PROPOSAL

STUDY OF ANTINUCLEON ANNIHILATIONS AT LEAR WITH OBELIX,
A LARGE-ACCEPTANCE AND HIGH-RESOLUTION DETECTOR,
BASED ON THE OPEN AXIAL FIELD SPECTROMETER

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1. INTRODUCTION

1.1 Strong interaction physics at LEAR: pre-ACOL output and post-ACOL prospects

Whilst the prime motivation for the CERN p̅p Collider program was the search for the mediators of weak interactions (RUB 77), the prime motivation for the construction of the LEAR facility was the study of antiproton interactions at low energies and of the hadronic structures produced in their annihilation. At the time of LEAR’s conception (DAL 77a,b; GAS 77a; KIL 77) and of the first LEAR Workshop (KAR 79) the main emphasis was placed on protonium (p̅p atom), on baryonium (qq̅qq̅ andqq̅q̅q̅q̅ multiquark structures), on the dependence of p̅p annihilation at rest from the angular momentum of the initial state, on formation experiments exploiting the high momentum resolution of the p̅ beam, and on the possibility to have access, in formation experiments exploiting the high momentum resolution of the p̅ beam, to a large set of quantum numbers, both at very low energies and in the charmonium region. The interest of meson, glueball, and hybrid spectroscopy at LEAR has only arisen (BAR 82; AST 82a) since the time of the second LEAR Workshop (ERI 82), and a new possibility to search also for broad structures was proposed there (AST 82b). A clear signature of a resonance with constituent glue would prove the fundamental point in QCD, i.e. that the mediators of the strong interaction force between quarks can interact between themselves. This point of central importance is highly non-trivial experimentally. A decisive contribution can be made at LEAR in the mass region where a resonance was already clearly observed in 1963 data in p̅p at rest (see Fig. 2.1) (ARM 69), and where 20 years later the best glueball candidate has been established in e+e− colliding rings (COO 85).

LEAR started operation in 1983. It has progressively reached, and in many cases largely exceeded, the design specifications, and has become a reliable, fully operational machine, as well as being a sophisticated storage ring at the forefront of accelerator technology.

Experiments have logged a large amount of data and these are being analysed. This requires caution and good understanding of the apparatus in order to avoid hasty, premature conclusions. Such work is under way, but in the meantime a number of experimental facts have been verified or discovered which firmly establish some of the new physics possibilities that were sought with LEAR (ERI 82, GAS 79, KAR 79). We should like to single out the following findings:

- The ground state of protonium has been observed unambiguously in annihilations without prongs in the final state (AST 85c) (see Fig. 2.2).
- The 2P level of protonium decays dominantly (98%) by annihilation (AST 85c) (see Figs. 2.2 and 2.3).
- p̅p annihilation at rest in gas occurs from nP and nS levels in comparable fractions (AST 84a).

- The request, in coincidence with p̅p annihilation at rest in H₂ gas at NTP and with a low-mass X-ray detector, of an X-ray in the 1-3 keV energy window (L-line energy region), selects annihilation events dominantly (> 90%) in the P-wave because of the tolerable inner bremsstrahlung background (see Fig. 2.3) (AST 84a; GAS 85a; LAN 85; RUC 85).

- Strong dynamical effects appear in exclusive final states in p̅p annihilation at rest when the S/P-wave composition of the initial state is changed (see Figs. 2.3 and 2.4) (AST 84a).

- p̅p annihilation in flight into exclusive final states is not covered below 400 MeV/c by any existing experiment, and only the π⁺π⁻ and K⁺K⁻ final states are studied above 400 MeV/c as a function of energy (PS170 85; PS172 85) and of target polarization (PS172 85).

- Experiments dedicated to inclusive p̅p annihilation channels (PS182 84; PS183 84, 85) and by-product inclusive measurements (PS171 85) have produced no new physics. They have given upper limits to the existence of new narrow resonances mostly in the energy region away from two-nucleon masses, where nucleon-antinucleon resonances and bound states should preferentially be searched for, and where measurements on exclusive non-annihilation channels (elastic and charge-exchange) show that interesting effects might be present (PS173 85).

- The ANTIN experiment (PS178 85) has shown that a useful n̄ beam can be forward-produced by charge exchange into a H₂ target and that the n̄ momentum can be well determined by time-of-flight measurement (see Fig. 6.5). The interest of n̄ beams was recognized for NN physics since the Karlsruhe Workshop (VOC 79), for formation experiments with I = 1, and for the possibility of studying strong interactions down to very low energies without Coulomb interference. This actually affected even the LEAR design that included four wedges in the centre of the bending magnets to accommodate a gas-jet target proposed for n̄ production (GIE 81). These physics motivations are even stronger today (BRE 85c), and we have an additional interest because of the possibility of a production experiment to search for mesons with constituent gluons from pure I = ± initial states.

- Streamer chamber studies of antiproton annihilation on nuclei have demonstrated that a fraction (increasing with energy) of the incoming antiprotons annihilate inside the nucleus (STR 85a,b,c) (see Figs. 2.14 and 2.15). These results point to the possibility of comparing annihilations i) on a free nucleon, ii) on the nuclear surface, and iii) in the interior of the nucleus. This gives the possibility of using the p̅, which is an extended object, to
probe collective quark-gluon aspects of nuclear matter which cannot be explored in scattering experiments. Questions such as whether the antiproton finds nucleons with extended bag structures in the nucleus, and whether $\bar{p}$ interactions inside the nucleus involve more than one nucleon in a small interaction volume, can be addressed.

Already from this short overview it clearly appears that new physics has emerged at LEAR, mostly from experiments looking at exclusive reactions.

These results are due not only to the unique working conditions achieved by the machine (LEF 85) but also to long and dedicated detector development work which has resulted in large acceptance detectors capable of studying exclusive channels (AST 86; BRE 84b, 85b; GAS 78a,c, 81; STR 81, 82b, 83, 84a,b,d,e).

However, the performances of even the most successful detectors used at LEAR for annihilation into exclusive hadronic channels are far below those of the detectors used in $e^+e^-$ rings at comparable centre-of-mass energies (DM 2 81; MAR 84; XB 82). ASTERIX operates an upgraded version (AST 80, 86) of a first-generation $e^+e^-$ detector (DM 1 76) which originally was not designed for high rates, and the Streamer Chamber Group has the only detector which visualizes events down to the vertex, but which can stand only low rates.

From further analysis of the data, and from 1986 data, we expect other results of qualitative interest and quite a number of quantitative results (e.g. P-wave annihilation branching ratios of $p\bar{p}$ at rest).

However, the work on strong interaction physics at LEAR clearly extends into at least the next five years. Extrapolating from past experimentation in the $q\bar{q}$ meson sector and from theoretical expectations, the spectroscopy of mesons with constituent gluons will require much more experimental work. The study of annihilation dynamics (annihilation mechanisms and dependence of final-state variables on the quantum numbers of the initial state) is only beginning, as quantitative results are not yet available for P-wave $p\bar{p}$ annihilation. There are no data for $\bar{n}$ annihilations ($I = 1$), nor for different spin states, and the energy dependence has not yet been measured in the most important energy region (0-400 MeV/c bombarding antinucleon momentum). In spite of a number of important measurements (STR 84c,f, 85a,b,c), the study of $\bar{n}$ annihilation in nuclei has only started at LEAR. The success in establishing the experimental signature of annihilation inside nuclei motivates promising research, not so much in terms of systematics across the nuclei table but rather in depth, by looking for rare processes (PON 56; FAL 83; ILJ 83) that would, however, be clear signatures of qualitative new physics in terms of nuclear structure at the quark-gluon level and in terms of new excited states of nuclear matter (RAF 82b, STR 82c). Proto- nium is a fundamental system where NN strong interactions play a dominant role. In the same way as for other fundamental atoms ($p^+e^-, e^+e^-, \mu^+\mu^-$), it can be
used to perform high-precision experiments as the system has a long life on the time scale of strong interaction. At LEAR three groups are at present investigating the ground state of this atom and its atomic cascade as function of target density (AST 85; PS174 85; PS175 85). The $p\bar{p}$ co-rotating beams operation (LEA 80; M0H 85) will make it possible to produce beams of $p\bar{p}$ atoms in vacuum according to a scheme (GAS 77b) that will permit high-accuracy protonium spectroscopy (GAS 77a, 78b, 85). With this scheme a gain in resolution exceeding $10^3$ is possible compared with present experiments. Consequently, strong interaction effects in the singlet and triplet sublevels of the $2P$ level will become accessible to measurement.

In summary, the field of strong interaction physics at LEAR in the post-ACOL era is extremely interesting and appears potentially highly rewarding. The main topics are

- spectroscopy of states with constituent gluons,
- $qq$ meson spectroscopy,
- $NN$ interaction dynamics,
- high-precision experiments,
- quark-gluon aspects of nuclear matter,
- highly excited states of nuclear matter.

Work in these fields cannot be episodic, and in view of the strong physics case, of the necessary long-range program, and of the good-quality measurements needed, it requires adequate instrumentation matching the high standards set by the accelerator component of the facility. As is now normal in high-energy physics, the basic instrument is a complete spectrometer (or better two competing ones) with high resolution, good particle identification, 4\% acceptance, high efficiency, a flexible trigger, and the capability to withstand high rates. Such devices, which have been developed and operated for high-energy physics, need important investment in terms of work and money. The detector requirements and the basic features of annihilation physics at low energies (high $p_T$, low c.m. momentum, high rates) quite naturally lead physicists to take advantage of the experimental lessons learnt from $e^+e^-$ rings and the ISR, this latter machine having had the highest luminosity and by far the highest rates.

The groups that form our collaboration are actively involved in experiments at LEAR, and have expertise in constructing and running magnetic spectrometers and in detector development. The program that we propose is the natural extension of the lines of research in which we are at present engaged, and which we have vigorously pursued and developed since the conception of LEAR (AST 80-86; BRE 82-85; GAS 77-86; ILJ 82-83; STR 81-85). The early closure of the ISR and the very co-operative attitude of the Axial Field Spectrometer (AFS) Collaboration have made available to our collaboration the main hardware and software.
components of the most advanced ISR detector. This has given solid backing to
the design of an ambitious but realistic detector. This detector has profession-
ally documented design performances, and it capitalizes on the availability of
the open axial field magnet (AFM) plus the AFS jet drift chambers (AFS 78-82),
on AFS software and advice, on the availability of CHARM I detector components
(CHA 78-83) for the external highly segmented calorimeter, and on experience in
detector development inside our collaboration for the central and end-cap pro-
jection chambers and for the TOF detector. The institutes outside CERN are main-
ly funded in the sector of nuclear physics. They will take care of the detector
electronics and installation, and have requested from the funding agencies of
the home institutes the necessary $6 \times 10^9$ Swiss francs. The design character-
istics of the proposed detector compare with and are often an improvement on the
best equipment in operation (at lower rates) in $e^+e^-$ rings at c.m. energies
below 4 GeV.

1.2 Summary of the research programme and of
the main features of the experimental apparatus

We plan to study $\bar{p}$ and $\bar{n}$ annihilations on $H_2$, $D_2$, and heavier gas targets
at rest, in small energy steps near threshold (with $H_2$ and $D_2$ targets), and at
1000 and 1800 MeV/c. We intend to give help to the LEAR team for $H^-$ monitoring,
to measure the yield of $p\bar{p}$ atoms produced with $p\bar{H}^-$ co-rotating beams, and later
on to initiate high-resolution protonium spectroscopy (IDEFIX).

We will use an extracted $\bar{p}$ beam with momentum between 100 and 1800 MeV/c, an
$\bar{n}$ beam forward-produced by charge exchange onto a well-shielded liquid $H_2$
target and, later on, the beam of $p\bar{p}$ atoms.

The main motivations of the experiment are:
- glueball, hybrid, $qq\bar{q}\bar{q}$ and $q\bar{q}$ meson spectroscopy;
- dynamics of NN interactions, with study of the dependence of final states of
different types upon the quantum numbers of the initial state (angular momen-
tum, isospin, energy, and eventually spin);
- precision measurements of strong interaction effects on $p\bar{p}$ atoms;
- quark-gluon aspects of nuclear matter;
- search for highly excited states of nuclear matter.

