order of 20 to 30 % [Bunce *et al.* (1976)] as shown in fig. 4.4. The same pattern has been observed in an energy range extending from 10 to 2000 GeV.

Fig. 4.4 - Polarization of lambdas produced by 400 GeV protons as a function of p_T and x_F (from [Kunne *et al.* (1993)]).

These data lead to a systematic study of inclusive hyperon polarization whose results at a fixed $p_T \approx 1$ GeV/c and fixed $x_F \approx 0.5$ are summarized in fig. 4.5 [see Heller (1990) and references therein].

Simple rules based on the idea that the hyperon polarization is mainly determined by the spin and isospin coupling of valence quark(s) explain most qualitative features of the data as explained in fig. 4.6 [De Grand and Miettinen (1981)]. More recent data show that the situation may not be so simple [Devlin (1994)].

Fig. 4.5 - Inclusive hyperon polarization as a function of collision energy for data with $p_T \approx 1$ GeV/c and $x_F \approx 0.5$ (from [Kunne et al. (1993)]).

Fig. 4.6 - Schematic diagrams of valence quark production for hyperons. The arrows represent the spin of the valence quarks and diquarks and the spin of the hyperon (from [Heller (1990)]). The sign of the hyperon polarization follows from the assumption that the strange quark polarization is always negative.

Inclusive electro-production has large cross-sections in the energy region 10 to 20 GeV and lambdas are easy to identify through their two-body decays. A large number of experiments have been done in the 70's and early 80's and their momentum distribution is well understood in terms of an invariant structure function

$$F_{inv} = \frac{E_h}{\sigma_{tot}} \frac{d^3\sigma}{dp_h^3},$$

where σ_{tot} is the total inclusive cross-section, as shown in fig. 4.7.

Fig. 4.7 - Distributions of the invariant structure function for Λ -production with various projectiles. The data for each process are normalized to corresponding inelastic cross-section. The curve illustrates a prediction of a diquark fusion model with arbitrary normalization by [Donnachie (1980)] (from [Kunne *et al.* (1993)]).

Fig. 4.8 - Polarization of photoproduced Λ 's [Abe *et al.* (1984)].

As in pp scattering some substantial polarization, although with large error bars, was found in real photo-production induced by 20 GeV photons at SLAC as shown in fig. 4.8. A complete study of Λ , Σ^0 , Σ^+ , Σ^- , Ξ^0 , Ξ^- and Ω^0 could be made with a 15 GeV electron beam and a 4π -detector. In particular all these channels can be identified separately which was not the case in hadron induced reactions where it was not possible to know if a Λ was produced directly or if it came from the decay of an hyperon with a larger mass (e.g. $\Sigma^0 \rightarrow \Lambda \gamma$).

Photo-production of polarized lambdas in exclusive reactions has also been proposed for the ELFE facility.

4.2.2. Measurement of transverse spin distributions [Kunne et al. (1993)]

The second experimental reassessment of spin effects at high energy comes from Deep Inelastic Scattering (DIS) of leptons on polarized targets which has shown that the spin of a nucleon is only partly carried out by the valence quarks and that the orbital momentum and the gluon (or sea quark) spins play an important role. Existing experiments have concentrated on longitudinal structure functions which are related to the spin composition of the nucleon at the quark level. The spin dependent structure function $g_1(x)$ has been measured on polarized protons, deuterons and ^3He (neutrons) at SLAC ; (E142/143 Collaboration) [Anthony et al. (1993)] and at CERN (EMC and SMC Collaborations) [Adeva et al. (1993)]. Three combined analyses of world data on nucleon spin structure functions have recently appeared in [Adeva et al. (1994) ; Ellis and Karliner (1993) ; Anselmino et al. (1994)]. The fraction of the spin carried by the valence quarks $\Delta u + \Delta d + \Delta s$ is found to be 0.16 ± 0.21 (SMC data) to 0.29 ± 0.14 (E142 data), the contribution Δs of the strange quark spin, being of the order of -0.10 to -0.20 depending on the analysis.

These values are far from the naive quark model which predict $\Delta u + \Delta d = 1$, $\Delta s = 0$ if gluon and orbital contributions are neglected but they are close to the prediction of the Skyrme model for light quarks [Ellis et al. (1988)]. Besides the longitudinal spin structure function $g_1(x)$, there are other fundamental polarized structure functions : $g_2(x)$ measured with longitudinally polarized leptons on a transversely polarized target and $h_1(x)$, the quark "transversity distribution".

The transverse spin distributions are fundamental structure functions which are independent of the longitudinal ones. They are therefore an important piece of hadronic physics which remains to be explained [Artru and Mekhfi (1990) ; Cortes et al. (1992) ; Jaffe and Ji (1991) ; Ji (1994)]. They cannot be measured in pure DIS because transverse spin asymmetries are suppressed in this case. In contrast, in polarized Drell-Yan with both protons polarized transversely as proposed for the RHIC polarized collider, or in polarized semi-inclusive DIS, transverse asymmetries arise at the leading twist level. In the latter case one may measure the azimuthal dependence in the production of the leading hadrons since they will "remember" the transverse polarization of the struck quark or one may measure the polarization of the leading baryon as shown in fig. 4.9.

The transverse spin distribution h_1 is defined as the difference between a quark distribution with the spin parallel and anti-parallel to that of the proton :

$$h_1(x) = \frac{1}{2} \sum_f e_f^2 [q_{f_n}(x) - q_{f_{-n}}(x)],$$

where $q_{f_n}(x)$ and $q_{f_{-n}}(x)$ are distributions of quarks with transverse spin parallel or antiparallel to the transverse spin of the nucleon and the sum is over all flavours.

Fig. 4.9 - Feynman diagram of the reaction $e^- N \rightarrow e^- X \Lambda$ (from [Kunne et al. (1993)]).

One of the cleanest way to determine h_1 is to measure the polarization of the leading Λ in the $ep \rightarrow e' \bar{\Lambda} X$ reaction induced by unpolarized electrons [Artru (1990)].

4.2.3. Experimental considerations

The Λ weak decay to $p\pi^-$ is parity non conserving with a branching ratio of $63.9 \pm 0.5 \%$. The distribution of the proton direction with respect to the spin direction of the Λ is :

$$N(\theta^*) = N_o(1 + \alpha P_\Lambda \cos \theta^*)$$

where P_Λ is the Λ -polarization ; θ^* is the angle between the proton and the normal to the Λ production plane; α is the confortably large weak decay constant [PDG (1994)] : $\alpha = 0.642 \pm 0.013$.

One would like not only to identify the Λ and distinguish it from direct $p\pi$ production but also to determine if it has been produced in a $\gamma^* N \rightarrow K \Lambda$ interaction or if it comes from the decay of heavier hyperons. This means that the following chains of events have to be reconstructed :

$$\begin{array}{cccccc} K\Lambda & , & K\Sigma^0 & , & K\Sigma^+ & , & K\Sigma^- & , & KK\Xi^- & , & KK\Xi^0 \\ \Downarrow p\pi^- & & \Downarrow \Lambda\gamma & & \Downarrow p\pi^0, n\pi^+ & & \Downarrow n\pi & & \Downarrow \Lambda\pi^- & & \Downarrow \Lambda\pi^0 \\ & & \Downarrow p\pi & & & & & & \Downarrow p\pi & & \Downarrow p\pi \end{array}$$

Due to the large number of particles to be detected and identified, one needs a detector as hermetic as possible (4π -detection) to avoid bias in the final measured polarization which could be caused by large acceptance cuts.

Electro-production estimates have been done by two groups in separate proposals. The first estimate [Anton *et al.* (1993)] aims at exclusive production and follows the PEGASYS proposal for SLAC [PEGASYS (1990)].

For the measurement of Λ -polarization in semi-inclusive reactions of the type $ep \rightarrow e'\Lambda X$ [Kunne *et al.* (1993)] there is no need for identification of the strange mesons. For this experiment, the MEMUS detector described in section 7.4 seems a good choice as long as a solution is found to accomodate a polarized target in a non negligible transverse holding field.

A set-up which would suit better the h_1 experiment [Kunne *et al.* (1993)] is the FAST (Forward Angle Spectrometer) detector described in section 7.3. These events are characterized by a fast moving lambda emitted at forward angle within the 25° angular acceptance of FAST. The target being in front of the spectrometer, there would be no counter-indication on the use of a polarized target.

Detailed simulations and count rate estimates can be found in the full ELFE Report [ELFE (1993)].

4.3 - Photo- and electro-production of ϕ -mesons at large p_T [G. Audit *et al.* (1993)]

As we have seen in section 4.1, exclusive production of ϕ -mesons in electro- induced reaction is governed by the VDM process at low momentum transfers and by hard two-gluon exchange at high momentum transfer. It is then an ideal tool to learn about these simple mechanisms.

At low momentum transfer ($-t \leq 0.4 \text{ (GeV/c)}^2$), the photo-production cross-section is purely diffractive and takes the form [Behrends *et al.* (1978) ; Fries *et al.* (1978) ; Barber *et al.* (1982)]

$$\frac{d\sigma}{dt} = \left(\frac{d\sigma}{dt} \right)_{t=0} (\exp Bt).$$

It exhibits a change in slope around $-t = 0.4 \text{ GeV}^2$ (fig. 4.10). Below $-t \approx 0.4 \text{ (GeV/c)}^2$ the slope parameter is $B = 6 \pm 0.5 \text{ (GeV/c)}^{-2}$, above $-t \approx 0.4 \text{ (GeV/c)}^2$ it takes the value $B \approx 4 \text{ (GeV/c)}^{-2}$. Existing data are limited to $-t \approx 1.1 \text{ (GeV/c)}^2$. Above that value the VDM process, shown as a dot-dashed curve, predicts a smooth extrapolation as e^{-6t} which is already contradicted by existing data. A smooth extrapolation as p_T^{-6} is expected from dominance by incoherent hard scattering mechanisms.

The cross-section due to the two gluon exchange graph takes a relatively simple form [Cudell (1990) ; Landshoff and Nachtman (1987)]

$$\frac{d\sigma}{dt} \sim \left| \frac{2\mu_0^2 + t}{(m_\phi^2 + Q^2 + 2\mu_0^2)(m_\phi^2 + Q^2 - t)} F_1(t) \right|^2$$

where $F_1(t)$ is the proton form-factor parametrized as

$$F_1(t) = \frac{4m_p^2 - 2.8t}{(4m_p^2 - t)(1 - t/0.7)^2}$$

with m_p the proton mass ; μ_0^2 is a momentum scale introduced by a regularization procedure on the gluon propagator [Cudell et al. (1989)] : it is of the order of $\mu_0^2 = 1.2 \text{ GeV}^2$. The t -dependence of the ϕ -photo-production cross-section in the two gluon exchange model is shown as a dashed-line (long dash) in fig. 4.10. It exhibits a zero for $t = -2\mu_0^2 \approx -2.4 \text{ GeV}^2$, a very characteristic feature which would sign clearly a 2-gluon exchange mechanism for ϕ -production.