We propose a large-acceptance and high-resolution detector based on the
magnet and the drift chamber of the open axial field spectrometer (AFS 78-82)
to study annihilation physics at LEAR in ACOL time. The detector (shown in
Figs. 1.1 and 1.2) features 4π acceptance and high segmentation for charged and
neutral particles, charged-kaon identification up to 1 GeV/c, high momentum re-
solution for $(p - p)/(p - p)$ at 1 GeV/c charged particles and $p_{T}^{0}$, fine granularity,
excellent angular resolution ($\Delta \alpha \sim 3$ mrad), and three-dimensional shower recon-
struction for gammas. It measures $\bar{p}$ atomic X-rays, the recoil proton of $\bar{p}n$ annihila-
tions in deuterium, and nuclear particles and fragments emitted in $\bar{p}$ anni-
hilations on nuclei. It permits the unambiguous and complete identification of a
large number of exclusive annihilation channels containing charged and neutral
particles, to trigger on them and to reconstruct intermediate resonant states.
It uses gas targets that permit the study of $p\bar{p}$ S- and P-wave annihilations at
rest, the measurement of the recoil proton in $\bar{p}n$ annihilation in deuterium down
to low recoil momenta the detection of low-energy nuclear products in $\bar{p}$ annihi-
lations on nuclei. The target exchange is simple and quick, and at each beam
momentum the data on different targets can be taken in exactly the same experi-
mental conditions.

The detector is positioned with the magnet axis on the neutral line of $p\bar{p}$
atoms. It will measure the annihilation vertex necessary for high-accuracy
protonium spectroscopy. To this purpose the end-caps will be instrumented with
X-ray drift chambers in order to detect Doppler-shifted X-rays.
2. PHYSICS MOTIVATIONS AND OBJECTIVES

2.1 Particle physics

2.1.1 Glueballs and hybrids

Glueballs (qq and qgg) and hybrid mesons (q̄q) are hadronic structures expected in the QCD framework where gluons not only mediate the strong force between quarks but also play the role of constituent particles [for theoretical reviews see (CLO 84), (BAR 84), and (NAR 85)]. Gluon exchanges mediate the forces acting between the glueball or hybrid constituents. The experimental demonstration of the existence of glueballs and/or hybrids would therefore prove a basic principle of QCD -- that gluons interact between themselves -- and would also give additional evidence of their existence.

The mass range where glueballs and hybrids are expected and where there are experimental candidates can be covered at LEAR. Nucleon-antinucleon annihilations are a copious source of mesons present in the final state or in intermediate states, and are therefore a useful tool for studying meson spectroscopy and decays and searching for exotic structures. The production of structures with constituent gluons can be favoured in NÑ annihilations, as gluons are produced in the annihilation of constituent quarks and antiquarks of the original NÑ pair. As mentioned in the introduction, in 1963 already a clear resonance signal was observed in pp at rest (ARM 63; BAI 67) at the mass and in the channel K±π where the best glueball candidate has recently been established in e+e− storage rings (see Fig. 2.1).

The qgg and q̄q structures can have quantum numbers that are not accessible to q̄q pairs. This is a unique and distinctive feature that would permit the establishment of the glueball or hybrid nature of a state. To see these exotics it is therefore necessary to run production experiments, whilst formation experiments make it possible to identify only structures with the non-exotic quantum numbers accessible to the initial NÑ pair.

Predictions concerning the width of these exotics are not too restrictive, and both narrow and broad states have to be searched for.

In order to assess the nature of new states, it is also necessary to establish and study the properties of their decay channels, in particular those containing kaons.

Considering the points mentioned above, we plan to search for narrow and broad structures that could be candidates for glueballs and hybrids, and to study their spectroscopy and decay channels with production experiments on p̄p, p̄n, and n̄p with H2 and D2 targets. This represents a natural extension of the program of the ASTERIX experiment, in terms of isospin and energy, but with a much more powerful and complete detector.
A production experiment gives access to exotic quantum numbers. At rest and with a \(\bar{p}\) beam momentum of 100 MeV/c, each antiproton gives one annihilation event.

A production experiment relies on a complete identification of exclusive final states and on the detector resolution in order to see, with good sensitivity, any narrow structures in the mass spectra of intermediate states. The momentum resolution for prongs will be typically three times better than in ASTERIX at 1 GeV/c, charged kaons will be identified at all momenta up to 1 GeV/c, and \(\gamma's\) will be detected with full efficiency and excellent angular resolution. We will therefore have higher sensitivities than with ASTERIX for finding narrow structures, and many more channels will be accessible.

We plan to search for new structures in the mass spectra of intermediate states, and to study their properties also by comparing data taken in the same experimental conditions from different sets of initial states.

In a \(\mathrm{H}_2\) gas target annihilation at rest occurs from \(S\) and \(P\) atomic states with a fraction of \(S\)-wave annihilation (from all \(nS\) atomic states) between 20\% and 60\% (AST 84a). Detection, in coincidence, of \(L\) X-rays down to the 2P level of the \(\bar{p}\) atom selects \(P\)-wave annihilations (from the 2P atomic level) with an \(S\)-wave contamination well below 10\% (mostly due to X-ray internal bremsstrahlung background in the \(L\) X-ray region) (see Figs. 2.2 and 2.3). In \(\bar{p}d\) the fraction of \(P\)-wave annihilation is likely to be higher. These experimental results (AST 85c; LAN 85) confirm expectations, which were already at the time of the LEAR proposal amongst the strongest motivations for \(\bar{p}\) physics at rest in gas, for two reasons: a) annihilations from \(P\)-wave may enhance the probability of producing higher spin objects at rest (GAS 77b); b) comparison of \(S\)- and \(P\)-wave annihilation data can be used to identify also broad structures (OBE 85).

The isospin of the initial state is 0 and 1 in \(\bar{p}p\) annihilations, and 1 in \(\bar{p}n\) (\(\bar{n}p\)) annihilations. The isospin distribution of the initial states can be changed by changing the target (from \(\mathrm{H}_2\) to \(\mathrm{D}_2\)) or the beam (from \(\bar{p}\) to \(\bar{n}\)).

We can compare \(\bar{p}p\) data from dominant \(P\)-wave annihilation and from comparable \(S/P\)-wave annihilations, and compare \(\bar{p}n\) data with \(\bar{p}n\) data (from \(\bar{p}d\) annihilation with a measured recoil proton) and \(\bar{n}p\) data. By using the same apparatus in the same conditions (e.g. same stop distributions or same interaction volumes) and with the same software, the comparison factorizes away

i) detector acceptances,

ii) detector efficiencies,

iii) reconstruction biases, and

iv) phase space,

and differences in the spectra immediately indicate dynamical effects. We will, for instance, identify the exclusive final-state \(K^+K^-\bar{\nu}\) in \(\bar{p}p\) annihilations, and make a comparison between the \(K^+K^-\) mass spectrum with dominant \(P\)-wave annihi-
lation and the $K^+K^-$ mass spectrum with comparable fractions of $S$- and $P$-wave annihilation. These spectra can then be compared with the $K^+K^-$ mass spectrum of $K^+K^-\pi^-$ ($K^+K^-\pi^+$) final states in $p\bar{n}$ ($\bar{n}p$) annihilations (correcting for phase-space changes using the measured momentum of the recoil proton and of the incoming $\bar{n}$). Data with different $S$-wave and $P$-wave contributions taken by the ASTERIX experiment and bubble chambers show marked differences (see, for example, Figs. 2.4 and 2.5). With OBELIX we aim to make the comparison quantitative and (with the proper weights, which will have to be measured) to subtract the spectra, one from the other, to search also for new broad objects.

In order to explore the mass range above $2m_p$, production experiments with high incoming beam momentum will be necessary. In these measurements the distribution of angular momenta of the initial state will be larger, and the possibility of direct comparison of data sets taken at the same energy with different angular momentum distributions will be lost.

2.1.2 $q\bar{q}$ and $qq\bar{q}\bar{q}$ mesons

In $NN$ annihilations the search for glueballs and hybrids goes in parallel with the observation of light mesons, which are produced abundantly in $NN$ annihilations. For any new structure eventually found, except those with exotic quantum numbers inaccessible to $q\bar{q}$ and $qq\bar{q}\bar{q}$ structures, it will be difficult to establish its glueball or hybrid nature unless the SU(3) nonet in which it could be classified is not full (see Table 2.1). Light quarks of low-mass mesons explore mostly the confinement region of the potential, and data test non-perturbative QCD calculations (BAR 82). In the following we quote statements from a recent theoretical review (CHA 82), which clearly point out the intrinsic physics interest of low-mass meson spectroscopy:

'... Hadron spectroscopy would perhaps be dull and dated today if we were really in control of the theory of strong interactions. But that is far from the case. We probably do know the theory, QCD, but our understanding of its long-distance dynamics is still exceedingly primitive. In these circumstances we will have a great deal to learn from the spectrum, both about dynamics and about new forms of hadronic matter, such as glueballs and multiquark states.

In the realm of dynamics an outstanding puzzle is the simplicity of the light hadron spectrum. Why do relativistic, strongly coupled bound states appear in just the configurations expected in a non-relativistic model with an instantaneous potential? This simplicity made possible the discovery of quarks as early as 1964 but is itself still unexplained. In the bag model, which is a relativistic
Table 2.1
The more frequently accepted members of (q̅q) nonets

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</table>
phenomenology, the low-lying states are the usual ones but excited states are predicted with exotic quantum numbers — for instance, $q\bar{q}$ states with $J^{PC} = 0^{-}$ which never appear in the non-relativistic model. These extra states correspond to the spurious translation modes of the self-consistent field approximation of nuclear physics, where they are spurious because nuclei are well described by instantaneous potentials. But in QCD we don't know whether they exist because we are not in control of the dynamics. The issue is how quickly the collective field, which is the bag, responds to the motion of the quarks. This is a fundamental dynamical question, which is open in theory and experiment.

There are other related puzzles in the light hadron spectrum, all characterized by the unexpected success of simple ideas, sometimes outrageously simple. Why does single gluon exchange correctly give the spin dependence of the light s-wave mesons and baryons? Why do ideal mixing and the O(2) rule work for the light mesons? Most recently, why do sum rules based on a short distance expansion provide a good description of the light meson spectrum? All these puzzles suggest an unexpected weakness in the strength of the strong interaction. Indeed the authors of Ref. (6) have maintained the need for a smaller value of the QCD parameter $\Lambda$, which is now gaining support in other quarters.

The spin dependence of the potential is a difficult, still uncracked problem. Naive extrapolation of the single gluon exchange ansatz from the light hadrons is not successful, which undercuts the significance of the apparent success for the light hadrons. Generalizations of the Breit Potential of QED assume the confining potential can be approximated by exchange of quanta of definite spin or spins, an assumption which has no close connection with current ideas about the origin of the confining force.

What about multiquark states? — their apparent absence is another aspect of the puzzling success of the simple non-relativistic $q\bar{q}$ spectrum. Should we have seen them or not? Indeed, have we seen them? Jaffe and Johnson have used the bag model to find a very amusing set of answers: yes and yes. That is, we should have, and we have, but we didn't know it. Using single gluon exchange to compute hyperfine splittings they find that the lowest mass $q\bar{q}qq$ states are a collection of nine scalar mesons with the non-exotic quantum numbers of a $q\bar{q}$ nonet. The most recent data supports their reading of the $\delta$ and $S^+$ as members of this nonet (though there is a problem with the interpretation of the $\delta$). The success of the simple $q\bar{q}$ spectrum is explained
by the result that most $\bar{q}qqq$ states can fall apart into two $\bar{q}q$ pairs and are therefore too broad to produce discernible bumps in mass histograms.

'Nothing illustrates more clearly the value of detailed knowledge of the hadron spectrum than the present effort to determine whether the $\bar{K}K$ enhancement at 1440 MeV is a glueball. There may be three $\bar{q}q$ states near this mass with large $\bar{K}K$ decay modes: the even and odd charge conjugation axial mesons $E$ and $H'$ and the radially excited pseudoscalar which I call $Z'$. Of these only $E(1420)$ has found its way into the little orange book of the Particle Data Group, so it is natural to consider that it might be the enhancement found last year at SPEAR in radiative $\psi$ decay. There is however strong evidence that the SPEAR 1440 is not the $J^P = 1^+$ $E(1420)$ of the little orange book but is instead a pseudoscalar first discovered in $\bar{p}p$ annihilation at CERN. I believe it is very likely that this state is a glueball.

'With just the earlier CERN data and without the observations from radiative $\psi$ decay, it would have been difficult if not impossible to realize that this state may be a glueball. ...

'The one to two GeV region is certain to be very complicated. Just considering $\bar{q}q$ mesons there are an enormous number of states, many with confusingly similar masses and decay modes. To understand the interesting physics we will need high statistics data. Recent history teaches that each advance in statistics brings into view structure which cannot be seen in any other way. The advances of the past have brought the impressive knowledge of the meson spectrum that is reviewed here. We are not yet at the end of this progression. It is clear that we still have much more to learn.'

Our experiment, besides contributing to the observation of new mesons, would in particular provide good measurements of meson-decay branching ratios not only into pions but also into kaons.

2.2 $\bar{N}N$ interactions

2.2.1 Dynamics of $\bar{N}N$ annihilations

Annihilation is the most important process in $\bar{N}N$ interactions at low energies, as it dominates over elastic scattering and charge-exchange reactions. Its study is therefore essential to the understanding of $\bar{N}N$ forces and, more generally, strong interactions between hadrons at a microscopic level and at small distances. The number and variety of annihilation final states and of intermediate resonant states, and the dependence of their branching ratios or
partial cross-sections on the quantum numbers of the initial state (energy, angular momentum, isospin, spin), are a challenge for theoretical predictions and require a detailed experimental study.

Dynamical models were developed at the beginning of $\bar{p}$ physics to explain the branching ratios of $p\bar{p}$ and $\bar{p}n$ annihilations measured at rest in bubble chambers [for a review see (ARM 69)]. At that time the assumption was made that $p\bar{p}$ annihilation at rest in liquid $H_2$ occurs all in $S$-wave because of the strong Stark mixing coupled to $nS$-wave annihilation (DAY 60). Subsequently the experimental observation of the channel $p\bar{p} \to \pi^0 n^0$ in liquid $H_2$ (BAS 78; DEV 73) showed that there is a fraction of $P$-wave annihilation also in liquid $H_2$. In the seventies, interest moved to annihilation effects in the framework of potential models of $NN$ interactions (SHA 78). In these models the potential is made up from two contributions; one contribution comes from NN potential terms, G-parity transformed; a second one, with a real and an imaginary component, comes from the real and the virtual annihilation channels [see, for example, (VIN 78)]. The annihilation contribution was taken in nearly all models as being energy-, angular momentum-, isospin-, and spin-independent, just for simplicity.

Concerning real annihilation channels, it was suggested, at the time when the proposal for the LEAR facility was discussed, that the study of the dependence on angular momentum was possible in $p\bar{p}$ at rest in gas by exploiting the X-ray information from the atomic cascade (DAI 79; GAS 78b; KLE 79). ASTERIX has begun to realize this program. An increasing number of theoretical groups have recently become interested in the dynamics of annihilation (CHR 84; DAL 82; DOV 85; GRE 82; HAR 85; RUB 77; VIN 78) and have started calculating branching ratios and ratios of branching ratios.

We intend to contribute experimentally to this fundamental sector of $NN$ interactions with a systematic study, by measuring the dependences of the dynamics of several types of final states (which can be classified according to strangeness, multiplicity, and charge composition) on the quantum observables of the initial state (angular momentum, isospin, energy, and eventually -- if possible -- spin).

In the following, we examine these types of dependences in some detail. Of course, dedicated measurements will be feasible when channels of critical importance will be suggested by theory in order to discriminate between annihilation models. In several cases the dynamics is restricted by selection rules. Relevant selection rules are reproduced in Tables 2.2 and 2.3.
### Table 2.2 (ARM 69)

**Selection rules for $NN$ annihilations into pionic final states**

<table>
<thead>
<tr>
<th>State</th>
<th>$J^\pi$</th>
<th>$C$</th>
<th>$I$</th>
<th>$G$</th>
<th>$2\pi^0$</th>
<th>$\pi^+\pi^-$</th>
<th>$3\pi^0$</th>
<th>$\pi^-\pi^+\pi^0$</th>
<th>$4\pi^0$</th>
<th>$\pi^-\pi^+ + 2\pi^0$</th>
<th>$2\pi^- + 2\pi^+$</th>
<th>$5\pi^0$</th>
<th>$\pi^-\pi^+ + 3\pi^0$</th>
<th>$2\pi^-2\pi^+\pi^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1S_0$</td>
<td>$0^+$</td>
<td>+1</td>
<td>0</td>
<td>$\frac{1}{2}$</td>
<td>X</td>
<td>X</td>
<td>Z</td>
<td>Z</td>
<td>$-$</td>
<td>$-$</td>
<td>$-$</td>
<td>Z</td>
<td>Z</td>
<td>$-$</td>
</tr>
<tr>
<td>$^3S_1$</td>
<td>$1^-$</td>
<td>-1</td>
<td>1</td>
<td>$\frac{1}{2}$</td>
<td>X</td>
<td>X</td>
<td>Z</td>
<td>Z</td>
<td>$-$</td>
<td>$-$</td>
<td>Z</td>
<td>Z</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>$^1P_1$</td>
<td>$1^+$</td>
<td>+1</td>
<td>0</td>
<td>$\frac{1}{2}$</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Z</td>
<td>Z</td>
<td>$-$</td>
<td>$-$</td>
<td>X</td>
<td>Z</td>
<td>$-$</td>
</tr>
<tr>
<td>$^3P_0$</td>
<td>$0^+$</td>
<td>+1</td>
<td>1</td>
<td>$\frac{1}{2}$</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>Z</td>
<td>Z</td>
<td>$-$</td>
<td>$-$</td>
<td>Z</td>
<td>Z</td>
<td>$-$</td>
</tr>
<tr>
<td>$^3P_1$</td>
<td>$1^+$</td>
<td>+1</td>
<td>0</td>
<td>$\frac{1}{2}$</td>
<td>X</td>
<td>X</td>
<td>Z</td>
<td>Z</td>
<td>$-$</td>
<td>$-$</td>
<td>Z</td>
<td>Z</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>$^3P_2$</td>
<td>$2^+$</td>
<td>+1</td>
<td>1</td>
<td>$\frac{1}{2}$</td>
<td>X</td>
<td>X</td>
<td>Z</td>
<td>Z</td>
<td>$-$</td>
<td>$-$</td>
<td>Z</td>
<td>Z</td>
<td>$-$</td>
<td>$-$</td>
</tr>
</tbody>
</table>


### Table 2.2 (ARM 69)

**Selection rules for $np \rightarrow nn$ ($\ell \leq 5$)**

<table>
<thead>
<tr>
<th>State</th>
<th>$J^\pi$</th>
<th>$I$</th>
<th>$G$</th>
<th>$2\pi^0$</th>
<th>$\pi^-\pi^+ + \pi^0$</th>
<th>$2\pi^- + \pi^+ + \pi^0$</th>
<th>$\pi^- + 3\pi^0$</th>
<th>$3\pi^- + 2\pi^+$</th>
<th>$2\pi^- + \pi^+ + 2\pi^0$</th>
<th>$\pi^- + 4\pi^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1S_0$</td>
<td>$0^+$</td>
<td>1</td>
<td>$-1$</td>
<td>X</td>
<td>$-$</td>
<td>$-$</td>
<td>$-$</td>
<td>Z</td>
<td>Z</td>
<td>Z</td>
</tr>
<tr>
<td>$^3S_1$</td>
<td>$1^-$</td>
<td>1</td>
<td>+1</td>
<td>$-$</td>
<td>Z</td>
<td>Z</td>
<td>$-$</td>
<td>Z</td>
<td>Z</td>
<td>Z</td>
</tr>
<tr>
<td>$^1P_1$</td>
<td>$1^+$</td>
<td>1</td>
<td>+1</td>
<td>X</td>
<td>Z</td>
<td>Z</td>
<td>$-$</td>
<td>Z</td>
<td>Z</td>
<td>Z</td>
</tr>
<tr>
<td>$^3P_0$</td>
<td>$0^+$</td>
<td>1</td>
<td>$-1$</td>
<td>Z</td>
<td>X</td>
<td>X</td>
<td>Z</td>
<td>Z</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>$^3P_1$</td>
<td>$1^+$</td>
<td>1</td>
<td>$-1$</td>
<td>X</td>
<td>$-$</td>
<td>$-$</td>
<td>Z</td>
<td>Z</td>
<td>Z</td>
<td>Z</td>
</tr>
<tr>
<td>$^3P_2$</td>
<td>$2^+$</td>
<td>1</td>
<td>$-1$</td>
<td>Z</td>
<td>$-$</td>
<td>$-$</td>
<td>Z</td>
<td>Z</td>
<td>Z</td>
<td>Z</td>
</tr>
</tbody>
</table>

*From Lee and Yang (1956). $X$ means strictly forbidden, i.e., by $P$ or $C$ conservation. $Z$ means forbidden by $G$ parity conservation.

### Allowed and Forbidden Modes in $pp \rightarrow R^0K^0$ if Only $S$ and $P$ States are Considered

<table>
<thead>
<tr>
<th>Initial state</th>
<th>Final state</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J^\pi$</td>
<td>$K^+K^0 + K^0K^-$</td>
</tr>
<tr>
<td>$C = +1$</td>
<td>$C = -1$</td>
</tr>
<tr>
<td>$^1S_0$</td>
<td>$0^+$</td>
</tr>
<tr>
<td>$^3S_1$</td>
<td>$1^-$</td>
</tr>
<tr>
<td>$^1P_1$</td>
<td>$1^+$</td>
</tr>
<tr>
<td>$^3P_0$</td>
<td>$0^+$</td>
</tr>
<tr>
<td>$^3P_1$</td>
<td>$1^+$</td>
</tr>
<tr>
<td>$^3P_2$</td>
<td>$2^+$</td>
</tr>
</tbody>
</table>

*X means forbidden by charge conjugation (C). XX means forbidden by parity (P). XX(XX) means forbidden both by $P$ and $C$, and $[I = \ell]$ gives the relative $(R^0K^0)$ angular momentum in the allowed transitions.

### Selection Rules for Some Reactions $pp \rightarrow R^0K^0\pi^0$ from $S$ States of Protonium

<table>
<thead>
<tr>
<th>$J^\pi$</th>
<th>$(K^+K^0 + K^0K^-)X_0$</th>
<th>$(K^+K^0 - K^0K^-)X_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1S_0$</td>
<td>$0^+$</td>
<td>XX</td>
</tr>
<tr>
<td>$^1S_1$</td>
<td>$1^-$</td>
<td>XX(0.1)</td>
</tr>
<tr>
<td>$^3P_0$</td>
<td>$0^+$</td>
<td>[I = 0]</td>
</tr>
<tr>
<td>$^3P_1$</td>
<td>$1^+$</td>
<td>X(2.0)</td>
</tr>
<tr>
<td>$^3P_2$</td>
<td>$2^+$</td>
<td>[I = 2]</td>
</tr>
</tbody>
</table>

*From Snow (1962). XX means forbidden by parity and angular momentum conservation; X means forbidden by charge conjugation conservation only; (I, L) is the lowest angular momentum configuration allowed; I is the relative angular momentum of the $(R^0K^0)$ system and L that of $X_0$ relative to the $(R^0K^0)$ center of mass.
Table 2.3 [subset from TRI 65]

Selection rules for pp annihilations at rest in two-body channels.
2.2.1.1 Initial-state dependences

a) Angular momentum

We will measure branching ratios for \( p \bar{p} \) data at rest with a \( \bar{p} \) stop trigger, and data with the request for a L X-ray in coincidence. The first set of data will have a fraction \( s \) of S-wave annihilation (from all \( nS \) levels populated), and a fraction \( p = 1-s \) of P-wave annihilation, with \( s \) of the order of 20-50%.

The second set of data will have \( s \) determined mainly by the ratio between the X-ray background in the L X-ray energy region and the L X-ray yield. The order of magnitude in the second case is \( s \leq 5\% \). In both cases, the parameter \( s \) can be determined in several independent ways by measuring final states forbidden by selection rules in S-wave or in P-wave, and can be cross-checked through measurements of the X-ray yields of the atomic cascade of protonium at various target densities. Once \( s \) (\( \bar{p} \) stop) and \( s \) (L X-ray in coincidence) are established, the appropriate normalization factors will be available for deriving the pure S-wave and P-wave annihilation spectra, and for measuring pure S- and P-wave annihilation branching ratios of final and intermediate states.