There are essentially no data on ϕ electro-production. Due to the increase of their squared mass Q^2 , virtual photons are more point-like than real photons above $Q^2 = 1 \text{ (GeV/c)}^2$ as deduced from a comparison of the $p(e, e' \rho^0)p$ and $p(\gamma, \pi^0)p$ reaction at the same total c.m. energy [Brasse et al. (1975) ; Blume et al. (1983)] : hard scattering is expected to show up at smaller values of p_T or t . The variation of the cross-section as a function of Q^2 provides another test of the reaction mechanism. For example the VDM picture predicts a simple $1/(Q^2 + m_\phi^2)$ dependence whereas two gluon exchange would lead to a more complex Q^2 dependence as shown above.

Fig. 4.10 - The two extrapolations of the $\gamma p \rightarrow \phi p$ reaction above $p_T = 1 \text{ GeV/c}$ (from [Audit et al. (1993)]).

Counting rate estimates for ϕ electro-production in the MEMUS detector (section 7.4) with $E_0 = 15$ GeV, $\nu = 10$ GeV, a luminosity of $10^{36} \text{ cm}^{-2}.\text{s}^{-1}$ and a $\Delta t = \Delta Q^2 = 0.1 \text{ (GeV/c)}^2$ binning have been carried out using the VDM model up to $-t = 1 \text{ (GeV/c)}^2$ and the 2-gluon exchange model between 1 and 3 (GeV/c)^2 . The number of ϕ -mesons reconstructed per hour is shown in fig. 4.11.

Fig. 4.11 - Number of reconstructed ϕ per hour for the electro-production cross-section, as explained in the text (from [Audit et al. (1993)]).

Experiments on a nuclear target would allow to test two-gluon exchange from 2 different quark clusters (hidden colour component).

4.4 - Charmonium Production [Benhar et al. (1993)]

Electro-production of hidden charm (J/ψ , ψ' , χ , η_c) is one of the most important theoretical tool to understand how QCD applies at intermediate energies. The Vector Meson Dominance is questionable for J/ψ production in the ELFE kinematical regime since the lifetime of the $c\bar{c}$ component of the photon can be made short enough to dampen coherence effects.

4.4.1. Elastic production of J/ψ and ψ'

It is expected that elastic hidden charm production (J/ψ , ψ') is dominated by two-gluon exchange has explained in section 4.1. In this picture the photon first fluctuates as a compact far off-shell $c\bar{c}$ pair which is put-on-shell by 2 gluon interactions with the nucleon and converted into a real J/ψ . For this mechanism to be dominant, the coherence time has to be of the order of a nucleon radius which, due to the large mass of the c -quark, can be achieved at rather low Q^2 -value (smaller than 10 (GeV/c)^2).

J/ψ and ψ' production differ only by their final state wave-functions which let them behave in a very different way when propagating in a nucleus, as will be shown below.

4.4.2. Inelastic production of J/ψ and ψ'

This mechanism is conventionally described by the Colour Singlet Model (CSM) of fig. 4.3. Its cross-section is directly proportional to the nucleon gluon structure function. The domain of kinematical validity imposes that the mass M_X of the recoiling system X has to be, typically, larger than 3 GeV.

The completely differential electro-production cross-section can be written

$$\frac{d\sigma^{eN \rightarrow e' J/\psi X}}{d\nu dQ^2 dx dP_T d\phi} \sim G(\eta, M_\psi^2) \Gamma_{e^+e^-}^{J/\psi} (\Sigma_{T+} \in \Sigma_L + \sqrt{\epsilon(1+\epsilon)} \Sigma_\phi \cos \phi + \Sigma_{2\phi} \cos 2\phi)$$

where ϕ is the azimuthal angle, ϵ the polarization factor defined in section 2.3 and $G(\eta, M_\psi^2)$ is the gluon distribution at the scale of the J/ψ mass.

Ratios of differential to total cross-section give access to the four structure functions Σ_T , Σ_L , Σ_ϕ and $\Sigma_{2\phi}$ (the gluon distribution and decay width $\Gamma_{e^+e^-}^{J/\psi}$ factor out). The azimuthal dependence in ϕ has been measured by the NMC Collaboration [Allasia et al. (1991)] but it is not precise enough to draw any conclusion on the structure functions.

The colour singlet model has been used to calculate the ratio of the longitudinal $d\sigma_L/dQ^2$ and transverse $d\sigma_T/dQ^2$ cross-sections after integration on ϕ , x , P_T^2 and ν . Estimates of the longitudinal counting rate for a 90 day running time at 25 GeV and a luminosity of $10^{36} \text{ cm}^{-2} \cdot \text{s}^{-1}$ range from 10^5 counts at $Q^2 = 1 \text{ (GeV/c)}^2$ down to 500 counts at $Q^2 = 10 \text{ (GeV/c)}^2$. These measurements are essential to determine with a good precision the gluon distribution function of the nucleon. The use of a polarized electron beam and polarized targets would allow to extract the **polarized** gluon structure function [Guillet (1988)].

Mechanism for ψ' inelastic production is very similar to J/ψ production except for the final state wave-function. The estimated ratio of J/ψ to ψ' production is of the order of five [Berger and Jones (1981)] which is compatible with existing photo-production data [Barate et al. (1987), Ahmed et al. (1994)].

4.4.3. χ and η_c production

Not being vector mesons, χ - and η_c -states must have production mechanisms which are different from J/ψ and ψ' production. In hadro-production two gluons are sufficient to produce a χ -state (to fulfill colour and parity conservation), whereas three are necessary for J/ψ production, therefore χ production is favored. In electro-production only two gluons are necessary to produce a J/ψ whereas three gluons are necessary for χ -production, as shown in fig. 4.12. χ -production cross-sections are then expected to be smaller than J/ψ ones which is compatible with present experimental upper limits.

Fig. 4.12 - Elastic production of η_c and χ at large p_T (from [Benhar et al. (1993)]).

In exclusive reactions at large p_T both the charmonium and the nucleon are produced in a point-like configuration which should lead to a double colour transparency effect involving a "mini-meson" and a "mini-hadron" (see section 2.3).

4.4.4. Charmonium in a nucleus

The systematic study of elastic J/ψ production off various nuclei and comparison with ψ' elastic production will help to understand the formation of the hadronic state. This problem is of a high importance for the interpretation of the data from high energy heavy ion collisions since J/ψ suppression has been proposed as a signature for the formation of a Quark Gluon Plasma (QGP). In electro-production the J/ψ propagation in a nucleus can be studied cleanly in the absence of QGP [Brodsky and Mueller (1988)].

Elastic J/ψ production is cleaner than inelastic reactions to study charmonium production mechanisms in a nucleon : the scattered proton recoiling as a whole, the nucleus environment is less perturbed.

Existing photo-production data have been taken at very high photon energies (120-280 GeV) [Sokoloff et al. (1986) ; Amaudruz et al. (1992)] thereby the formation length, defined as the time it takes the $c\bar{c}$ pair to recombine and form a vector meson V , is much larger than the size of a nucleus and the J/ψ is formed well beyond the target.

The measurement of the transparency ratio T_N for photo-production cross-sections of J/ψ and ψ' will allow a systematic study of a totally new regime in which the formation length becomes comparable to or smaller than the nuclear radius.

T_N has been evaluated using the approach of [Kopeliovich and Zakharov (1991)] and of [Benhar et al. (1992)] as shown in fig. 4.13. At 15 GeV there is little difference between the Glauber prediction and nuclear transparency calculations. This is one reason why charmonium production would benefit from the 30 GeV option of ELFE, the other being that the absolute cross-sections are more comfortable at 30 GeV.

Fig. 4.13 - Nuclear transparency for quasi-elastic photoproduced charmonium, evaluated according to the approach of [O. Benhar et al. (1992)], as a function of the target mass number. The solid lines show the results for the J/ψ at $\nu = 15$ GeV and 120 GeV. The prediction of the Glauber theory (dashed line) is also shown for comparison. The dash-dot line represents $T_N(\psi')$ at $\nu=20$ GeV.

Fig. 4.13 shows a very peculiar feature already discussed in section (2.3) on colour transparency : for ψ' production the transparency is larger than one in light and medium mass nuclei (anti-shadowing). This pattern contradicts the naive expectation according to which the ψ' being larger in size and having a larger total cross-section with the nucleon

$$\sigma_{tot}(\psi'N) \sim 2.5 \sigma_{tot}(J/\psi N)$$

should experience a stronger attenuation while travelling through the target. This highly non trivial comportment comes from the node in the ψ' wave-function (see fig. 3.9). It has been confirmed by experimental data from the FNAL E772 experiment in which the forward J/ψ and ψ' produced in pA collisions have been measured [Alde et al. (1991)] and found to have similar A -dependence. Since inelastic J/ψ production is mediated by gluon exchange, nuclear effects can be also used to measure the gluon distribution of a nucleon imbedded in a nucleus as compared to a free nucleon and in particular to check the prediction of [Frankfurt et al. (1990)] that in the range $0.3 \leq \eta \leq 0.6$ one should observe an enhancement of the gluon distribution.

4.4.5. Feasibility and counting rates

The J/ψ is easily detected through its $\mu^+\mu^-$ decay (B.R. = 5.97 ± 0.25 %). Its natural width is 88 ± 5 keV and therefore it appears clearly in an invariant mass spectrum of dimuon pairs, only limited by the experimental energy resolution. Detection at small J/ψ angles is possible through the angular opening of the $\mu^+\mu^-$ pair. Background comes from the Bethe-Heitler di-muon production (see section 2.2.2) and mesons decaying incoherently to a μ^+ or a μ^- in the final state [Breton and Martin (1991)].

The only problem is really to get a large enough luminosity to overcome the small cross-sections. Although taken at high energies (280 GeV for the CERN muon experiments) existing data have limited statistics : less

than $10^3 J/\psi$ events on iron [Aubert et al. (1983),(1985)] and 279 events on hydrogen and deuterium [Amaudruz et al. (1992)], at a luminosity of $10^{31} \text{ cm}^{-2} \cdot \text{s}^{-1}$.

Fig. 4.14 - Total elastic and inelastic cross-sections for J/ψ production as a function of the incident electron energy. The scattered electron energy is larger than 2 GeV and the scattering electron angle is larger than 2° (from [Benhar et al. (1993)]).

Elastic and inelastic production cross-section are shown in fig. 4.14. The elastic cross-section follows the calculations of [Schuler and Terron (1992)]. The inelastic cross-section is obtained within the colour singlet model rescaled by a factor of about five to reproduce the partial differential cross-sections, a problem which is related to the fact that there is no clear separation of elastic and inelastic events for existing exclusive measurements [Berger and Jones (1981)]. Cross-sections are predicted to be about 2 to 3 orders of magnitude smaller than at 280 GeV but this will be compensated by a five orders of magnitude increase in luminosity ($10^{36} \text{ cm}^{-2} \cdot \text{s}^{-1}$). With a typical detector like the Di-Muon Spectrometer (DMS) discussed in section 7.4, Monte-Carlo simulations show that, with kinematical cuts ensuring a clean detection of both the scattered electron and the di-muon pair, almost $5 \cdot 10^6 J/\psi$ can be produced elastically and $5 \cdot 10^5$ inelastically in a 90 day run at 25 GeV, allowing a fine binning to be made in ν , z , p_T or Q^2 . The separation between elastic and inelastic events and between J/ψ and ψ' , which is presently done crudely by kinematical cuts on z and p_T , would be done here by fully identifying the final state including the proton or light charged particles.