The analysis of the angular momentum dependence for \( \bar{p}n \) annihilation in deuterium is more complex, as the angular momentum of the \( \bar{p} \) orbiting around the D nucleus is not necessarily the same as that of the \( \bar{p}n \) system at annihilation (BIZ 72).

A study of the angular momentum dependence of \( \bar{n}p \) annihilations seems possible with the \( \bar{n} \) beam since, because of the absence of Coulomb forces, S-wave annihilation dominates at very low momenta, and the fraction of P-wave annihilation increases gradually with the \( \bar{n} \) momentum. With a view to measuring the occurrence of intermediate resonances produced in \( \bar{n}p \) annihilation, it should be noted that a change of \( \bar{n} \) momentum in the range 100-300 MeV/c does not change the available phase space very much, as the total energy in the centre of mass varies only from 1878 to 1900 MeV. However, the \( \bar{n} \) momentum must be well measured to be able to impose momentum balance on the kinematical reconstruction of each final state.

b) Isospin

Proton-antiproton annihilation occurs from a mixture of \( I = 0 \) and \( I = 1 \) isospin states, whereas \( \bar{p}n \) and \( \bar{n}p \) initial states are pure \( I = 1 \).

We intend to study the isospin dependence of \( \bar{NN} \) annihilations by measuring and comparing \( \bar{p}p \) and \( \bar{p}n \) annihilations of antiprotons at rest in \( H_2 \) and \( D_2 \) targets, and \( \bar{n}p \) annihilations with forward-produced antineutrons bombarding a \( H_2 \) target.

Figure 2.6 shows a basic limitation encountered in measuring \( \bar{p}n \) annihilations in bubble chambers (BIZ 69; CRE 65): the recoil protons with momenta below 100 MeV/c could not be measured because they give a too short, non-
observable, or non-measurable track. More than 70% of the $\bar{p}n$ annihilations are events with spectator protons below 100 MeV/c. This momentum region is the one where the impulse approximation works better and the recoil proton can be treated as a spectator of the annihilation reaction. We will cover nearly all this region, as our central detector makes it possible to observe slow recoil protons with momenta down to 30 MeV/c. The measurement of the proton momentum vector is essential for the total momentum balance and the determination of the invariant mass of intermediate resonances.

Table 2.4 shows the $p\bar{p}$ annihilation branching ratios measured in liquid $H_2$. Table 2.5 shows the $\bar{p}n$ annihilation branching ratios measured in liquid $D_2$.

The analysis of $\bar{n}p$ annihilations in $H_2$ is conceptually simpler as there are no rescattering or final-state interaction problems, which may be present in the $\bar{p}n$ case in $D_2$. The $\bar{n}$ beam produced by charge exchange is a broad-band one with a momentum distribution that is continuous between 100 and 300 MeV/c (see subsection 6.3). The good time-of-flight measurement which we envisage is of critical importance as we need to measure precisely the momentum of each $\bar{n}$ interacting into the target. Annihilations of $\bar{n}p$ always give at least one prong, which facilitates the reconstruction and normalization procedures. The estimated number of all $\bar{n}p$ interactions is compatible with the maximum data-acquisition rate. The $\bar{n}$ measurements require a high-intensity $\bar{p}$ beam: $10^6 \bar{p}$ give typically $10^3 \bar{n}$, of which about 10 interact in the target volume. A liquid $H_2$ target would give higher rates but at the expense of a poorer kinematical reconstruction of reactions with three or more prongs.

We will study the variation with the incoming $\bar{n}$ momentum of the partial annihilation cross-sections (this could produce evidence of narrow states near threshold). We are also investigating the possibility of measuring $\bar{n}$ scattering, as the annihilation point of the scattered $\bar{n}$ can be very well determined in the HDSPC and the HARGD detectors.

c) Energy

Most of the pre-LEAR experimental work on $NN$ annihilations has been done with antiprotons interacting in hydrogen bubble chambers. Apart data at rest, the information available is limited to momenta exceeding 300 MeV/c (below this value, annihilation in flight has not been investigated owing to the too poor pre-LEAR low-energy beams).

A systematic channel-by-channel survey of the 300-2000 MeV/c region is also missing.

Annihilation in flight into exclusive final state is not covered at LEAR, apart from the channels $e^+e^-$ and $\pi^+\pi^-/K^+K^-$ in $p\bar{p}$ annihilation.

If a resonance couples to the $NN$ channel, and has preferred decay channels, a peak can be identified by measuring the rate of occurrence of those channels
Table 2.4 (AST 80)

Contribution of pionic states to pp annihilations at rest in liquid H₂

<table>
<thead>
<tr>
<th>Final state</th>
<th>Resonant intermediate state</th>
<th>Percentage of all annihilations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CERN</td>
<td>Columbia</td>
</tr>
<tr>
<td>all neutral particles</td>
<td>4.1 ± 0.3</td>
<td>3.2 ± 0.5</td>
</tr>
<tr>
<td>π⁺π⁻</td>
<td>0.37 ± 0.03</td>
<td>0.32 ± 0.03</td>
</tr>
<tr>
<td>π⁺π⁻ π⁺π⁻</td>
<td>6.9 ± 0.35</td>
<td>7.8 ± 0.9</td>
</tr>
<tr>
<td></td>
<td>ρπ</td>
<td>5.8 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>ρπρ</td>
<td>0.24 ± 0.07</td>
</tr>
<tr>
<td>π⁺π⁻ MM</td>
<td>35.8 ± 0.8</td>
<td>34.5 ± 1.2</td>
</tr>
<tr>
<td></td>
<td>γπ⁺π⁻</td>
<td>0.8 ± 0.1</td>
</tr>
<tr>
<td>2π⁺2π⁻</td>
<td>6.9 ± 0.6</td>
<td>5.8 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>A⁺⁻ π⁺π⁻</td>
<td>2.0 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>L⁺ φπ⁺π⁻</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ρ²π⁺π⁻</td>
<td>0.90 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>ρ⁺π⁺π⁺ π⁺π⁻</td>
<td>1.50 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>ρ⁺π⁺π⁺ π⁺π⁻</td>
<td>0.12 ± 0.12</td>
</tr>
<tr>
<td>2π⁺2π⁻ π⁺π⁻</td>
<td>19.6 ± 0.7</td>
<td>18.7 ± 0.9</td>
</tr>
<tr>
<td></td>
<td>ωπ⁺π⁻</td>
<td>3.0 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>ωρπ⁺π⁻</td>
<td>2.1 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>ωρ⁺π⁺π⁻</td>
<td>1.7 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>ρ²π⁺π⁺ π⁺π⁻</td>
<td>13.7 ± 0.6</td>
</tr>
<tr>
<td></td>
<td>ρ⁺π⁺π⁺ π⁺π⁻</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B⁺⁻ π⁺π⁻</td>
<td>0.7 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>L⁺ φπ⁺π⁻</td>
<td></td>
</tr>
<tr>
<td></td>
<td>γπ⁺π⁻</td>
<td>0.35 ± 0.04</td>
</tr>
<tr>
<td></td>
<td>A⁺⁻ π⁺π⁻</td>
<td>0.13 ± 0.03</td>
</tr>
<tr>
<td>2π⁺2π⁻ MM</td>
<td>20.8 ± 0.7</td>
<td>21.3 ± 1.1</td>
</tr>
<tr>
<td></td>
<td>γπ⁺π⁻</td>
<td>0.11 ± 0.02</td>
</tr>
<tr>
<td>3π⁺3π⁻</td>
<td>2.1 ± 0.2</td>
<td>1.9 ± 0.2</td>
</tr>
<tr>
<td>3π⁺3π⁻ π⁺π⁻</td>
<td>1.9 ± 0.2</td>
<td>1.6 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>ω2π⁺2π⁻</td>
<td>1.3 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>ωπ⁺π⁻</td>
<td>0.17 ± 0.05</td>
</tr>
<tr>
<td></td>
<td>ωπ⁺π⁻</td>
<td>0.04 ± 0.01</td>
</tr>
<tr>
<td>3π⁺3π⁻ MM</td>
<td></td>
<td>0.3 ± 0.1</td>
</tr>
</tbody>
</table>

(*) This table updates the one published by R. Armenteros and B. French in High Energy Physics, Vol. 4 (New York, N. Y., 1969), with data published later by the CERN-Columbia de France Collaboration. In quoting percentages for resonance production, no corrections have been made for decay modes not occurring in the given final state.
Table 2.5 (ARM 69)
Contribution of pionic states to pn annihilations at rest in liquid D₂

<table>
<thead>
<tr>
<th>Final state</th>
<th>Intermediate resonant state</th>
<th>Percentage of all annihilations a</th>
<th>Bettini et al. (1987)</th>
<th>Anninos et al. (1985)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n^- + np^0 ) ((m = 1, 2, \ldots))</td>
<td>-</td>
<td>16.4 ± 0.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( n^- + p^0 )</td>
<td>-</td>
<td>≤ 0.7</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( 2n^- + n^+ + mp^0 ) ((m = 0, 1, 2, \ldots))</td>
<td>-</td>
<td>59.7 ± 1.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( 2π^- + π^+ )</td>
<td>( ρ^0 + π^- ) ( (0.65) )</td>
<td>1.57 ± 0.21</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>( f^0 + π^- ) ( (0.94) )</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( 2π^- + π^+ + π^0 )</td>
<td>( ρ^+ + 2π^- ) ( (0.9 ± 0.4) )</td>
<td>21.8 ± 2.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>( ρ^0 + π^- + π^0 ) ( (0.7) )</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>( ρ^- + π^- + π^- ) ( (3.9 ± 0.8) )</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>( A_2^0 + π^- ) ( (3.3) )</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>( ω^0 + π^- ) ( (0.41 ± 0.08) )</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>( χ^0 + π^- ) ( (0.25) )</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( 3π^- + 2π^+ ) ((m = 0, 1, 2, \ldots))</td>
<td>-</td>
<td>(23.4 ± 0.7)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( 3π^- + 2π^+ )</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( 3π^- + 2π^+ + π^0 )</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( 4π^- + 3π^+ + mp^0 ) ((m = 0, 1, 2, \ldots))</td>
<td>-</td>
<td>(12.0 ± 3.0)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( 4π^- + 3π^+ + mp^0 )</td>
<td>-</td>
<td>(0.39 ± 0.07)</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* All resonant rates are included in those given for the corresponding final state. Resonant rates have been corrected to also take into account their decays into neutral particles.
in N\bar{N} annihilation as a function of energy and thus determining the energy and
the width of the resonance.

In case of two-body and quasi-two-body decays, a phase-shift analysis can
be performed and the quantum numbers of broad objects identified. We are not
especially interested in scanning the energy region above 400 MeV/c, as exotic
quantum numbers are not accessible in formation experiments. The region near to
the threshold is instead of great interest because of the chance to explore,
with a good instrument, an unknown energy region near to a threshold where one
is sensitive to the details of the N\bar{N} potential.

OBELIX will be able to cover the momentum range from rest up to 2 GeV/c,
with good performances also at high momenta owing to the high granularity and
excellent angular resolution of all the detector components in the forward
region also.

Angular resolution is critical in the reconstruction of the invariant
masses. The relative error on angles increases with energy because the angle
between daughter particles shrinks owing to the energy boost and the c.m.
momentum boost.

One or two high-statistics data-takings should, however, be done with the
\bar{p} beam in order to have access, through a production experiment, to higher-mass
objects in gluon- and quark-meson spectroscopy.

To have orders of magnitude, Table 2.6 gives partial annihilation cross-
section measurements at 3.28 GeV/c and 5.7 GeV/c \bar{p} beam momentum on a H\textsubscript{2} target.

d) Spin

The study of the spin dependence of \bar{p} annihilations seems at present the
more difficult one -- among the studies of the dependence on the quantum numbers
of the initial states -- as it is not possible to polarize a low-momentum \bar{p} beam
(around 600 MeV/c) by scattering of \bar{p} on \textsuperscript{12}C (BEA 85). It remains to be seen
whether at higher momenta (around 1000 MeV/c) this possibility exists. However,
these beam momenta are less interesting, as they are away from the region where
annihilation is the dominant process.

Spectacular spin effects (\sigma_{T\uparrow} = 3\sigma_{T\downarrow}) (RIC 82) for the reaction p\bar{p} \rightarrow n\bar{n}
with \bar{p} impinging on a polarized target. A beam of almost completely polarized
antineutrons could be produced if the prediction is confirmed. One experiment
has been proposed for the study of this effect and could be installed upstream
of our equipment; and eventually it would be feasible to use our powerful spect-
rometer to study annihilations of polarized antineutrons.

The hope of comparing p\bar{p} annihilations at rest from the singlet and triplet
ground states signed by the K\alpha X-ray -- subject to the still unverified possibil-
ity that the \textsuperscript{1}S\textsubscript{0} and \textsuperscript{3}S\textsubscript{1} states are sufficiently separated by strong inter-
Table 2.6 (ARM 69)
Contributions of pionic states to $\bar{p}p$ annihilations in flight at high beam momenta

<table>
<thead>
<tr>
<th>Final State</th>
<th>Intermediate resonant state</th>
<th>Cross section (mb) $^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+\pi^-$</td>
<td>-</td>
<td>$&lt;0.025$</td>
</tr>
<tr>
<td>$\pi^+\pi^-\eta^0$</td>
<td>$\rho^0\pi^+$, $\rho^+\pi^0$</td>
<td>$0.5 \pm 0.2$, $(&lt; 0.05)$</td>
</tr>
<tr>
<td>$\pi^+\pi^-\eta^0$</td>
<td>$(&lt;0.05)$</td>
<td></td>
</tr>
<tr>
<td>$2\pi^+2\pi^-$</td>
<td>-</td>
<td>$6.7 \pm 2.0$</td>
</tr>
<tr>
<td>$2\pi^+\pi^- + \pi^0$</td>
<td>$\rho^0\pi^+\pi^+$, $f^0\pi^+\pi^-$</td>
<td>$0.8 \pm 0.1$, $(&lt; 0.05)$</td>
</tr>
<tr>
<td>$2\pi^+ + 2\pi^- + \pi^0$</td>
<td>-</td>
<td>$4.5 \pm 0.6$</td>
</tr>
<tr>
<td>$2\pi^+ + 2\pi^- + \eta$</td>
<td>$\rho^0\eta^0$, $\rho^+\eta^0$, $f^0\eta^0$</td>
<td>$(1.3 \pm 0.3)$, $(1.0 \pm 0.3)$, $(0.6 \pm 0.3)$</td>
</tr>
<tr>
<td>$3\pi^+ + 3\pi^-$</td>
<td>$\rho^0\eta^0$, $\rho^+\eta^0$, $f^0\eta^0$</td>
<td>$0.9 \pm 0.1$</td>
</tr>
<tr>
<td>$3\pi^+ + 3\pi^- + \pi^0$</td>
<td>$\rho^0\eta^0$, $\rho^+\eta^0$, $f^0\eta^0$</td>
<td>$(&lt; 0.05)$</td>
</tr>
<tr>
<td>$3\pi^+ + 3\pi^- + \eta$</td>
<td>-</td>
<td>$2.7 \pm 0.3$</td>
</tr>
<tr>
<td>$3\pi^+ + 3\pi^- + \eta^0$</td>
<td>$\rho^0\eta^0$, $\rho^+\eta^0$, $f^0\eta^0$</td>
<td>$(&lt; 0.05)$</td>
</tr>
<tr>
<td>$3\pi^+ + 3\pi^- + \eta^0$</td>
<td>$\rho^0\eta^0$, $\rho^+\eta^0$, $f^0\eta^0$</td>
<td>$(&lt; 0.05)$</td>
</tr>
<tr>
<td>$4\pi^+ + 4\pi^-$</td>
<td>$\eta^0\eta^0$, $\omega\eta^0$</td>
<td>$2.4 \pm 0.5$</td>
</tr>
<tr>
<td>$4\pi^+ + 4\pi^- + \eta^0 + m\pi^0$</td>
<td>$\eta^0\eta^0$, $\omega\eta^0$</td>
<td>$0.10 \pm 0.03$</td>
</tr>
</tbody>
</table>

$^a$ From Ferbel et al. (1966).

$^b$ The cross sections for intermediate resonant states are included in those for the corresponding final state.

---

Partial Cross Sections for Different Pionic Final States in $\bar{p}p$ Annihilations at 5.7 GeV/c

<table>
<thead>
<tr>
<th>Final State</th>
<th>Cross section (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+\pi^-$</td>
<td>$&lt;0.05$</td>
</tr>
<tr>
<td>$\pi^+\pi^-\eta^0$</td>
<td>$&lt;0.3$</td>
</tr>
<tr>
<td>$\pi^+\pi^-\eta^0$</td>
<td>$(4.5 \pm 1.2)$</td>
</tr>
<tr>
<td>$2\pi^- + 2\pi^-$</td>
<td>$0.11 \pm 0.03$</td>
</tr>
<tr>
<td>$2\pi^+ + 2\pi^- + \eta^0$</td>
<td>$0.75 \pm 0.11$</td>
</tr>
<tr>
<td>$2\pi^+ + 2\pi^- + m\eta^0$</td>
<td>$8.3 \pm 1.4$</td>
</tr>
<tr>
<td>$3\pi^+ + 3\pi^-$</td>
<td>$0.26 \pm 0.06$</td>
</tr>
<tr>
<td>$3\pi^+ + 3\pi^- + \eta^0$</td>
<td>$1.40 \pm 0.30$</td>
</tr>
<tr>
<td>$3\pi^+ + 3\pi^- + m\pi^0$</td>
<td>$4.9 \pm 0.4$</td>
</tr>
</tbody>
</table>

$^a$ From Blockmann et al. (1966).
action to give a measurable splitting in the $K^0\alpha$ line--is hindered by the exceedingly large yield of X-ray internal bremsstrahlung, as compared with the $K^0\alpha$ line yield.

2.2.1.2 Final-state dependences

The study and the comparison of final and intermediate states of different types is indispensable if one wants to get a clear phenomenological picture of annihilation and to establish the nature and quantum numbers of any new resonant states eventually found. This is true for the various types of initial states that are made accessible by changing the beam ($\vec{p}$, $\vec{n}$) and/or the target in our experiment. The $pp$ case is examined in some detail in Section 5 where--in view of the performances of our experiment discussed in Section 3 and summarized in Section 4--also signal and background estimates for various cases are given.

In this section we limit the discussion to underlining some physics and experimental facts.

a) Strangeness

The presence of kaons in the final state implies an annihilation reaction with a creation diagram of a quark-antiquark pair (the $s\bar{s}$ one). This type of diagram is different from the recombination one, which is generally assumed to dominate annihilation reactions.

Final states with kaons have been studied in bubble chambers, looking for channels with a visible $K_S^0$. Table 2.7 gives the branching ratios for those channels for annihilation at rest (with dominant S-wave) in liquid $H_2$.

With OBELIX we will extend that study to channels with a $K^+K^-$ pair, increase the statistics dramatically as we can trigger on $K_S^0$ and $K^\pm$, and make the study with both S- and P-wave initial states.

When kaons are present in the final state, the number and the average momentum of pions is reduced, and essentially all particles in the final state are different from each other. Thanks to the powerful particle identification of OBELIX, all particles are recognized and no combinatorial background is present when intermediate resonances are searched for. This is a very different situation from the case where many charged pions--or, even worse, many many gammas--are present in the final state.

Figures 2.7 and 2.8 show the missing mass recoiling against a $\pi^+\pi^-$ pair and against a $K_S^{0*}\phi^0$ pair in $pp$ annihilations. The difference in physical background below the $\pi^+$, $\eta$, and $\phi(\omega)$ peaks is dramatic. With OBELIX we will be able to measure also the missing mass recoiling against a $K^+K^-$ pair, and then decay products of the recoiling object will be measured too.
Table 2.7 (ARM 69)

Contributions of kaonic channels with one detected K<sup>0</sup><sub>S</sub> in p̅p annihilation at rest in liquid H<sub>2</sub>