The cross-section for ψ' electro-production being a factor of 5 smaller than for J/ψ and the branching ratio to $\mu^+\mu^-$ being another factor of 3 to 10, it is expected to measure one ψ' for every 50-100 J/ψ 's.

χ -production has not yet been observed due to the inability of existing set-ups to detect its decay products.

4.5. Open and associated charm production [Berthot et al. (1993)]

4.5.1. Physics Motivation

Associated and open charm photo-production have clear advantages over J/ψ production:

- cross-sections are much larger (by a factor of 20 at energies up to 60 GeV [Aubert et al. (1983a),(1983b)]).

- in associated charm production the initial nucleon and the charmed baryon have two quarks in common which simplifies the study of polarization transfer from one to the other. Moreover in the case of Λ_c production, the lightest charmed baryon, the Λ_c decays weakly $\Lambda_c \rightarrow \Lambda \pi^+$ with a parity violating decay parameter $\alpha_{\Lambda_c} \sim -1_{-0.0}^{+0.4}$ [Avery et al. (1990)] which allows a self analysis of the Λ_c polarization, similarly to the Λ case.

Open charm production is described by the photon-gluon fusion mechanism depicted in fig. 4.2. The calculations are done in first order of pQCD, the large mass of the charmed quark ensuring a hard enough gluon exchange. The production cross-section is governed by the factor $\exp(-\pi m_q^2 / \kappa)$ where κ is a phenomenological string constant. This implies a strong suppression of heavy quark production. Detailed calculations have been done within different models: duality with VDM [Fritzsch (1977) ; Fritzsch and Streng (1978)], QCD sum rules [Novikov (1978)] and others [Babcock et al. (1978)].

Fig. 4.13 - Prediction of charmed particle production rates. Figure from [Alvarez (1992)].

As an example of such theories the rates for the photo-production of different charmed mesons and baryons on a nucleon as calculated by [Alvarez et al. (1992)] is shown in fig. 4.13 as a function of the incident photon energy. In the ELFE domain ($E_\gamma < 30$ GeV) it is dominated by Λ_c and D_0 production with little background from other reactions.

4.5.2. Experimental conditions

Counting rates have been calculated using the photo-production cross-sections given by [Novikov (1978)] in the sum-rule approach :

$$\sigma_c^{\gamma} = 250(nb) \times \begin{cases} 2.75 \times \text{Log}(1/x) & \text{for } x < 0.01 \\ 0.044 \times x^{-1.225} & \text{for } 0.01 < x < 0.3 \\ 0.056 \times (1-x)^3 & \text{for } x > 0.3 \end{cases}$$

where $x = \nu_{th}/\nu$, ν_{th} being the photon energy at the J/ψ threshold :

$$\nu_{th} = \frac{1}{2} M_{J/\psi}^2 + M_N M_{J/\psi}.$$

This estimate is compared in fig. 4.14 to existing data and to predictions by [Fritzsch (1977); Fritzsch and

Fig. 4.14 - Total cross-section of charm photoproduction (from [Berthot et al. (1993)]).

Streng (1978)]. The photon-gluon fusion model underestimates the experimental data by a factor of 2 while VDM calculations overestimate them by about the same factor.

Detailed simulations using a generator of charmed events and the code "JETSET 73" from CERN for computing decay channels can be found in [Berthot et *al.* (1993)]. Counting rate estimates at 30 GeV range from a few to a few thousand charmed events per second depending on the experimental set-up (tagged or bremsstrahlung real photons, or virtual photon beams) and luminosity (up to $10^{35} \text{ cm}^{-2} \cdot \text{s}^{-1}$).

4.6. Concluding remarks on strangeness and charm production

Strangeness and charm electro-production is at the border of two worlds : the mesonic world where the degrees of freedom are mesons and baryons as emphasized in the Vector Dominance Model and the partonic world dominated by gluon exchange mechanisms. It will shed some light on how the elementary parton degrees of freedom become asymptotic (or effective) at long range where hadrons dominate.

Since the elementary cross-sections are intrinsically small they must be overcome by large luminosities and a high duty cycle. Polarized electrons and the measurement of polarization observables will allow to separate mechanisms competing when only cross-sections are measured. Since the time scale of confinement and hadronization is of the order of 1 fm the use of the nucleus as a target gives access to a new variable : the formation length. Energies of interest are of the order of 15-30 GeV only, otherwise the whole hadronization takes place in the vacuum.

5. HADRONIZATION IN NUCLEAR MATTER AND COLOUR NEUTRALIZATION

5.1. Physics case

The use of nuclear targets of different sizes allows to characterize the different steps of the hadronization process in semi-inclusive electro-production :

- the primary hard interaction between the incoming photon and a quark from the target nucleon
- the development and propagation of a partonic cascade
- and finally the formation of physical hadrons in the final state.

The geometry of the process is shown in fig. 5.1. In the perturbative QCD improved quark-parton model (QPM), the inclusive cross-section is interpreted as the incoherent sum of scatterings off point-like constituents in the proton. In order to calculate the hadron distributions, the QPM has to be combined with models which describe the formation of a hadron jet out of the parton cascade. The semi-inclusive cross-section, normalized to the number of scattered leptons can be written in the following general form :

$$\frac{E_h}{\sigma_{tot}} \frac{d\sigma}{dp_h} = \frac{1}{\sum_i e_i^2 q_i(x, Q^2)} \sum_i e_i^2 q_i(x, Q^2) D_{q_i}^h(p_{q_i}, p_h)$$

where the sum is over quark flavours ; e_i are the charge of the quark, $q_i(x, Q^2)$ are quark distribution functions entering in the nucleon structure functions and p_{q_i} and p_h are the quark and hadron momenta respectively.

Fig. 5.1 - Definition of the variables used to describe the hadronic final state (from [Anton et al. (1993)]).

The fragmentation function $D_{q_i}^h(p_{q_i}, p_h)$ parametrizes the probability for the formation of a hadron h with momentum p_h from a struck quark q_i with momentum p_{q_i} .

The factorization into parton distributions q_i and fragmentation functions $D_{q_i}^h$ is supported by experiments [Mc Elhaney and Tuan (1973) ; Seghal (1977)] which show that the fragmentation functions depend very little on the kind of high energy reaction investigated [Arneodo et al. (1987) ; Althoff et al. (1984)] except for a slight Q^2 -dependence well understood in the framework of pQCD [Baier and Fey (1979)].

Hard gluon radiation and non-perturbative effects, like the influence of the primordial transverse momentum of the struck quark or soft gluon radiation, lead to a rather complicated dependence on z , W and Q^2 as measured by the EMC, CLEO and TASSO Collaborations.

At ELFE it is proposed to put the emphasis on the measurement of fast hadrons in the current fragmentation region where the hadrons take away a substantial fraction of the energy of the virtual photon (large z). By measuring the nuclear attenuation ratio :

$$R_A = \left(\frac{1}{\sigma_A} \frac{d\sigma_A}{dz} \right) / \left(\frac{1}{\sigma_D} \frac{d\sigma_D}{dz} \right)$$

of hadron yields on a nucleus A and on deuterium D , one eliminates ill-defined constant factors. Existing data from the EMC Collaboration [Ashman et al. (1991)] and SLAC [Osborne et al. (1978)] are shown in fig. 5.2. They seem to indicate a strong variation of R_A with ν between 5 and 25 GeV but they result from the combination of two experiments at rather different Q^2 (1 and 6.5 (GeV/c)²). Nuclear effects become negligible at higher energies ($\nu > 50$ -100 GeV) since then the hadronization takes place outside the nucleus. On the experimental point of view, it would be important to verify the variation of R_A as a function of ν and to measure its Q^2 - and A -dependence. The region of $\nu = 5$ -15 GeV is particularly significant since, it is in this region that R_A changes most rapidly. As we will see below it corresponds to a propagation of the struck quark over a distance of 5-15 fm where the nucleus, which has a similar radius, acts most effectively. On the theoretical side the existing data on R_A have been compared to two calculations : the string model [Czyzewski and Savicki (1992)] and the gluon bremsstrahlung model [Kopeliovich and Nemchik (1991)].

String model

The string model [Anderson et al. (1983a) ; Ingelman (1987) ; Artru (1983)] defines precisely the space-time structure of the hadronization process. After the primary interaction, a colour string is stretched between the struck quark and the nucleon remnants. Then the leading quark is decelerated by the colour field with a string tension $\kappa \approx 1$ GeV/fm until it loses all its energy after a time $\tau_{\max} \approx \nu/\kappa$. During that time the string is being broken and $q\bar{q}$ pairs are produced from the vacuum by the colour field. The corresponding hadrons are ordered in time, and thus, can be numbered by their rank, the energy fraction z carried by hadrons of subsequent ranks being determined by the fragmentation function.

Fig. 5.2 - Dependence on the nuclear attenuation on the virtual photon energy ν . The data are from SLAC [Osborne et al. (1978)] (triangle) and EMC [Ashman et al. (1991)] (open circles). The string model calculation is from [Czyzewski and Savicki (1992)] and the gluon bremsstrahlung model from [Kopeliovich and Nemchik (1991)] (from [Anton et al. (1993)]).

The processs can be divided in two steps having different time scales : the "yo-yo" time τ_y [Chmaj (1987)] corresponds to the point where the two constituents of the hadron meet for the first time, and the constituent time τ_c [Bialas and Gyulassy (1987)] is the time of appearance of the first constituent of the produced hadron. These two times are related to z through :

$$\tau_y = \frac{\nu}{\kappa} z(1 - \ln z) \quad ; \quad \tau_y - \tau_c = \frac{z\nu}{\kappa},$$

the only free parameter being the string tension κ . They are shown in fig. 5.3.

The constituent time τ_c determines the moment at which the inelastic interactions of the string can perturb the production of the final hadron [Bialas and Czyzewski (1989) ; Czyzewski (1990)]. This happens through soft colour interactions of the ends of the string with the nuclear medium [Gyulassy and Plumer (1990) ; Kopeliovich (1990) ; Czyzewski and Sawicki (1992)].

The string model has found an extensive use in the phenomenology of particle production in hadron-hadron collisions [Werner (1989) ; Werner and Koch (1990)] and it is the basis of the Lund model [Anderson et al. (1983)]. It gives a good fit to the nuclear attenuation R_A as a function of ν as shown in fig. 5.2.

Fig. 5.3 - Characteristic times in the string model. The yo-yo time corresponds to the point where the two constituents of the hadron meet for the first time. The constituent time is the time of creation of the first constituent of the hadron (from [Anton et al. (1993)]).

Gluon bremsstrahlung model

In this approach, one defines a formation time as the time needed to screen the colour of the initially struck quark, resulting in a colourless wave-packet which converts later into a final hadron. The nuclear attenuation is assumed to result from the interactions of the colourless state with the nuclear medium [Kopeliovich (1990) ; Kopeliovich and Nemchick (1991)]. The predictions of the gluon bremsstrahlung model for R_A as a function of ν are shown in fig. 5.2. They do not differ strongly from the string model results since in both cases the energy loss of the quark is found to be similarly distributed in time [Niedermayer (1986)].