<table>
<thead>
<tr>
<th>Final state</th>
<th>Intermediate resonant state</th>
<th>\text{Rates} \times 10^{3}</th>
<th>\text{(a)}</th>
<th>\text{(b)}</th>
</tr>
</thead>
<tbody>
<tr>
<td>K&lt;sup&gt;−&lt;/sup&gt;K&lt;sup&gt;−&lt;/sup&gt;</td>
<td>—</td>
<td>1.1 \pm 0.1</td>
<td>0.96 \pm 0.08</td>
<td></td>
</tr>
<tr>
<td>K&lt;sup&gt;0&lt;/sup&gt;&lt;sub&gt;S&lt;/sub&gt;K&lt;sup&gt;0&lt;/sub&gt; + K&lt;sup&gt;0&lt;/sup&gt;&lt;sub&gt;S&lt;/sub&gt;K&lt;sup&gt;0&lt;/sup&gt;</td>
<td>—</td>
<td>0.010 \pm 0.012</td>
<td>0.008 \pm 0.008</td>
<td></td>
</tr>
<tr>
<td>K&lt;sup&gt;0&lt;/sup&gt;&lt;sub&gt;S&lt;/sub&gt;K&lt;sup&gt;0&lt;/sub&gt;</td>
<td>—</td>
<td>0.71 \pm 0.10</td>
<td>0.80 \pm 0.05</td>
<td></td>
</tr>
<tr>
<td>K&lt;sup&gt;0&lt;/sup&gt;&lt;sub&gt;S&lt;/sub&gt;K&lt;sup&gt;0&lt;/sub&gt;π&lt;sup&gt;0&lt;/sup&gt; + K&lt;sup&gt;0&lt;/sup&gt;&lt;sub&gt;S&lt;/sub&gt;K&lt;sup&gt;0&lt;/sup&gt;π&lt;sup&gt;0&lt;/sup&gt;</td>
<td>—</td>
<td>1.46 \pm 0.26</td>
<td>1.56 \pm 0.12</td>
<td></td>
</tr>
<tr>
<td>K&lt;sup&gt;0&lt;/sup&gt;&lt;sub&gt;S&lt;/sub&gt;K&lt;sup&gt;0&lt;/sub&gt;π&lt;sup&gt;0&lt;/sup&gt; (K&lt;sup&gt;0&lt;/sup&gt;&lt;sub&gt;S&lt;/sub&gt; \rightarrow K&lt;sup&gt;0&lt;/sup&gt;&lt;sub&gt;π&lt;/sub&gt;π&lt;sup&gt;0&lt;/sup&gt;)</td>
<td>—</td>
<td>\sim 0</td>
<td>0.24 \pm 0.08</td>
<td></td>
</tr>
<tr>
<td>K&lt;sup&gt;0&lt;/sup&gt;&lt;sub&gt;S&lt;/sub&gt;K&lt;sup&gt;0&lt;/sub&gt;π&lt;sup&gt;0&lt;/sup&gt;</td>
<td>K&lt;sup&gt;0&lt;/sup&gt;&lt;sub&gt;S&lt;/sub&gt;π&lt;sup&gt;0&lt;/sup&gt;</td>
<td>0.35 \pm 0.02</td>
<td>0.43 \pm 0.05</td>
<td></td>
</tr>
<tr>
<td>K&lt;sup&gt;0&lt;/sup&gt;&lt;sub&gt;S&lt;/sub&gt;K&lt;sup&gt;0&lt;/sub&gt;π&lt;sup&gt;0&lt;/sup&gt; (n \geq 1)</td>
<td>—</td>
<td>0.64 \pm 0.03</td>
<td>0.71 \pm 0.08</td>
<td></td>
</tr>
<tr>
<td>K&lt;sup&gt;0&lt;/sup&gt;&lt;sub&gt;S&lt;/sub&gt;K&lt;sup&gt;0&lt;/sub&gt; (η \rightarrow neutral)</td>
<td>0.155 \pm 0.033</td>
<td>0.16 \pm 0.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>K&lt;sup&gt;0&lt;/sup&gt;&lt;sub&gt;S&lt;/sub&gt;K&lt;sup&gt;0&lt;/sub&gt; (ω \rightarrow neutral)</td>
<td>0.089 \pm 0.026</td>
<td>0.11 \pm 0.04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>K&lt;sup&gt;0&lt;/sup&gt;&lt;sub&gt;S&lt;/sub&gt;K&lt;sup&gt;0&lt;/sup&gt;π&lt;sup&gt;0&lt;/sup&gt;</td>
<td>—</td>
<td>4.25 \pm 0.55</td>
<td>4.25 \pm 0.20</td>
<td></td>
</tr>
<tr>
<td>K&lt;sup&gt;0&lt;/sup&gt;&lt;sub&gt;S&lt;/sub&gt;K&lt;sup&gt;0&lt;/sub&gt;π&lt;sup&gt;0&lt;/sup&gt; (K&lt;sup&gt;0&lt;/sup&gt;&lt;sub&gt;S&lt;/sub&gt; \rightarrow K&lt;sup&gt;0&lt;/sup&gt;&lt;sub&gt;π&lt;/sub&gt;π&lt;sup&gt;0&lt;/sup&gt;)</td>
<td>0.85 \pm 0.16</td>
<td>1.05 \pm 0.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>K&lt;sup&gt;0&lt;/sup&gt;&lt;sub&gt;S&lt;/sub&gt;K&lt;sup&gt;0&lt;/sub&gt;π&lt;sup&gt;0&lt;/sup&gt; (K&lt;sup&gt;0&lt;/sup&gt;&lt;sub&gt;S&lt;/sub&gt; \rightarrow K&lt;sup&gt;0&lt;/sup&gt;&lt;sub&gt;π&lt;/sub&gt;π&lt;sup&gt;0&lt;/sup&gt;)</td>
<td>0.57 \pm 0.12</td>
<td>0.69 \pm 0.07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A&lt;sub&gt;1&lt;/sub&gt;π&lt;sup&gt;0&lt;/sup&gt; (A&lt;sub&gt;2&lt;/sub&gt; \rightarrow K&lt;sup&gt;0&lt;/sup&gt;&lt;sub&gt;S&lt;/sub&gt;π&lt;sup&gt;0&lt;/sup&gt;)</td>
<td>—</td>
<td>0.64 \pm 0.07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A&lt;sub&gt;2&lt;/sub&gt;π&lt;sup&gt;0&lt;/sup&gt; (A&lt;sub&gt;3&lt;/sub&gt; \rightarrow K&lt;sup&gt;0&lt;/sup&gt;&lt;sub&gt;S&lt;/sub&gt;π&lt;sup&gt;0&lt;/sup&gt;)</td>
<td>—</td>
<td>0.25 \pm 0.06</td>
<td></td>
<td></td>
</tr>
<tr>
<td>K&lt;sup&gt;0&lt;/sup&gt;&lt;sub&gt;S&lt;/sub&gt;K&lt;sup&gt;0&lt;/sub&gt;π&lt;sup&gt;−&lt;/sup&gt;π&lt;sup&gt;−&lt;/sup&gt;</td>
<td>—</td>
<td>2.01 \pm 0.26</td>
<td>1.95 \pm 0.23</td>
<td></td>
</tr>
<tr>
<td>K&lt;sup&gt;0&lt;/sup&gt;&lt;sub&gt;S&lt;/sub&gt;K&lt;sup&gt;0&lt;/sub&gt;π&lt;sup&gt;−&lt;/sup&gt;π&lt;sup&gt;−&lt;/sup&gt;</td>
<td>—</td>
<td>2.41 \pm 0.36</td>
<td>2.26 \pm 0.45</td>
<td></td>
</tr>
<tr>
<td>K&lt;sup&gt;0&lt;/sup&gt;&lt;sub&gt;S&lt;/sub&gt;π&lt;sup&gt;−&lt;/sup&gt;π&lt;sup&gt;−&lt;/sup&gt; (p \rightarrow K&lt;sup&gt;0&lt;/sup&gt;&lt;sub&gt;S&lt;/sub&gt;π&lt;sup&gt;−&lt;/sup&gt;)</td>
<td>—</td>
<td>0.18 \pm 0.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>K&lt;sup&gt;0&lt;/sup&gt;&lt;sub&gt;S&lt;/sub&gt;π&lt;sup&gt;−&lt;/sup&gt;π&lt;sup&gt;−&lt;/sup&gt;</td>
<td>—</td>
<td>4.47 \pm 0.53</td>
<td>4.69 \pm 0.55</td>
<td></td>
</tr>
<tr>
<td>K&lt;sup&gt;0&lt;/sup&gt;&lt;sub&gt;S&lt;/sub&gt;π&lt;sup&gt;−&lt;/sup&gt;π&lt;sup&gt;−&lt;/sup&gt;</td>
<td>—</td>
<td>1.49 \pm 0.22</td>
<td>1.10 \pm 0.14</td>
<td></td>
</tr>
<tr>
<td>K&lt;sup&gt;0&lt;/sup&gt;&lt;sub&gt;S&lt;/sub&gt;π&lt;sup&gt;−&lt;/sup&gt;π&lt;sup&gt;−&lt;/sup&gt; (ω \rightarrow π&lt;sup&gt;−&lt;/sup&gt;π&lt;sup&gt;−&lt;/sup&gt;π&lt;sup&gt;−&lt;/sup&gt;)</td>
<td>0.836 \pm 0.118</td>
<td>0.77 \pm 0.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>K&lt;sup&gt;0&lt;/sup&gt;&lt;sub&gt;S&lt;/sub&gt;π&lt;sup&gt;−&lt;/sup&gt;π&lt;sup&gt;−&lt;/sup&gt; (η \rightarrow π&lt;sup&gt;−&lt;/sup&gt;π&lt;sup&gt;−&lt;/sup&gt;π&lt;sup&gt;−&lt;/sup&gt;)</td>
<td>0.059 \pm 0.020</td>
<td>0.035 \pm 0.014</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eπ&lt;sup&gt;−&lt;/sup&gt;π&lt;sup&gt;−&lt;/sup&gt; (E \rightarrow K&lt;sup&gt;0&lt;/sup&gt;&lt;sub&gt;S&lt;/sub&gt;π&lt;sup&gt;−&lt;/sup&gt;π&lt;sup&gt;−&lt;/sup&gt;)</td>
<td>—</td>
<td>0.14 \pm 0.035</td>
<td></td>
<td></td>
</tr>
<tr>
<td>K&lt;sup&gt;0&lt;/sup&gt;&lt;sub&gt;S&lt;/sub&gt;π&lt;sup&gt;−&lt;/sup&gt;π&lt;sup&gt;−&lt;/sup&gt;</td>
<td>—</td>
<td>0.59 \pm 0.08</td>
<td>0.71 \pm 0.07</td>
<td></td>
</tr>
<tr>
<td>K&lt;sup&gt;0&lt;/sup&gt;&lt;sub&gt;S&lt;/sub&gt;π&lt;sup&gt;−&lt;/sup&gt;π&lt;sup&gt;−&lt;/sup&gt; (E \rightarrow K&lt;sup&gt;0&lt;/sup&gt;&lt;sub&gt;S&lt;/sub&gt;π&lt;sup&gt;−&lt;/sup&gt;π&lt;sup&gt;−&lt;/sup&gt;)</td>
<td>—</td>
<td>0.71 \pm 0.07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>K&lt;sup&gt;0&lt;/sup&gt;&lt;sub&gt;S&lt;/sub&gt;π&lt;sup&gt;−&lt;/sup&gt;π&lt;sup&gt;−&lt;/sup&gt; (E \rightarrow K&lt;sup&gt;0&lt;/sup&gt;&lt;sub&gt;S&lt;/sub&gt;π&lt;sup&gt;−&lt;/sup&gt;π&lt;sup&gt;−&lt;/sup&gt;)</td>
<td>—</td>
<td>0.10</td>
<td>0.10</td>
<td></td>
</tr>
</tbody>
</table>

* Column (a) refers to the experiment performed at Brookhaven by Baltay and co-workers. Values not quoted in the text are from Baruch (1968). Column (b) refers to the experiment performed at CERN by Armenteros and co-workers. Values not quoted in the text have been supplied by Montanari (1967).
b) Multiplicity

Very high multiplicity events are rather rare. These events cannot be produced directly by a simple rearrangement mechanism. High statistics can be collected in our case because of the large acceptances, the trigger facilities, and the high interaction rates that can be tolerated by the detector. Preference could be given to high-multiplicity reactions with kaons and charged pions and up to two $\gamma$'s in the final state, so as to minimize combinatorial backgrounds.

c) Charge

Subject to charge conservation, different combinations of charged plus neutral particles may occur at a given multiplicity. Thus when only pions are produced, the list of possible final states containing up to five pions is as shown in Table 2.8. Each final state has been subdivided into groupings of particles such as might appear if quasi-two-body intermediate states were the only contributors.

The determination of a final state with $n$ pions is easier if all the pions are charged. It is generally less difficult to measure the momentum of a charged track than the momentum of a $\pi^0$, since for the latter the directions and the energies of two $\gamma$-rays have to be measured. Also, in the case where several pions are present, whilst it is easy to pick up and reconstruct charged tracks, there is a combinatorial problem in uniquely assigning two $\gamma$'s to a $\pi^0$ which results in a non-negligible background under the signal.

The physics is determined by the relative number of charged and neutral pions. We will illustrate this remark with the example of two $\pi^0$'s in the final state and a $\pi^+$ and $\pi^-$. In the first case $C = P = +$, $I = 0$. For the second, $C = P = (-1)^1$, $I = 0,1$. This example shows clearly the advantages and limitations of each final state. Although $C$, $P$, $I$ quantum numbers are not restricted for the $\pi^+\pi^-$, the $\pi^0\pi^0$ final state can only occur with fixed $C$, $P$, and $I$. For instance, resonances decaying into $\pi^0\pi^0$ will also decay into $\pi^+\pi^-$; the reverse is not true (e.g. $\varphi^0 \rightarrow \pi^0\pi^0$). Nevertheless, if seen in $\pi^0\pi^0$, one had gone a long way towards determining the quantum numbers. The same is not true for $\pi^+\pi^-$. In the case of three pions there are two restrictions (advantages) which apply to the $3\pi^0$ final state: i) it cannot be in an $I = 0$ state; ii) the $(\pi^0\pi^0)$ cannot be in $I = 1$. Again no such limitations apply to $\pi^+\pi^-\pi^0$.

Table 2.8 shows that if forced to choose between a detector favouring column (a) or (b), one would pick column (b) if one is only interested in annihilation into pions.

Only the annihilation $p\bar{p} \rightarrow \pi^0 X^0 \rightarrow \pi^0 + (\pi^+\pi^-\pi^0)$ is, in principle, inaccessible to $p\bar{p} \rightarrow 2\pi^+2\pi^-$. 
Table 2.8
Final states containing up to five pions

<table>
<thead>
<tr>
<th>a)</th>
<th>b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^0\pi^0$</td>
<td>$\pi^+\pi^-$</td>
</tr>
<tr>
<td>$\pi^-\pi^+\pi^0$</td>
<td>$\pi^-\pi^0$</td>
</tr>
<tr>
<td>$\pi^0\pi^0\pi^0$</td>
<td>$\pi^0(\pi^0\pi^0)$</td>
</tr>
<tr>
<td>$\pi^+(\pi^-\pi^0\pi^0)$</td>
<td>$\pi^0(\pi^-\pi^0)$</td>
</tr>
<tr>
<td>$\pi^0(\pi^+\pi^-\pi^0\pi^0)$</td>
<td>$\pi^0(\pi^-\pi^-\pi^-\pi^-)$</td>
</tr>
<tr>
<td>$\pi^+(\pi^-\pi^0\pi^0\pi^0)$</td>
<td>$\pi^+(\pi^-\pi^0\pi^0\pi^0)$</td>
</tr>
<tr>
<td>$\pi^+(\pi^-\pi^0\pi^0\pi^0)$</td>
<td>$\pi^+(\pi^-\pi^-\pi^-\pi^-)$</td>
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<td>$\pi^+(\pi^-\pi^0\pi^0\pi^0)$</td>
<td>$\pi^+(\pi^-\pi^0\pi^0\pi^0)$</td>
</tr>
<tr>
<td>$\pi^+(\pi^-\pi^0\pi^0\pi^0)$</td>
<td>$\pi^+(\pi^-\pi^-\pi^-\pi^-)$</td>
</tr>
</tbody>
</table>
There are, however, final states of undoubted interest, such as $\pi^+\pi^-\eta^0$; or, more generally, final states in which, besides the $\eta^0$, there is a particle not having an important decay mode into charged particles only. These can be detected only if the detector has good $\gamma$-ray detection efficiency.