These models lead to very different predictions for R_A at large values of z as shown in fig. 5.4 for $\mu + \text{Cu} \rightarrow$ hadrons at $\nu = 35$ GeV. The gluon bremsstrahlung model predicts no attenuation at large z for the following reason : to be converted into a colourless state, the quark has to radiate gluons during the formation time and then it loses energy. To keep a large part of the initial energy of the system ($z \rightarrow 1$) it has to do it very quickly reducing the formation zone to :

$$\ell_f \approx c\tau_f \leq \frac{\nu}{\kappa}(1-z) \rightarrow 0$$

Being colourless most of the time, the formed object will be subject to the colour-transparency phenomenon (see section 3) and $R_A \rightarrow 1$ as $z \rightarrow 1$.

Fig. 5.4 - Nuclear attenuation ratio vs z at $\nu = 35 \text{ GeV}$ in Cu. Theoretical calculations as in fig. 5.2 (from [Anton et al. (1993)]).

On the contrary, in the string model, at $z = 1$ the constituent time disappears and the object propagating through the nucleus is fully coloured most of the time leading to an attenuation increasing strongly with z . Existing data on $\mu + \text{Cu}$ at $\nu \approx 35 \text{ GeV}$ do not reach a large enough value of z to distinguish between the two models [Ashman et al. (1991)]. Older SLAC data on $e + \text{Sn}$ at $\nu \approx 10 \text{ GeV}$ seem to qualitatively confirm the string model but with large error bars as seen in fig. 5.5 [Osborne et al. (1978)].

Other topics of interest which can be addressed in hadronization studies include :

- the broadening of transverse momentum distributions of hadrons caused by reinteractions of the leading quark during hadronization : here again string models and the gluon-bremsstrahlung approach make very different predictions

- the production of hadrons with various flavours : in the string model the effective attenuation of a quark at the early stage of the hadronization is strongly flavour-dependent. Therefore the production of fast kaons should be suppressed more than that of pions [Kopeliovich (1990)]. Moreover negative kaons should be attenuated more strongly than positive ones. Such measurements, which will be possible at ELFE, will enable to distinguish between various mechanisms of strangeness production

- the mechanism of baryon electroproduction is more complicated than that of mesons and it is even less understood. One semi-phenomenological approach to treat this problem is the concept of diquarks [DIQUARKS (1988)] in which the proton is seen as a quark-diquark system. Diquark models make definite predictions for yields of forward baryons and experimental data are badly needed [Kroll et al. (1991a,b)].

Fig. 5.5 - Nuclear attenuation ratio R_A vs the energy fraction carried by the hadron for a Sn target. The data [L.S. Osborne et al. (1978)] are averaged over a broad range of ν with an average value of $\sim 10 \text{ GeV}$. Theoretical predictions : dotted line = gluon bremsstrahlung model [Kopeliovich and Nemchik (1990)], solid line and dashed lines = string models [Czyzewski and Savicki (1992) ; Gyulassy and Plumer (1990)].

5.2 - Proposed experiment [Anton et al. (1993)]

It is proposed to measure the semi-inclusive hadron production rate for pions, kaons and protons as a function of ν , Q^2 , z , and mass-number A . The range $\nu = 5\text{-}15 \text{ GeV}$ will be covered in a first stage, up to 30 GeV in the second stage. The emphasis will be on fast hadrons carrying more than one-half of the transferred energy ($z > 0.5$).

The main observable will be the attenuation factor R_A defined above. The A dependence will involve measurements on hydrogen, deuterium and heavier nuclei with different root mean square radii : ^4He (1.68 fm), ^{12}C (2.47 fm), ^{40}Ca (3.45 fm), ^{208}Pb (5.5 fm). The deuteron data will serve as a reference target for a $Z = N$ nucleus. Hadron multiplicities, angular distributions and the transverse momentum distributions will also be measured. Fragmentation function $D_h(z)$ of the proton and the neutron will be determined with high statistics.

Finally, although the main focus of the experiment is on the fast hadrons, low energy hadrons whose multiplicity is an indication of the excitation of the remnant nucleus, will also be detected. For very low energy hadrons a special emphasis will be put on the neutrons which are immune to electromagnetic interactions.

Fig. 5.6 - Simulations of energy and angular distributions of scattered electrons and produced hadrons from the Lund fragmentation model (from [Anton *et al.* (1993)]).

Simulations with the LUND fragmentation model [Anderson *et al.* (1983)] have been done resulting in the energy and angular distributions shown on fig. 5.6 calculated at $E_e = 15$ GeV for $W > 2$ GeV and $3 < Q^2 < 4$ (GeV/c)². The electron are strongly forward peaked up to $\theta_e = 30$ degrees which limits the Q^2 -range to $Q^2 \leq 17$ (GeV/c)².

The hadron distributions are less forward-peaked than the electrons but leading hadrons with $z \geq 0.5$ are produced in a forward angle with opening smaller than 40°. Their energy goes from 1 GeV to almost the incident energy at $z = 1$.

The detector requirements are given in Table 5.1. Since a good particle identification is necessary, a combination of fast calorimeters, fast Ring Imaging Cerenkov (RICH) counters, conventional Time-of-Flight (TOF) and dE/dx separation techniques will have to be used.

Detector parameter	Specification
Angular acceptance	3° to 30-40°
Energy resolution	about 1 %
Angular resolution	few m.rad
Particle ID	e, π, K, p
Electron energy	1 to 30 GeV
Hadron energy	1 to 25 GeV

Table 5.1 - Detector requirements for semi-inclusive hadron production experiment

Two experimental solutions have been investigated (see section 7 for details)

- a two-spectrometer solution set-up,
- a large solid angle detector (FAST or MEMUS).

Due to the large minimum angles, imposed by mechanical constraints, between the two spectrometers and with respect to the incident beam, the first option would limit the exploration to angles larger than 15°, missing a large part of the interesting kinematical region since the electrons are very forward peaked. Moreover the Q^2 - and ν -exploration can only be done with many discrete settings leading to prohibitive times (1000 h per z bin of 0.1 for a 1 % statistical accuracy at a fixed $\nu = 10$ GeV). Therefore large solid angle detectors are definitely more appropriate.

A comparison of the FAST and MEMUS 4π -detectors (see section 7) shows that FAST seems more appropriate for hadronization studies. Counting rates have been estimated at 15 GeV with the PEPSI code assuming 250 hours of running time at a luminosity of $10^{34} \text{ cm}^{-2}.\text{s}^{-1}$, in the angular range 3°-25° and $W > 2$ GeV. The theoretical ν -dependence of the attenuation ratio R_A for $z > 0.5$ is shown as a function of ν in fig. 5.7 for ^{40}Ca . Two models have been used [Bialas and Chmaj (1983) ; Low and Gottfried (1978)] showing very large differences. A typical event simulated with PEPSI is shown in fig. 5.8. One remarkable fact about this event is the realization that the true event multiplicity at ELFE will not be very large (up to about 10).

Fig. 5.7 - Attenuation ratio $R = \sigma_A / \sigma_D$ for semi-inclusive scattering by Ca ($A=40$) as a function of ν with cuts on $z > 0.5$. In the top graph the theoretical model is from [Low and Gottfried (1978)] in which the formation time depends on the hadron mass as $\tau_f = \tau_0 z \nu / m_h$. In the bottom one the mass-independent model of [Bialas and Chmaj (1983)] is computed (from [Anton *et al.* (1993)]).

6. DEEP INELASTIC SCATTERING AT $x > 1$

6.1 - Physics case

Deep Inelastic Scattering of electrons and muons represents the major source of knowledge on the nucleon structure in terms of quarks and gluons. A step further will be to understand the mechanism of quark confinement in nuclei.

Significant data on DIS in nuclei have been obtained in the last few years [Aubert et al. (1983), (1985) ; Arnold et al. (1984)] in the range $0 < x < 1$. Contrary to naive expectations the structure function of bound nucleons turned out to be different from that of free nucleons over the whole x -range, a phenomenon which has been given the name of "EMC-effect" although it has different causes for different values of x . These results indicate that the quark distribution is modified by the nuclear medium (see e.g. the review paper by [Sloan et al. (1988)]). Explanations range from non-standard nuclear configurations expressed in terms of few-nucleon correlations [Frankfurt and Strikman (1981),(1988)] to effects of multi-quark clusters [Vary (1984); Vary and Harindranath (1986)].

In inclusive electron scattering by a nuclear target $A(ee')X$, the yield at $x = 1$ is mainly due to quasi-elastic (Q.E.) scattering on a nucleon at rest. Some cross-section can be generated at $x > 1$ from the smearing of the Q.E. peak by Fermi motion of the nucleon inside the nucleus and by inelastic processes (including deep inelastic scattering) on moving nucleons.

In the parton picture, x is interpreted as the fraction of the target longitudinal momentum carried by the struck quark (in the infinite momentum frame). At $x > 1$, the struck quark should receive momentum from the nuclear medium or at least from another nucleon. In principle, in DIS from a nuclear target of mass number A , x can vary from 0 to A , but at $x = A$ the whole momentum of the nucleus would be carried out by the single struck quark, which is very unlikely. The study of the region $x > 1$ for large Q^2 ($Q^2 > 15$ (GeV/c)²) for which the scattering from a stationary or slowly moving nucleon is forbidden, is a way to single out short-distance (high momentum) aspects of the nuclear dynamics.

Some data are available at $x > 1$ but they correspond to relatively small values of Q^2 (below 8 (GeV/c)²) and they are quasi-elastic in nature as shown on ³He and ⁴He data fig. 6.1 [Day et al. (1979), (1987), (1989) ; Bosted et al. (1990) ; Rock et al. (1992)]. Since the cross-section decreases steeply for $x > 1$, large luminosities are necessary to reach the highest Q^2 -value at which deep inelastic will dominate quasi-elastic mechanisms ($Q^2 > 8$ (GeV/c)² at $x = 1$ and $Q^2 > 10$ (GeV/c)² at $x = 1.5$) [Day (1991) ; Ciofi degli Atti et al. (1992) ; Ciofi degli Atti and Simula (1993)].

Large Q^2 -values will also minimize final state interaction (FSI) effects which are still important for Q^2 of the order of a few (GeV/c)² [Benhar et al. (1991)].

6.2. Proposed experiment [Bing et al. (1993)]

It is proposed to measure deep inelastic inclusive and semi-exclusive reactions at $x > 1$ on a large set of targets starting on the deuteron and extending to more complex systems such as ³He, ⁴He, ¹²C, ⁵⁶Fe... This would allow to improve our understanding of the A -dependence of the EMC effect and to determine

uniquely the occurrence and probability of correlations involving more than two nucleons (e.g. 3-N correlations) or clusters with a large number of quarks ($9q$, $12q$,...). A particular emphasis will be put on the deuteron as the first target of interest since its wave-function, in terms of nucleonic constituents, is much better controlled and FSI are minimized. Exclusive DIS on deuterium will also provide a unique way to measure the ratio of DIS structure function of the neutron and the proton $F_2^n(x) / F_2^p(x)$ at $x \approx 1$. Existing data extend only to $x \approx 0.8$ and they cannot be extrapolated uniquely to $x = 1$. QCD predictions for this ratio, based on different numerical models exist and can be checked with precise data in the range $x \approx 0.8$ -1.

Fig. 6.1 - The effect of nucleon-nucleon correlations on the Q.E. cross-sections for ^3He and ^4He . The short dashed and long dashed curves represent contributions from the uncorrelated and correlated parts of the spectral function. The full line is the total contribution [C. Ciofi degli Atti *et al.* (1992)]. See the text for references of the experimental data.

Data at large x and large Q^2 would also allow to pin down higher twist effects (of order $1/Q^2$) in both the Q.E. and DIS regions [Whitlow (1990) ; Milsztajn *et al.* (1990)].

Inclusive electron deuteron data extending up to $x = 1.2$ have been obtained at SLAC in the range of $Q^2 = 2.5$ -10 $(\text{GeV/c})^2$ [Schutz *et al.* (1977)]. They can be explained as the result of the contributions of

three different mechanisms : Q.E., smearing of $3q$ inelastic reactions and $6q$ contributions . It has been shown by [Yen et al. (1990)] that the Q.E. contribution is still significant up to 8 (GeV/c)^2 and it is only above that value that it is overcome by deep inelastic processes.

Recent data from SLAC [Filippone et al. (1992)] do not show any scaling of the structure functions with x , but if one uses a more appropriate kinematical variable, the Nachtmann variable ξ [Georgi and Politzer (1976)] defined as :

$$\xi = \frac{2x}{1 + \sqrt{1 + \frac{4M^2x^2}{Q^2}}},$$

which takes into account the finite mass of the target, then onset of scaling is observed for values of Q^2 as low as 2 (GeV/c)^2 .

The measurement of the excitation energy of the recoil system $\varepsilon = M^* - m$, where M^* is the missing mass and m the nucleon mass, allows to separate the Q.E. contribution ($\varepsilon \approx 0$) from the deep inelastic contribution which can be studied as a function of ε . For a given virtual photon γ^* emitted at an angle θ_γ , the angle $\theta_{\gamma p}$ with the proton follows an ellipsoidal distribution around the γ^* as shown in fig. 6.2. This ellipsoid gets smaller as ε increases from zero (Q.E. kinematics) to a maximum value $\varepsilon_{\max}$ which depends on the virtual photon angle. To separate the Q.E. contribution from the inelastic one, the precision on ε must be better than the pion mass.

Counting rates have been estimated using a theoretical model by [Liuti (1990)] which fit existing SLAC data. The scattered electron and the recoil proton will be detected in coincidence in a spectrometer and a large acceptance detector, respectively. The spectrometer has an angular acceptance $\Delta\Omega = 10 \text{ msr}$ and momentum acceptance $\pm 5 \%$. The momentum resolution will be of the order of 10^{-3} in order to determine ν with a precision better than the pion mass (see section 7.2 for more details on the spectrometer). The proton detector must have a large gap (1 m) but a limited energy resolution ($\Delta E_p = 2 \%$) and angular resolution ($\Delta\theta_p = 1^\circ$) which is ensured by a field of about 1.5 T.

The background has been estimated by using particle production data from SLAC. Contamination coming from the hadronization of the remnant neutron (which is not detected) has been calculated with the Lund event generator and found very small.

Counting rates have been estimated for a 15 GeV electron beam of $20 \mu\text{A}$ on a 17 cm liquid target, giving a luminosity of $10^{38} \text{ cm}^{-2}.\text{s}^{-1}$. They show that a reasonable statistical uncertainty can be achieved for the semi-exclusive $d(e,e'p)X$ reaction at $x = 1.5$ in about 100 days of counting. The only difficulty will be to handle a flux of $5.10^8 \pi^+/s$ in the proton detector which is easily feasible with a 100 % duty-factor and a moderate segmentation of the detector.

In a second stage the same experiment will be done with heavier target nuclei, giving information on the possible existence of larger structures (more than $2N$ or $6q$) in the nucleus.

Fig. 6.2 - Kinematics of the $d(e, e'p)X$. The proton momentum is proportional to the distance between the interaction point and an ellipsoid specific of the excitation energy ϵ of the γ -neutron system. The shaded area corresponds to the detection domain of the proton momentum.

7. DETECTORS

7.1. Introduction

The physics program requires an extended set of large detection set-ups. They can be divided into three categories:

- a pair of high resolution spectrometers : they allow the detection of, at most, two charged particle in coincidence at the largest luminosity ($\ell \approx 10^{38} \text{ cm}^{-2}.\text{s}^{-1}$) and with good momentum resolution ($\Delta p < 10^{-3}$) at the expense of the solid angle,

- forward angle detectors : in fixed target experiments the reaction products benefit from the center-of-mass boost and are emitted preferentially in a narrow forward cone ($\theta < 30^\circ\text{-}40^\circ$). Two such detectors have been studied : a general purpose Forward Angle SpecTrometer (FAST) and a detector dedicated to the detection of $\mu^+\mu^-$ pairs, the Di-Muon Spectrometer (DMS). The maximum luminosity will be in the range of $10^{36}\text{-}10^{37} \text{ cm}^{-2}.\text{s}^{-1}$ and the momentum resolution $\Delta p/p < 10^{-2}$. The event multiplicity will be of the order of 10.

- a near 4π -detector MEMUS, for charged and neutral particle tracking : it has an asymmetric structure with a larger integral field at forward angles, allowing the detection of fast particles, and a shorter path length in the backward direction where only slow particles are detected. The achievable luminosity will be of the order of $10^{35} \text{ cm}^{-2}.\text{s}^{-1}$ and the momentum resolution better than 10^{-2} .

Table 7.1 gives a grid indicating how the requirements of the physics program outlined in section 2 to 6 can be fulfilled by the different detectors.

The particle detectors must accomplish the following tasks common to most experiments :

- measuring the particle momentum : this is accomplished by magnetic fields and position sensitive detectors,
- identifying the particle : time-of-flight (TOF) and Cherenkov counters (threshold Cherenkov or Ring Imaging Cherenkov),
- fast triggering the event : hodoscopes of scintillators,
- measuring the total energy and separating charge/neutral events : hadronic and electromagnetic calorimeters,
- improving the event reconstruction near the target : vertex detectors.

	2 charged particles in coincidence	3 or more particles in coincidence	pair of spectrometers $\ell \approx 10^{38} \text{cm}^{-2} \cdot \text{s}^{-1}$ $\Delta p/p \sim 10^{-3}$	forward detector $\ell \approx 10^{36}-10^{37} \text{cm}^{-2} \cdot \text{s}^{-1}$ $\Delta p/p \sim 10^{-2}$ $3 < \theta < 30^\circ$ $0 < \phi < 180^\circ$	4π -hermeticity $\ell \approx 10^{35} \text{cm}^{-2} \cdot \text{s}^{-1}$ $\Delta p/p \sim 10^{-2}$	Polarized target
Virtual Compton Scattering (2-spectrometer option)		x	x+photon calorimeter			x
Virtual Compton Scattering (4π -detector option)		x			x	x
Meson form-factors		x		x		x
Nucleon and deuteron form-factors	x		x			x
Excited baryon form-factors	x		x			
Colour transparency	x		x			
Polarized production		x		x		x
J/ψ production		x		x		
Charm and strangeness		x			x	
Hadronization in nuclei		x			x	
$x > 1$ at high Q^2	x		x	(x)		

Table 7.1

Position sensitive detectors

Three types of detectors have been considered :

- Multi Wire Drift Chambers (MWDC), whose principle of operation is shown in fig. 7.1 [Fabjan (1994)] are commonly used in high energy physics experiments. Whereas in conventional Multiwire Proportional Chambers (MWPC) the energy resolution is practically limited to $\sigma \geq d / \sqrt{12}$, where d is the anode wire separation, the drift time measurement allows an interpolation with typically an order of magnitude better resolution limited by the gas properties, operating conditions and electronic read-out.

Practically, resolution of the order of $\sigma \sim 50\text{-}200 \mu\text{m}$ can be achieved with less electronic channels as compared to MWPC's but at the expense of the time resolution.

Fig. 7.1 - Principle of construction of the drift chambers. Cathode wires are connected to uniformly decreasing potentials, starting from ground in front of the anode. Field wires reinforce the field in the transition region to the next cell (from [Fabjan (1994)]).

- Micro-Strip Gas Counters (MSGC) : they have a structure similar to that of a MWDC but instead of being made of wires, the cathode and anode planes are made of strips deposited on a high resistivity substrate e.g. glass (fig. 7.2). A spatial resolution of $\sigma \approx 30 \mu\text{m}$ and trigger rates up to 1 MHz have been reported [Hilke and Innocenti (1992)] but multiple scattering is larger due to the thickness of the substrate. MSGC's are less radiation resistant than MWDC's although this is not considered as serious a limitation at ELFE as it will be at LHC. Another problem of MSGC's is the fact that they have still to be built on a large scale but they will benefit from the considerable developments done for the LHC at CERN [LHC (1992)].

Fig. 7.2 - Schematic view of a microstrip gas counter. Thin metallic anodes and wider cathodes are deposited on a support with high resistivity, e.g. glass or plastic. The narrow gas gap is closed by the drift electrode (from [Hilke and Innocenti (1992)]).

- Scintillating Fibers (SCF) : they have a high granularity (diameters down to $250 \mu\text{m}$ have been used and $60 \mu\text{m}$ fibers up to 2.3 m long are foreseen for the LHC [Hilke and Innocenti (1992)]) and fast response time (5-10 ns) but due to inefficiencies and cross-talks between adjacent fibers they have to be

used in a redundant number of layers (up to 4) to ensure a maximum efficiency, resulting in a rather large thickness.

Large tracking scintillating fiber (SCF) detectors, made of a few 10^6 units, are developed for LHC purposes and the challenge, here, is to find a small, fast, low noise photodetector. They have special features which make them more suitable than other types of detectors in electroproduction applications :

- Møller electrons emit, by synchrotron radiation effect, a large number of low energy transverse photons : these photons loose at most 50 keV in a one millimeter fiber against 100 keV for a relativistic charged particle allowing to discriminate them by amplitude analysis,
- fibers are made from material of low atomic number with reduced multiple scattering,
- they have a large radiation length thereby decreasing the rate of conversion of high energy Møller photons into e^+e^- pairs,
- the Møller background can be further decreased by the coincident use of two or more layers of fibers spaced by a few cm : low energy recoil electrons from the fiber in which the photon is first detected are bent in the magnetic field and do not reach the next fiber.

The characteristics of the different types of position sensitive detectors are compared in table 7.2. A hybrid system taking advantage of the quality of each detector according to the distance to the beam (for example SCF detectors near the target and cheaper MWDC's at larger angles) can be envisaged at the expense of a dead zone at the frontier of detectors of different types.

	Thickness	Rad. Length	Pos. Resol.	Dead Time	Max Rate/mm
MWDC	20-40 mg/cm ²	0.07-0.13 %	$\approx 200 \mu\text{m}$	$\leq 400 \text{ ns}$	100 kHz
MSGC	150-210 mg/cm ²	0.51-0.73 %	$\geq 30 \mu\text{m}$	$\sim 150 \text{ ns}$	1 MHz
SCF	30-110 mg/cm ²	0.07-0.25 %	$\geq 60 \mu\text{m}$	10-20 ns	$\geq 10 \text{ MHz}^*$

*) Assuming a 1 MHz maximum rate per fiber

Table 7.2 - Properties of position sensitive detectors

Particle Identification detectors

They have to discriminate and identify the following particles : electrons, muons, pions, kaons and protons. A combination of TOF and momentum analysis can be used only for low energy, non relativistic particles. For high energy particles, Cherenkov detectors are needed. Conventional threshold Cherenkov Counters can be used in a limited momentum range but all particles having a given velocity $\beta = v/c$ above threshold are detected.