2.2.2 Resonances and bound states

In this section we want simply to stress the point that resonances and bound states expected in several $NN$ interaction models are narrow and detectable, and are predicted mostly near threshold. We will study the region above threshold in detail with the $\bar{n}$ beam and with low-momentum $\bar{p}$, and a thin (gas) target that does not spoil the beam momentum definition. The region below threshold is explored in very great detail in the general annihilation studies; but it is also quickly scanned inclusively with good energy resolution and going very near threshold by measuring down to 30 MeV/c the momentum of the spectator proton in annihilations with neutrons in a $D_2$ target.

2.2.3 Real and virtual annihilation effects in protonium spectroscopy

The sum over all possible real annihilation channels in a given $(L,S)$ atomic level of protonium determines the hadronic width of the level. The total width is affected also by the probability of radiative transition to the lower atomic levels. The sum over all virtual annihilation channels in a given $(L,S)$ atomic level contributes to the hadronic shift of that level. Further contributions to the shift come from other non-virtual annihilation terms of the real part of the strong interaction potential such as virtual elastic scattering and charge exchange. Strong interactions perturb the QED potential governing the protonium spectrum. Such QED terms can be calculated precisely, and when theory will be well in control of the technology of the calculation of strong interaction effects, precise predictions for different $J^{PC}$ states can be made and experimentally checked.

Potential model approaches of protonium spectroscopy give the orders of magnitude of the effects:

- shift and width of $^1S$ and $^3S_1$: 0.2-1 keV
- shift and width of $^3P_2$, $^3P_1$, $^3P_0$, and $^1P_1$: 10-100 meV

[see, for example, (RIG 82)].

Measurements of X-rays (AST 85) emitted by protonium atoms that subsequently annihilate into only neutral particles have shown that the $^1S$ level is
shifted upwards by 0.5 keV. The signal is quite clear (11 st. dev.) but the data for the resolution do not permit investigation of the line structure.

Measurements in coincidence with a \( \pi^+ \pi^- \) final state could single out the \( ^3S_1 \) line, but this would mean a factor of \( 10^2 \) more in data-taking; also internal bremsstrahlung background is present in this final state.

It has also been seen that annihilation plays a dominant role in the 2P level (AST 85). However, with the resolution of present detectors it is hopeless to investigate its detailed structure.

We propose to complete the preparatory work necessary to realize the scheme shown in Fig. 2.15. If all practical conditions and theoretical calculations for protonium formation and \( \bar{H}^- \) stripping (ERA 79; FIO 83; COH 85) are confirmed experimentally, this will permit us to gain orders of magnitude in energy resolution and to start high-accuracy protonium spectroscopy.

The scheme foresees the formation of \( \bar{p}p \) atoms in flight, operating with the \( \bar{p}H^- \) co-rotating beams (GAS 77; GAS 82; MGH 85). This should simultaneously provide \( 10^2 \) to \( 10^5 \) \( \bar{p}p \) atoms per second with momentum dispersion of \( 10^{-3} \) to \( 10^{-5} \) depending on the cooling used in LEAR. These \( \bar{p}p \) neutral beams would emerge from the LEAR straight sections together with beams of \( H^0 \) atoms of typically 100 times higher intensity.

By combining K-edge differential absorbers with a large position-sensitive X-ray detector and exploiting the dependence of the Doppler shift both on the velocity of the (\( \bar{p}p \) atom) source and on the emission angle (SCH 74), protonium K-, L-, and M-line emission spectroscopy with an eventual energy resolution down to \( 10^{-5} \) appears possible. Indeed, resonant spectroscopy on one \( H^0 \) beam (DON 81) should permit the average \( H^0 \) velocity (and thus the average \( \bar{p}p \) atom velocity) to be measured to far better than \( 10^{-5} \) (COC 85). The K-edge of many elements is known to better than \( 10^{-5} \) (and noble gases used in the X-ray detector could also be used as differential absorbers) and the sensitivity to the angular dependence of the Doppler effect can be better than \( 10^{-5} \), with a 500 \( \mu \)m resolution on the radius of the annihilation vertex and of the X-ray absorption point.

Collinear laser spectroscopy on one \( \bar{p}p \) atomic beam is conceivable. Monitoring of the resonant frequency can be done for transitions between levels with different principal quantum numbers by dissociation due to motional electric field when traversing a static magnetic field (BRY 83) of the \( \bar{p}p \) atom in the excited \( n \) state, and by observing variations in the \( \bar{p}p \) atomic cascade when a resonant transition is made between levels of same \( n \).

Conceptually the main point of the scheme -- besides the huge increase in energy resolution -- is the possibility to compare the spectroscopy of \( \bar{p}p \) and \( \text{pe}^- \) atoms directly.
The energy resolution in this scheme is controlled by \((q_p/p)_{\text{LEAR}}\). A momentum resolution of \(q_p/p = 10^{-4}\) in LEAR results for the \(L\) transition (E ~ 2 keV), for \(\beta = 0.3\), in a resolution of 30 meV. This would make it possible to start the study of the 2\(P\) level structure, and \(q_p/p = 10^{-5}\) is possible with better cooling of the \(\bar{p}\) beam. The absolute accuracy of the measurements is limited by the accuracy on the \(\bar{p}p\) atom velocity. This is measured by the laser spectroscopy of the \(H^0\) beam (COH 85).

2.3 Antinucleon annihilations on nuclei

2.3.1 Quark-gluon picture of nuclear matter

Traditionally, the nucleus is regarded as a collection of relatively weakly bound nucleons. Thus the main characteristics of a nucleus can be attributed to two-body forces, described by the exchange of bosons. Such a picture holds until one probes interaction distances down to 1 fm, and is based on the vast amount of data accumulated in the last decades on the study of the nuclear structure. At shorter interaction distances, within the range of nuclear repulsion causing saturation, new phenomena arise that require new ideas for their explanation.

Recent attempts to describe the short-range region of the NN (NN) interaction apply quark models or quark bag models. In these cases the nuclei are considered as being built up of bags of quarks which, owing to the quark confinement, behave at large distances (> 1 fm) as baryons interacting in a conventional way by the exchange of bosons. At shorter distances (< 1 fm), the bags overlap and fuse to form bags of six (or more) quarks, and their interaction is due to quark and gluon exchanges. For example, the probability for quarks to cluster in nuclear matter and to form bags of three, six, and more quarks has been calculated for the \(^3\)He nucleus (FIR 81), and it turns out that three-quark bags (nucleons), 0.45 fm in radius, are formed with 83% probability, and that they fuse to form six- and nine-quark bags with 16% and 1% probabilities, respectively. In the case of \(^2\)H, the six-quark bag probability has been evaluated to be about 10% (KAL 84). These values indicate that quarks must be taken into account in order to reach valid conclusions when considering nuclear phenomena that involve short-range baryon interactions.

The increasing amount of data supporting the quark-gluon picture of the hadron structure seems to be rapidly leading to a new understanding of nuclear matter. Deep-inelastic scattering experiments probe the individual nucleons in a nucleus and have already revealed a difference in structure between free and bound nucleons: the EMC effect. Experiments involving annihilation of low-energy \(\bar{p}\) may instead yield information on the collective quark-gluon structure of nuclei. Moreover, because of the large energy being deposited inside the nucleus in a \(\bar{p}\) annihilation, highly excited nuclear states and even a new phase of hadronic matter could be formed and show up in the laboratory.
2.3.2 Antinucleon annihilations to show evidence of quark-gluon aspects of nuclear matter

There exists a class of \( \bar{p}A \) reactions which are forbidden unless one assumes that they involve more than one nucleon bound in the nucleus. Momentum conservation requires that the number of pions produced in a \( \bar{p}N \) annihilation process is greater than or equal to two. In the annihilation of an \( \bar{p} \) on a free nucleon, a single pion cannot be created. On the other hand, when annihilation occurs on a nucleus, reactions such as: \( \bar{p}A \to \pi(A-1)N \) are no longer forbidden. One-pion annihilation was observed (BIZ 69) in a deuterium bubble chamber, in which six cases of the reaction \( \bar{p}d \to \pi^- \) were registered. The probability for this reaction to take place amounted to \((0.9 \pm 0.4) \times 10^{-5}\) of the total number of \( \bar{p}d \) annihilation events. One can assume that there are two different quark mechanisms for the reaction \( \bar{p}d \to \pi^- \): a) the annihilation of two \( q\bar{q} \) pairs; and b) the annihilation of three \( q\bar{q} \) pairs and production of one \( q\bar{q} \) pair (see Figs. 2.9a and 2.9b).

In two-meson annihilation of the \( \bar{p}p \) system the rearrangement mechanism is very important (see Fig. 2.10a), and the contribution of the diagram with the annihilation of two \( q\bar{q} \) pairs (see Fig. 2.10b) is comparably small. We expect the same hierarchy for the mechanism of Figs. 2.9a and 2.9b, i.e. that the quark rearrangement mechanism of Fig. 2.9a will be dominant. At the same time the absolute value of the cross-section for the reaction \( \bar{p}d \to \pi^- \) as well as for the cross-section of the reaction \( \bar{p}(NN) \to \pi^- \) on two-nucleon clusters in nuclei will be dependent on the admixture of six-quark bags in nuclear wave functions. In terms of conventional nuclear physics the reaction \( \bar{p}(NN) \to \pi^- \) is crucially dependent on the probability of finding two nucleons at small internucleon distances. Estimates of the corresponding cross-sections were made by Iljinov et al. (ILJ 82). Obviously, for a process such as this to occur, two nucleons must be correlated at a small distance from each other. Therefore, investigation of this reaction will make it possible to obtain valuable information on the quark degree of freedom of the nucleus. The energy released in the reaction, \( Q = 2m_N - m_p = 1.74 \) GeV, is shared between the pion and the nucleon according to energy-momentum conservation. The secondary particles are emitted in opposite directions \((\theta_q, \theta_p = 180^\circ)\), (see Fig. 2.11). In the experimental study of the two-nucleon \( \bar{p}A \) absorption, the reaction \( \bar{p}(np) \to \pi^- \) is easy to detect and to trigger upon. To estimate its cross-section, one can use a 'quasi-deuteron' model as a zero approximation. This model has been developed to describe the two-nucleon absorption of pions by nuclei: \( \pi(NN) \to NN \). Within this model the \( \bar{p}NN \) absorption cross-section in a nucleus may be related to that of the similar reaction in deuterium: \( q_d(\pi^-) = \sigma_d(\bar{p}) \cdot (\sigma_d(\pi^-)) \). Data on \( q_d \) have been obtained in bubble chambers and from experimental cross-section values of the inverse reaction...
\( \pi^+ p \rightarrow d\pi^- \) using detailed balance. The cross-section of the reaction is likely to increase with the mass number of the nucleus target, since the relative weight of quasi-deuteron pairs (a six-quark bag) in medium and heavy nuclei exceeds their weight in deuteron by 10-100 times. In particular, at \( E_p = 175 \text{ MeV} \) (600 MeV/c), the momenta of the proton and pion emitted in the \( pd \rightarrow pn\pi^- \) reaction are about 1.2 GeV/c and 1.12 GeV/c, respectively. The total cross-section is \( \sigma_d \approx 3 \mu\text{b} \). It is possible to assume that the dependence of the cross-section on the mass number of the nucleus has a behaviour similar to that of the two-nucleon absorption of pions, if both \((\pi\Lambda)\) and \((\bar{p}\Lambda)\) absorption occurs in the same nuclear density region (inside the nucleus). This condition is fulfilled for \( E_\pi \approx 250 \text{ MeV} \), where \( \sigma_{\bar{p}N}(175 \text{ MeV}) - \sigma_{\bar{p}N}(250 \text{ MeV}) \approx 100 \mu\text{b} \). In this case the empirical behaviour has the form \( \sigma = 3A^{1/3} \sigma_d \), and consequently \( \sigma_{\bar{p}He} \approx 100 \mu\text{b} \).

The large value of \( Q \) released in the absorption results in a small value of the specific distance \( r_{abs}^T \approx 1/m_n^2 \approx 0.2 \text{ fm} \). Therefore, the study of two-nucleon absorption can give information about the NN correlations at distances shorter than those studied by means of the two-nucleon absorption of pions, where \( r_{abs}^T \approx 1/m_N m \approx 0.6 \text{ fm} \). At such a distance the effects of quark structure may contribute essentially.