Ring Imaging Cherenkov (RICH) detectors enable essentially to identify pions, kaons and protons up to 30 GeV/c with a single device, by measuring the size of the ring of the Cherenkov light emitted by the particle when traversing a medium with a low index of refraction n_r . The size of the ring is determined by the emission angle given by $\cos\theta = 1/\beta n_r$, and by the distance between the radiator and the detector.

In order to cover the largest energy range, they usually associate liquid and gas radiators as shown in fig. 7.3. In this way one can achieve a good separation of e/π up to a few GeV/c, π/K up to 10 GeV/c and K/p up to 20 GeV/c. The overlap between liquid and gas radiator capabilities allows to cover a continuous range except in the case of the K/p separation where a gap remains between around 10 GeV/c.

For the detection of the photon two solutions are being studied :

- Multi-wire proportional chambers (MWPC) with a photosensitive TMAE gas converter which are rate limited,
- Fast RICH with photocathodes made of CsI ; this solution is much faster (signal width is ≤ 5 ns) but their sensitivity (number of photo-electrons per particle detected) is still marginal. Ageing may also be a problem.

RICH counters have benefited from considerable developments for LEP [Arnold et al. (1988)] the LHC and B-factory projects [Arnold et al. (1992) ; Guyonnet et al. (1993)]. A large effort of R and D is presently pursued for the LHC detectors within a special CERN program (RD26) [Aleksan et al. (1994); Di Mauro et al. (1994)].

Fig. 7.3 - Conceptual lay-out of a RICH detector associating a liquid and a gas radiator (from [Blok et al. (1994)]).

Calorimeters

Calorimeters measure the total energy of the particles. They also play a role in the trigger and detect the high energy photons resulting e.g. from π^0 or η decay. The following design goals for the ELFE calorimeters were selected :

- good energy resolution (≤ 140 MeV),
- fast response time,
- π/e discrimination to use them as a fast trigger for the electrons,
- good position resolution (for π^0 and η^0 reconstruction),
- good hermiticity (4π calorimetry).

Calorimeters are important ingredients of the future LHC detectors ATLAS and CMS and vigorous developments are being pursued to find out the best geometry and materials [Fabjan (1994)]. Examples of investigated materials are shown in table 7.3.

For calorimetry of hadrons and muons, one uses a set of absorbers interleaved with detectors of charged particles (scintillators or MWPC'S) as sketched in fig. 7.4. Hadronic calorimeters are commonly used at high energy facilities and developments aim essentially at lowering the cost of the read-out electronics.

Crystal	Density	Radiation length (cm)	Decay time (ns)	Peak emission (nm)
BGO	7.13	1.11	300	480
BaF ₂	4.89	2.06	0.6 620	210 310
CeF ₃	6.16	1.68	5 20	300 340
GSO: 2.5% Ce	6.71	1.39	31	450
ThF ₄	6.32	1.18	≤ 25	315,330,450
BaLiF ₃	5.24	2.13	≤ 25	435
PbF ₂	7.66	0.94	-	-
PbWO ₄	8.2	0.9	10 40	325,430

Table 7.3 - Characteristics of candidate crystals for precision electromagnetic calorimetry

Fig. 7.4 - Schematic representation of frequently used calorimeter readout techniques: (a) plates of scintillator optically coupled individually to a photomultiplier. (b) plates of scintillator readout by photon absorption and conversion in a wavelength shifter plate. (c) charge produced in an electron-transporting medium (e.g. liquified or high-pressure argon) collected at electrodes, which may also function as the passive absorber plates. (d) charge produced in a proportional gas and amplified internally on suitable readout wires (proportional or saturated gas amplification) (from [Fabjan (1994)]).

Vertex detector

Vertex detectors improve the momentum resolution by allowing an event reconstruction up to the target. Being placed close to the beam they are exposed to large yields of particles (up to 10^7 hits per mm at a luminosity of $10^{36} \text{ cm}^{-2} \cdot \text{s}^{-1}$) due essentially to Møller electrons. They will then have to be fast and finely segmented. The detectors of choice may be scintillating fiber chambers although their use in stray magnetic fields may be problematic or silicon vertex detectors.

Silicon pixels having 10^7 elements, $30 \mu\text{m} \times 300 \mu\text{m}$ each, are under developments. They would allow the most precise vertex reconstruction but they require further R and D on the read-out electronics, in particular to decrease the overall cost [Fabjan (1994)].

Trigger

In view of the large luminosity foreseen at ELFE and consequent high counting rates, several trigger levels will be necessary to ensure an efficient data collection. They can be classified along the time necessary to obtain an information and take the subsequent decisions :

- level 1 : this trigger is made with a scintillator signal, a fast evaluation of the total energy in an electromagnetic calorimeter to get a quick idea of the momentum transfer and a fast multiplicity read-out of the inner scintillating fiber chambers. Characteristics time for level 1 trigger is 10 to 100 ns.

- level 2 : preliminary determination of the momentum and energy transfer, identification of the leading particles besides the scattered electrons, sorting out of secondary vertices (if any). Characteristic time is 1 to 5 μ s.

- level 3 : crude on-line data reduction using identification information from the RICH, TOF and dE/dx and calculation of momentum and kinematics from the tracking chamber informations. Characteristic time is 100 μ s to 1 ms. With typical counting rates of up to a MHz expected at ELFE for inelastic events, parallel data processing will have to be used.

7.2. Spectrometers [I. Blomqvist *et al.* (1993)]

To generate the specifications of the spectrometers typical colour transparency ($e,e'p$) kinematics have been taken as representatives of the sort of experiment best suited for the spectrometer options. Some kinematical variables are given in table 7.4 where E' is the energy of the scattered electron ; P is the momentum of the knockout proton and T_p its kinetic energy ; θ_e and θ_p are respectively the electron and proton angles.

The kinematics and cost reduction arguments lead to two identical spectrometers for the electron and hadron detection with the following requirements :

- maximum momentum 15 GeV/c with possible upgrade up to 30 GeV/c,
- momentum at which the resolution is optimized = 10 GeV/c,
- momentum acceptance = ± 10 %,
- momentum resolution better than 10^{-3} ,
- minimum angle (with full solid angle) = 15° (6° on the hadron arm with reduced acceptance),
- vertical bending to accomodate extended targets,
- vertical acceptance $\gg$ horizontal acceptance.

Q^2 (GeV/c) ²	P GeV/c	E' GeV	T_p GeV	θ_e deg	θ_p deg
6.0	4.03	11.80	3.20	10.57	32.43
9.0	5.66	10.20	4.80	13.93	25.68
12.0	7.27	8.60	6.39	17.54	20.86
15.0	8.88	7.00	7.99	21.78	16.99
18.0	10.49	5.41	9.59	27.24	13.63
21.0	12.09	3.81	11.19	35.29	10.46

Table 7.4 - Kinematics for a typical ($e,e'p$) colour transparency reaction.

For cost reduction, a spectrometer as short as possible is required which leads to a superconducting design. The field of 2T at 10 GeV/c is limited by synchrotron radiation effects, which also limits the bending angle to 22° and imposes a rather large curvature radius of 42m. Other characteristics include :

- only three separate optical elements : a quadrupole Q focussing vertically, and two combined function magnets (CFM) which combine a dipole, a quadrupole and a weak sextupole field,
- magnets are of the " $\cos(n\theta)$ " type ($n = 1$: dipole, $n = 2$: Q -pole,...). The different functions have separate windings and power supplies. Their useful volume is a straight cylinder,
- a low level of geometrical aberrations insured by the small bending angle,
- the momentum resolution is obtained through a strong vertical beam focusing on the target and precise drift chambers ($\sigma \approx 50 \mu\text{m}$),
- point-to-parallel focusing in the horizontal plane,
- operation at momenta up to 30 GeV/c is obtained by mechanical reduction of the bending angle (see fig. 7.5) at the same dipolar field (only the first quadrupole will have to be upgraded). This will reduce the momentum resolution, but at 30 GeV the physics requirements are less stringent. Optical studies have been performed using the TRANSPORT code [Doornbos (1992)] and checked through direct ray-tracing including synchrotron radiation effects with SNAKE.

In conclusion it has been possible to conceive a set of relatively simple spectrometers which fulfill part of the physics program outlined in section 2 at 15 and 30 GeV without being too big (the overall length is ~ 30 m, the same as the HRS spectrometer from CEBAF operating at 4 GeV but with a much better resolution $\Delta p/p \sim 10^{-5}$).

Fig. 7.5 - Side view of the spectrometer at 22° (up) and 0° (down) bending angle (from [Blomqvist et al. (1993)]).

The spectrometer specifications and performances are given in Table 7.5.

For 10 GeV/c momentum at 22° bend angle :	
Distance target → focal point	32.5m
Focal plane angle	83.5°
Momentum acceptance	20% ($\pm 10\%$)
Solid angle (elliptical)	7 msr
Vertical/dispersive acceptance	± 91 mr
Horizontal/transverse acceptance	± 24 mr
Magnification M=	-1.56
Dispersion D=	2.55 cm/%
D/M	-1.63 cm/%
First order momentum resolution	$0.64 \cdot 10^{-4}$ FWHM
Overall resolution	$5 \cdot 10^{-4}$ FWHM (estimate)
Vertical/dispersive angle resolution	1 mrad FWHM
Horizontal/transverse angle resolution	1 mrad FWHM (0.5 mrad in parallel-point optics)
Resolution of horizontal position at target	1 mm FWHM
Qpole:	
distance target → Qpole entrance	4m
length	2.5 m
usefull radius	500 mm
field at usefull radius	2. T
CF1:	
distance Qpole exit → CF1 entrance	2 m
length	8. m
usefull radius	500. mm
field at usefull radius	dipole: 0.8T Qpole: 0.5T
CF2:	
distance CF1 exit → CF2 entrance	2 m
length	8. m
usefull radius	500.mm
field at usefull radius	dipole: 0.8T Qpole: 0.4T
distance CF2 exit → focal point	6 m

Table 7.5 - Spectrometer specifications and performances.

7.3. Forward Angle SpecTrometer (FAST) [Blok et al. (1993)]

7.3.1. Overall specifications

The FAST detector is designed for semi-exclusive experiments in which a scattered electron is detected in coincidence with fast hadrons (π , K , p , Λ ...) emitted at forward angles. It could be used for the study of meson form-factors (section 2.3) or hadronization processes in the case where fast hadrons are detected (section 5). Luminosities up to 10^{35} - 10^{36} $\text{cm}^{-2}.\text{s}^{-1}$ are foreseen.

In order to determine the optimum detector specifications, Monte-Carlo simulations of a typical hadronization geometry have been performed with the computer code PEPSI [PEPSI (1991)] which generates DIS events in a predefined kinematical domain. The elementary interaction between the virtual photon and the struck quark is calculated according to QCD in first order of α_s . The fragmentation into final hadrons is calculated with the JETSET code.

Assuming an incident electron energy of 15 GeV, the angular and momentum distributions of the scattered electrons and emitted hadrons have been simulated for $Q^2 = 3$ -4 $(\text{GeV}/c)^2$ and $W > 2$ GeV. The results are shown in fig. 5.6 (section 5.2). They clearly show that the electron angle does not need to be much larger than 30° ($Q^2 \leq 15$ $(\text{GeV}/c)^2$). The hadron angular distributions are less forward-peaked but if fast leading hadrons ($z > 0.5$) are selected (see fig. 7.6), then most of the hadron yield is again emitted within a cone of aperture of the order of 30° .

In order to cover the full Q^2 -range the spectrometer should reach almost the full incident beam energy. A transverse magnetic field of 2 Teslas is provided by a dipole as shown in fig. 7.7. Although the field is rather modest the magnet would be superconducting to take advantage of lower running costs, availability of large quantities of liquid helium to feed the superconducting cavities of ELFE, and possibilities of upgrade.

The uncertainty on the electron scattering angle is directly related to the uncertainty on the value of Q^2 and ϵ , the polarization parameter of the virtual photon. The uncertainty on Q^2 affects directly the uncertainty on the absolute cross-section σ . In order to limit the uncertainty on σ to 2 %, the angular resolution must be of the order of 2.5 mrad (FWHM).

The energy resolution is essentially of relevance to identify the final state. In particular one must distinguish, by missing mass determination, a Δ from a nucleon or a Λ from a Σ^0 . Hence the total energy resolution should be better than 70 MeV (FWHM) which is achieved with a momentum resolution of 0.5 % for both the electron and the hadron.

The FAST requirements are given in table 7.6 and the global lay-out is shown in fig. 7.7. Since a luminosity of 10^{35} $\text{cm}^{-2}.\text{s}^{-1}$ can be obtained with a 2 μA beam having a spot size below 1mm in diameter on a 2 mm thick liquid hydrogen target only, the interaction point is very small, making the track reconstruction easier compared to extended target schemes used in internal target configurations.

Fig. 7.6 - Correlation between angle and momentum for hadrons produced in deep-inelastic scattering at $E_0 = 15$ GeV. The forward peaking of the leading hadrons is illustrated in the right panel, where a cut on z , i.e. $z > 0.5$, has been imposed. Each successively smaller contour bounds a region with a factor of two higher counting rate (from [Blok et al. (1993)]).

Detector parameter	Specifications
Angular acceptance	≤ 30 degrees
Energy resolution (for each particle)	≤ 0.5 %
Angular resolution	≈ 2.5 mrad
Luminosity	$\geq 10^{35} \text{ cm}^{-2} \cdot \text{s}^{-1}$
Particle identification properties	$e, \pi, K, p, \dots$
Electron energy range	0.5 - 14 GeV
Hadron energy range	1 - 14 GeV

Table 7.6 - Detector requirements for semi-inclusive hadron production experiments at EEF

Fig. 7.7 - Basic lay-out of the conceptual design of the Forward-Angle Spectrometer (FAST) for ELFE. The dashed lines are drawn at 25° with respect to the incoming beam direction (from [Blok et al. (1993)]).

7.3.2. Detectors

Scintillating fibers

The momentum resolution has been calculated for different configurations and detector types. With scintillating fibers as position sensitive detectors giving a spatial resolution $\Delta x = 60 \mu\text{m}$ and a geometrical angular resolution better than 1 mrad. The momentum resolution is of the order of 0.4-0.5 % in the full range up to 15 GeV/c. In these calculations the effect of multiple scattering in the air (or in He bags) and in the position sensitive detectors has been taken into account. Even with a field of 1 Tesla, the momentum resolution is still better than 1 % at 15 GeV. The detectors would be placed above and below the horizontal plane to avoid deadly radiation damages.

RICH counter

A RICH counter with two radiators has been selected for FAST :

- a radiator made of 1 cm of liquid perfluoro-hexane (C_6F_{14}) having an index $n_r = 1.277$ ensuring a good π/K and K/p separation at low momentum (up to 5 GeV/c and 8 GeV/c respectively).
- a gaseous radiator made of perfluoro-pentane (C_5F_{12}) with a lower index of refraction $n_r = 1.00174$ for discrimination at high momentum (up to 30 GeV/c) for π/K and K/p and up to 8 GeV/c for e/π .

A rate estimate has been made with a luminosity of $10^{35} \text{ cm}^{-2} \cdot \text{s}^{-1}$ for a RICH placed 360 cm from the target: the rate would be only 40 Hz on average and the maximum rate in the photocathode near the beam would be of the order of 4 kHz.

At this rate the main difficulty may come from the pattern recognition electronics which has to be able to distinguish up to 40 simultaneous rings over an area of 1 m^2 , requiring an average processing time of less than 10 μs . This will require further *R* and *D* work.

Calorimeter

For the ELFE project a calorimeter has been studied, based on the use of Cerium fluoride (CeF_3) crystals which have the following qualities :

- the density (6.2 g/cm^3) and radiation length (1.6 cm) are comparable to those of BGO,
- the decay time constant is 5-20 ns (instead of 300 ns for BGO),
- the temperature dependence is very favorable ($< 0.1 \% / ^\circ\text{C}$ instead of $1.4 \% / ^\circ\text{C}$ for BGO),
- it emits in the visible region instead of in the ultraviolet,
- it has a good radiation hardness ($> 1 \text{ Mrad}$ for small samples).

The energy resolution is of the order of :

$$\sigma/E \approx 0.94 \% / E^{1/2} + 0.14 \% + 0.025 \% E^{1/3} + 0.50 \%,$$

resulting in a resolution of 125 MeV at 5 GeV and 310 MeV at 15 GeV which is sufficient for the proposed experiments in the low energy range but marginal at high energies.

The size of the blocks would be variable according to the distance from the beam in order to limit the individual rates : $8 \times 8 \times 40 \text{ cm}^3$ near the beam (100 kHz), $16 \times 16 \times 40 \text{ cm}^3$ for the blocks further to the beam (10 kHz in average). Their number would be of the order of one thousand.

Hodoscope

The hodoscope is made of thin scintillating material. Since it is used in conjunction with the calorimeter to discriminate between charged and neutral particles (a neutral particle leaves no signal in the hodoscope but is detected by the calorimeter, a charged particle is detected in both detectors), it is rather natural to use the same granularity as that of the calorimeter resulting in a system of :

- 30 horizontal strips, each $16 \times 475 \times 1 \text{ cm}^3$ working at a rate at 0.3 MHz in average (1.2 MHz for the strips nearest to the beam plane),
- 60 vertical strips each $16 \times 220 \times 1 \text{ cm}^3$ working at 0.15 MHz in average (0.6 MHz close to the beam).

7.3.3. Mechanical design

The FAST detector would have the following main mechanical characteristics :

- distance target-vertex detector : 40 cm
- distance target-front of dipole magnet : 50 cm
- magnet length : 100 cm
- magnet entrance gap $45 \times 45 \text{ cm}^2$; exit gap : $140 \times 140 \text{ cm}^2$
- distance target-first position sensitive detector : 10 cm
- distance between two position sensitive detectors : 100 cm
- distance target-RICH counter : 270 cm
- length of RICH counter : 150 cm
- distance between RICH and calorimeter : 10 cm
- distance target-calorimeter : 430 cm
- thickness of calorimeter : 40 cm

The open geometry leaves enough space for the insertion of a rather large polarized target. More details concerning the read-out system, count rates (both for selected experiments and for backgrounds) and crude cost estimates can be found in the full ELFE Report [Blok *et al.* (1993)].

7.3.4. Conclusions

The FAST detector has been specially designed for two key experiments to be done at ELFE : 1) the measurement of meson form-factors and 2) the study of hadronization in nuclei. The same instrument can be used for other experiments as well :

- study of the isospin distribution of the proton sea by comparing π^+/π^- ratios in semi-exclusive DIS [Levelt *et al.* (1991)],
- search for strange dibaryons [Aerts and Dover (1985)],
- study of DIS at $x > 1$ (see section 6),
- measurement of transverse spin distributions (see section 4.2).

Extension of the present design to higher energies (30 GeV) and luminosities (up to $10^{36} \text{ cm}^{-2}.\text{s}^{-1}$) may be envisaged in a stepwise approach.

7.4. Di-Muon Spectrometer [Malek et al. (1993)]

7.4.1. *Conceptual design*

As we have seen in section 4.4. the production of $c\bar{c}$ mesons with hidden charm (J/ψ , ψ' , χ) is particularly interesting. The $c\bar{c}$ state is signed by its di-muon decay mode $c\bar{c} \rightarrow \mu^+\mu^-$ for J/ψ and ψ' mesons and by the correlation between a J/ψ and a decay γ for the χ meson. The reaction to be studied is then :

$$e + \text{nucleus} \rightarrow e' + \mu^+\mu^- + X,$$

where X represents recoiling particles (mesons, protons, light ions) which should be detected and identified as much as possible.

Although simple in principle, this experiment represents a challenge due to the fact that the cross-sections are very low (5 pb and 0.2 pb for elastic and inelastic production at 20 GeV), so that a large luminosity of 10^{36} - $10^{37} \text{ cm}^{-2}.\text{s}^{-1}$ far above the limits of existing set-ups, must be achieved.

This is obtained by using the full ELFE beam intensity (50 μA on a 1 % radiation length target). The J/ψ elastic electro-production at 20 GeV has been simulated with an event generator based on the Vector Dominance Model. The resulting distributions for electrons and muons as a function of scattering angle and momentum are shown in fig. 7.8. It shows that the electrons are very forward peaked and their momentum is mostly below 10 GeV/c. The muons are much more broadly distributed both in angle (up to 50°) and in momentum (up to 20 GeV/c).

Based on the above kinematics, a conceptual design for a dedicated di-muon detector is proposed which associates two different detectors :

- a dipole magnet covering the small angle region (0° - 10°) allowing to analyze momenta up to 9 GeV/c. A set of forward detectors (tracking chambers and muon detectors) will detect the scattered electrons and forward muons,
- a solenoidal detector detecting the backward ($10^\circ < \theta < 50^\circ$), high energy muons (2-20 GeV/c).

Such a combination would cover 90 % of the available J/ψ phase space. A schematic view of the instrument is shown in fig. 7.8 together with its main characteristics.

7.4.2. *Detectors*

Each magnet will be equipped with muon detectors (iron walls, muon chambers and trigger hodoscopes), tracking chambers and calorimeters. The emphasis here will be on muon detection and identification since the other elements utilize the techniques described in section 7.1.

Fig. 7.8 - Kinematics of elastic electro-production of J/ψ at 20 GeV. Muon and electron correlation between momentum and angle in the laboratory frame (from [Malek et al. (1993)]).

Fig. 7.9 - Schematic view of the DMS detector (from [Malek et al. (1993)]).

Muon identification

The forward end of each magnet will be equipped with an iron wall mixed with planes of muon chambers. At large angles (10° - 50°) the return yoke of the solenoid will be used as absorber. The propagation of various particles (e, μ, π) through the iron wall has been studied with GEANT [GEANT (1978),(1983)] which simulates particle-matter interactions. The thickness of the iron wall (50 cm) is such that almost 100% of the initial muons cross the wall but no electron (or charged particles produced by them) is detected after the wall. However pions are very difficult to stop especially for large momenta and they will have to be identified by the secondary showers they produce.

Di-muon mass distribution

The overall muon background has been calculated with the following three ingredients :

- production of $\mu^+\mu^-$ pairs through the Bethe-Heitler mechanism (see section 2.2. and [Tsai and Van Whitis (1966)]) whose total cross-section is of the order of 2 nb,
- calculation of incoherent muon spectra coming from electroproduction of mesons with LEPTO and JETSET (cross-section ~ 30 nb)
- simulation of meson decays with GEANT showing that 4.7 % of the mesons decaying incoherently give two muons or more in the detector volume.

The event generator has been run with an integrated luminosity of $5 \times 10^{38} \text{ cm}^{-2}$, one per cent of the required full luminosity and for electron angles $2^\circ < \theta_e < 10^\circ$. The resulting mass distribution is shown in fig. 7.10, assuming a 2 % energy resolution in the J/ψ missing mass. The good thing is that, despite its low production cross-section, the J/ψ can be easily identified. The bad things are 1) that the J/ψ rate is very low and justify the full luminosity of $10^{37} \text{ cm}^{-2}.\text{s}^{-1}$ and 2) that there is an enormous background at low energy which must be reduced at the trigger level since it will dominate the counting rate and detector occupancy.

Di-muon trigger

If the trigger is set on any coincidence of two muons, the total background rate is 3.5×10^4 events per second at a luminosity of $10^{37} \text{ cm}^{-2}.\text{s}^{-1}$. This rate is too high for reconstruction purposes so it would be interesting to reduce it at the first trigger level. One simple way to do it is to remark that when a "real" di-muon coming from a J/ψ desintegration is emitted, if one muon is emitted at a forward angle ($\theta < 10^\circ$), the other will be emitted at a larger angle ($\theta > 10^\circ$). Then instead of triggering on any two muons one can trigger on a forward muon μ_d detected in the dipole wall and one backward muon μ_s detected around the solenoid. When doing that, the low energy background is reduced by almost a factor of 10 down to 5×10^3 events per second, without affecting the counting rate of true J/ψ events as shown in fig. 7.10. A more detailed GEANT simulation with the following combination of triggers : $\mu_d \mu_d$, $\mu_s \mu_s$ and $\mu_s \mu_d$ shows that 83 % of the J/ψ events are accepted with the $\mu_s \mu_d$ trigger.

More details on radiative effects and background counting rates can be found in the full ELFE report [Malek et al. (1993)].

Fig. 7.10 - Two muon invariant mass distribution from the $e^- (20 \text{ GeV}) + p \rightarrow 2\mu + X$ reaction. Target thickness: 1 % radiation length. Integrated luminosity: $5 \cdot 10^{38}$ nucleons/cm². Full line : trigger 2μ or more. Hatched style peak: J/ψ inelastic component. Dashed line: trigger $\mu_s \mu_d$ (see text) (from [Malek et al. (1993)]).

7.4.3. Conclusions

A conceptual design of an apparatus to study charmonium production in semi-inclusive DIS at large luminosities (10^{36} - $10^{37} \text{ cm}^{-2} \cdot \text{s}^{-1}$) is proposed. Detailed simulations show that this experiment is challenging and that the detectors which will be needed are not yet readily available. Again, as in the case of the FAST detector, current R et D programs on detectors facing a much more hostile environment at the LHC or B-factories, give hope that satisfactory solutions will be found in due time.

7.5. Multiproduction Electroproduction Modular Upgradable Spectrometer (MEMUS)

7.5.1. *Overall specifications*

MEMUS is a large acceptance spectrometer with multiparticle detection capability for experiments related to the quark structure of nucleons and nuclei as proposed for the ELFE project, e.g. : virtual Compton scattering (section 2.2), proton electromagnetic form-factors (section 2.4), colour transparency (section 3), production of strangeness and charm (section 4).

The following requirements were taken into account :

- acceptance as close as possible to full 4π ,
- detection of charged and neutral particles,
- large luminosity capability (10^{35} - 10^{36} cm⁻².s⁻¹ for hydrogen, 10^{34} - 10^{35} cm⁻².s⁻¹ per nucleon for nuclear targets),
- high counting rate at forward angles,
- good particle identification,
- reasonable energy resolution (of the order of 1 % or better for charged particles, $2 \cdot 10^{-2} / \sqrt{E}$ for photons and electrons in the calorimeter),
- possibilities of evolution towards higher energies or different detector configurations.

7.5.2. *Magnet*

We have seen in several kinematical studies that, in semi-inclusive reactions induced by 15-30 GeV electrons, the electron distribution is strongly forward peaked ($\theta = 2$ - 45°).

The leading (fast) hadrons, and especially the pions, are also forward peaked but less than electrons requiring a detection extending up to $\sim 90^\circ$. On the other hand low energy hadrons coming from the hadronization process are emitted up to the largest angles ($\theta \geq 170^\circ$). Photons coming from the decay of neutral pions have also a broad angular distribution. These kinematical characteristics are best fulfilled by a solenoidal magnet as compared to a dipole or a toroid for the following reasons :

- the acceptance is the same for opposite charges allowing to measure, with a great precision, ratios of yields e.g. π^+ / π^- ,
- the symmetry is cylindrical with a full coverage of the azimuthal angle $\phi = 0$ - 360° ,
- the Møller scattered electrons (see section 7.3.3) can be easily kept in the beam pipe,
- the incident electron beam is parallel to the magnetic field, producing a minimum background.

In view of the above geometrical constraints and of the fact that the effective field integral must be much larger for energetic particles emitted at forward angles than for the slow hadrons principally produced at backward angles, the detector has to be asymmetric with the target placed near the entrance of the magnet. This characteristics is typical of a fixed target experiment as compared to e^+e^- or $p\bar{p}$ interactions at colliders which have usually a forward-backward symmetry.

The adopted solution and some of the characteristics are shown in fig. 7.11 and table 7.7. The magnetic field is about twice as large as fields used in present detectors at high energy facilities like LEP but it is still modest compared to the CMS project at LHC where B will be $4T$ in a volume eight times larger.

Solenoidal magnetic field	3T
Minimum forward angle	2°
Minimum transverse momentum	.05 to .10 GeV
Momentum resolution for $\theta > 5^\circ$	$\frac{\delta p}{p} \approx 0.5\%$
Momentum resolution for $2^\circ < \theta < 5^\circ$	$\frac{\delta p}{p} \leq 2\%$
Electromagnetic calorimeter (Forward part: $\theta < 40^\circ$)	$\frac{\delta p}{p} \approx \frac{2\%}{\sqrt{E}}$
Solid angle	98% of 4π
Luminosity	$\approx 10^{35}$ nucleon $\text{cm}^{-2} \text{s}^{-1}$

Fig. 7.11 - General design of the 4π -detector (MEMUS) (from [Bertin et al. (1993)]).

Coil	
Length	7.20 m
Inner radius	1.80 m
Outer radius	2.30 m
Field	3 T
Ampere turns	20×10^6 A
Return yoke	
Weight	1600 ton
Total length	9.30 m
Total radius	3.35 m

Table 7.7 - Characteristics of solenoid

7.5.3. Detectors

Fiber chambers or silicon pixel detectors placed near the target should provide a first estimate of charged particle multiplicity at the first level trigger and vertex reconstruction with a precision of a few mm at the second or third level trigger.

The tracking inside the solenoid is made by a cylindrical drift chamber (around the target) and a set of flat circular drift chambers at forward angles (fig. 7.11). Special care has to be taken to allow a large counting rate in a high background of soft Møller electrons and photons. To reduce the radiation length of the drift chambers to a minimum value (of the order of a few 10^{-5} per plane), the use of a light gas mixture (e.g. 83% helium-10 % CO_2 -7 % isobutane) and carbon wires is recommended [Burchat *et al.* (1992)].

A first estimate of the number of electronic channels gives 15000 for the central drift chamber and 20000 for the forward chambers.

The overall momentum resolution depends on the momentum of the particle and on the transverse length of its track in the magnetic field. Results of simulations are shown in fig. 7.12 in the case where the vertex is known with a good precision (point size interaction region) or not. These results show the importance of vertex reconstruction at forward angles (below 5°). In cases where the vertex is known, it is possible to obtain an overall resolution of 1 % or better in almost the full kinematical domain.

Particle identification will exploit a combination of TOF measurements (at low energy) and fast RICH. In MEMUS there will be four groups of scintillators : two at the end caps and two around the barrel. The segmentation will be larger (smaller units) at forward angles to decrease the number of counts to an acceptable level of 10^6 interactions per second in each sub-unit. The number of scintillators is estimated to be of the order of 400 covering a total surface of 90 m^2 and representing a volume of $3\text{-}4 \text{ m}^3$.

The electromagnetic calorimeter must measure accurately the energy of the scattered photons at forward angles ($\theta < 5^\circ$) and reconstruct the π^0 from its decay into 2γ with the best hermeticity (4π calorimetry).

Fig. 7.12 - Momentum resolution versus the momentum for different polar angles with known (top) an unknown (bottom) vertex.

7.5.4. Conclusion

MEMUS is a 4π -detector with an asymmetric structure which will allow to perform a large selection of semi-inclusive experiments at large luminosities (10^{35} - 10^{36} cm⁻².s⁻¹) proposed for the ELFE facility. Its main qualities are:

- efficient suppression of Møller direct electrons and secondary photons,
- azimuthal symmetry,
- same acceptance for positively and negatively charged particles,
- hermetic photon detection,
- easy extrapolation to higher energies (30 GeV option).

As compared with the FAST proposal, MEMUS has the advantage of an azimuthal symmetry and full 4π -coverage but the fact that the target is inside the solenoid may make problems for the use of large polarized targets which can be fit easily in front of FAST.

It is certainly an ambitious project whose technical requirements outperform existing set-ups but which is much less requiring than the LHC detectors. It could be built with present techniques but it would certainly benefit from R and D presently done in particular in the fields of drift chambers, electromagnetic calorimetry and fast RICH.

8. CONCLUSIONS

The ELFE project is the result of the dedication of about 200 physicists coming mostly from european countries with a large participation from France, Germany, Italy and the Netherlands.

It aims at exploring a fundamental question of physics : what is confinement ? For that purpose it would use a well understood probe, electrons with energy 15-30 GeV which reach the region of scaling where the virtual photon interacts directly with the quarks in the target. It will allow to investigate in detail the transition region between perturbative and non-perturbative QCD through the study of quark correlations in hadronic wave-functions. The accelerator is based on a conservative design which is an extrapolation of CEBAF but taking into account the latest technological progress since the beginning of the 90's.

The new facility would be characterized by a high luminosity and large (hopefully 100 %) duty cycle. These characteristics will represent a challenge for the detectors but they are less stringent than the ones faced by the LHC detectors for which a strong R and D action is being undertaken. Based on these developments four kind of detectors have been proposed which would cover the physics issues but which could also be merged into two or three broader purpose facilities.

The ELFE project got a very positive rating by NuPECC, the advisory body for nuclear physics in Europe, which made precise recommendations towards a timely realization. It is hoped that this support will favour the emergence of an enlarged, cohesive community whose task will be to refine the technical and physics options so that funding agencies in european countries will make a sound and motivated decision of building the new facility within the next 2-3 years.

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