In the \( \bar{p}\Lambda \) annihilation, processes are also possible in which no mesons at all are produced: \( \bar{p}\Lambda \rightarrow p(A-2)N \) (PON 56). An example of such a reaction is \( \bar{p}^3\text{He} \rightarrow pn \). One can imagine that the mesonless annihilation proceeds through the annihilation of two quarks belonging to one of the nucleons \( N_1 \), and another quark from a second nucleon \( N_2 \). The spectator nucleon \( N_2 \) takes the missing momentum (\( \approx 1.7 \text{ GeV/c} \)), see Fig. 2.12. The experimental signature of such events is unique and requires the best performance of our apparatus in order to identify and measure the outgoing \( p \).

An interesting feature of \( \bar{p} \) annihilation at rest is that there is the possibility to perform a detailed study of the absorption of mesons and of pionic resonances produced on the surface of the nucleus from correlated nucleons (ITJ 82). Such processes would result in the emission of a pair of correlated nucleons with opening angles of about 180° (see Fig. 2.13) and energies depending on the relevant process \( E_N \rightarrow m_\pi/2 \) in the case of pion absorption, and \( m_\eta/2 \approx 300 \text{ MeV} \) (800 MeV/c) or \( m_\omega/2 \approx 400 \text{ MeV} \) (950 MeV/c) if \( \eta \) or \( \omega \) mesons are absorbed, respectively. Since the \( \varphi \) meson has a very large decay width (\( \Gamma_\varphi = 158 \text{ MeV} \)) and a correspondingly small lifetime (\( \tau_\varphi = 4 \times 10^{-24} \text{ s} \)), it will decay into two pions before having time to interact with the nucleons of the nucleus. The respective quantities for the \( \omega \) and \( \eta \) mesons are the following: \( \Gamma_\omega = 10.1 \text{ MeV} \), \( \tau_\omega = 7 \times 10^{-23} \text{ s} \), and \( \Gamma_\eta = 0.85 \text{ keV} \), \( \tau_\eta = 8 \times 10^{-19} \text{ s} \). The study of such two-nucleon absorption processes will permit the investigation of very short range nuclear correlations, since the momenta of the nucleons produced in
the reaction determine the size of the interaction region: \( r_{abs}^F \sim 1/fm, m_N \sim 0.6 \text{ fm, } r_{abs}^K \sim 0.5 \text{ fm, } r_{abs}^\pi \sim 0.3 \text{ fm, } r_{abs}^\gamma \sim 0.2 \text{ fm.} \)

2.3.3 **Highly excited states of nuclear matter via \( \bar{p} \) annihilations inside nuclei**

It is of the greatest interest to know whether a quark-gluon plasma (quagma) can be created and recognized as such in laboratory experiments. There is evidence that quarks in ordinary nuclei are deconfined at least partially. Tunnelling of quarks from one nucleon to another could cause correlations and clustering in nuclei. For example, in the phenomenological bag model, quarks are assumed to be confined within the nucleon radius \( R \). When the internuclear spacing becomes shorter than \( 2R \), the bags interpenetrate and their constituents form multiquark clusters; partial deconfinement then occurs. The existence of these multiquark clusters may increase the probability of forming droplets of quagma during annihilation of antiprotons in nuclei.

The excitation and decay of the portions of nuclear volume where annihilation occurs (fireballs) with baryon number \( b \gtrsim 1 \), that is, containing more than one nucleon, might favour the formation of quagma in a nucleus. These conditions may be achieved by annihilation of \( \bar{p} \) penetrating deeply into a complex nucleus, where the fireball may coalesce with neighbouring nucleons.

The streamer chamber experiment at LEAR has shown that there is the possibility of distinguishing between \( \bar{p} \) annihilations occurring at the surface of the nucleus and those occurring deep inside its volume, by measuring the multiplicities and the geometry of the annihilation products and nuclear fragments (STR 85a,b,c). See Figs. 2.14 and 2.15. With OBEIX it will be possible to exploit these features at the trigger level.

The study of the production of hadronic matter in a quark-gluon phase is a difficult task. It is common opinion that enhancements in hyperon and strangeness production could be typical signatures of quagma. If the probability of quagma production were not small, we would expect to find a clear signal comparing single-particle spectra, \( K/\pi, \Lambda/K, \Lambda/p \), for heavy and light nuclei. In order to show clearly a signal, events corresponding to annihilation of antiprotons deep inside nuclei should be compared with surface annihilations. Another possibility is to measure the spectra of strange particles in coincidence with high-momentum spectator protons.
When comparing data of different annihilation types, an excess in the amount of strange particles is a sign of interesting effects. For example, in $p\bar{p}$ annihilation at rest, a $\Lambda\bar{\Lambda}$ pair cannot be created, because of energy conservation (the minimum c.m. energy for the $\Lambda\bar{\Lambda}$ system is 2231.2 MeV). However, when low-energy $\bar{p}$ annihilate in nuclei, $\Lambda$-particle production is possible. Below 1 GeV/c the reaction $\bar{p}d + \Lambda + X$ seems to be consistent with a double-scattering mechanism (MAN 83) in which a $K^-$ is exchanged (see Fig. 2.16). On the other hand, studying the same reaction at rest (BIZ 69), other authors have shown that a large fraction of these events cannot be described by $K^-$ rescattering, but have to be considered as three-body annihilations (CUJG 84). The $\Lambda$ emission probability for $\bar{p}$ stopping in deuterium is $P_\Lambda \approx 3.6 \times 10^{-3}$ of the annihilation events (BIZ 69). This value decreases, with the increase of $\bar{p}$ energy, down to $P_\Lambda \approx 2.5 \times 10^{-3}$, near the threshold of $\Lambda\Lambda$ pair production. Afterwards, $P_\Lambda$ increases with energy. In deuterium, the $K^0_S$ emission probability is higher ($P_{K^0_S} \approx 16 \times 10^{-3}$) than that of $\Lambda$ production (BIZ 69; OH 73).

In the case of complex nuclei (C, Ti, Ta, Pb), the absorption of low-momentum $\bar{p}$ ($\lesssim 300$ MeV/c) was found (CON 84) to produce $\Lambda$ hyperons with a frequency $P_\Lambda = (19 \pm 4) \times 10^{-3}$, which is about five times that in deuterium. In this low-statistics experiment (CON 84), the $K^0_S$ emission has not been measured. The reaction $\bar{p}^{181}_{\text{Ta}} + \bar{p}K^0_S + X$ ($\bar{p} = \Lambda, \bar{\Lambda}$, or $K^0_S$) at 4 GeV/c has been studied (MIY 84) with good statistics, and a strong enhancement of $\Lambda$ production was observed. The $K^0_S$ production is less frequent ($P_{K^0_S} = 50 \times 10^{-3}$) than that of $\Lambda$'s ($P_\Lambda = 118 \times 10^{-3}$). The opposite of what occurs in the case of deuterium. Preliminary data from the streamer chamber experiment with neon (STR 85c) show that, at 600 MeV/c, $P_\Lambda \sim 2 \times 10^{-3}$ and $P_\Lambda > P_{K^0_S}$. In these two experiments the $\Lambda$ and $K^0_S$ rapidity distributions agree, and show that ($p, 13N$) and ($p, 3N$) systems in the c.m.s. are involved respectively in their production. These hot clusters emit the $\Lambda$ and $K^0_S$ particles equally into the forward and backward hemispheres in their ($p, 13N$) c.m. frames, with an evaporation-like mechanism (MIY 84), but at temperatures not high enough to induce a phase transition to quagma (SHU 80). On the other hand, this kind of mechanism is somewhat questionable because the time required for the particle emission is much smaller than that needed for the statistical decay of a thermalized source. In fact the nucleons in the $\bar{p}$ absorption process cannot reach statistical equilibrium in a very short time (reaction time). An isotropic angular distribution of the reaction products (MIY 84) does not necessarily correspond to a slow evaporation-like emission, but may be compatible with an explosion-like decay of a hot spot. Hence the study of $\Lambda$ and $K^0_S$ emission and the measurement of the $K^0_S/\Lambda$ ratio ($> 1$ for deuterium and $< 1$ for heavier nuclei) for the $\bar{p}$ annihilation in $A \sim 13N$ and $A \gg 13N$ nuclei is of great interest for understanding the properties of highly excited nuclear matter.
in order to discover whether quark degrees of freedom of the fireball come into play and to see whether resonant states are formed.

In the last years, there have been predictions about $\bar{p}$ annihilations on nuclei, based on the assumption that the basic mechanism is the point-like annihilation of the impinging $\bar{p}$ with a single nucleon, producing pions (as in free space), each of which initiates a cascade inside the nucleus. A specific intranuclear cascade (INC) calculation (CUG 85), performed to fit neon multiplicity data, gives a lower mean multiplicity (6.0 against the experimental value $6.67 \pm 0.24$ at 600 MeV/c) and no correlation between high multiplicity and deep annihilation. However, the calculation was based on an INC model, which was interpreted as a strict spallation model, and low-energy nucleons were neglected. On the basis of preliminary calculations the authors suggest that other fragmentation mechanisms, such as evaporation or percolation, should be considered. In these fragmentation models the number of emitted nucleons is very close to the number of excited ones, which in turn is correlated to the depth of the annihilation point. At present it is not clear whether this disagreement is due to exotic phenomena or to the inadequacy of the theories when dealing with multifragmentation, that is when deriving the number of emitted nuclear fragments from the number of excited nucleons.

Streamer chamber charged-particle multiplicity data show that the $\bar{p}$ interaction is dominated by surface annihilations on quasi-free nucleons with a small, but not negligible, percentage of deep annihilations. The detection of deep annihilations is of interest, because theoretical works predict that they might develop through mechanisms such as the annihilations on more than one nucleon (CUG 84; DER 85) with excitation of new degrees of freedom of the nuclear matter (RAF 80, 82; PHA 83). These mechanisms are different from those included in the standard physics of the INC models. Signatures of these exotic phenomena could be the enhancements in hyperon and strange-meson production and the emission of a large number of energetic nuclear fragments. In particular, the calculations were aimed at describing the background on which, hopefully, would be superimposed signals of more exotic processes. Such a possibility was put forward some years ago (RAF 82), with the suggestion of a picture of the growing of large quark bags. If such an extended quark-gluonic blob is formed, the production of strange mesons would be enhanced (RAF 80, 82). It was noted that $K\bar{K}$ production in the annihilation on deuterium is experimentally correlated to a large spectator high-momentum tail and that this process is possible in the model with new degrees of freedom for nuclear matter (RAF 82). Consequently, in
order to observe a quark blob, a strangeness trigger should be used and the momentum distribution of high-momentum spectator protons should be looked at. Indeed, such an experiment has been carried out in deuterium. In $\bar{p}d$ annihilation in flight containing a $K\bar{K}$ pair, a long tail in the momentum distribution of the spectator proton has been observed (OH 73). When analysing the momentum distribution of protons emerging from $\bar{p}d + pK\bar{K} \rightarrow n's$ reactions, the spectator proton behaviour below 0.2 GeV/c fits well the expectations based on a standard d-wave function, whilst a thermal distribution seems to exist above 0.2 GeV/c. This behaviour seems to occur only in the channel containing a kaon pair. This effect could be interpreted as an annihilation reaction where the observed proton is a constituent of the hadronic fireball rather than a simple spectator. Thus a first signal for the annihilation on two nucleons could have been seen in $\bar{p}d$, and it would be of great interest to see if a similar effect would occur in $\bar{p}A$ annihilations. Here, in particular, a 4$\pi$ geometry is of great help in selecting events in which all remaining nucleons share the annihilation energy. Simultaneous enhancement of the strangeness yield would give confirmation of the arguments presented.

Annihilations inside nuclei of $b > 1$ fireballs are quite probable also in other models (CUG 84) that predict enhancement of the strangeness production, compared with free $NN$ annihilations, considering a conventional hadronic phase. In the high-energy tail of the nucleon spectrum this last model predicts, for $b = 1$, protons with a temperature of $T = 110$ MeV, whilst the former model (NUE 85) predicts a $T = 160$ MeV slope in the case of quarka formation.

2.3.4 Multiquark resonances

OBELIX will make possible the search for $\bar{p}n$ and $p\bar{p}$ systems in pick-up reactions such as

$$\bar{p}^2H \rightarrow (\bar{p}n)p,$$

$$\bar{p}^4He \rightarrow (\bar{p}n)^3He,$$

$$\bar{p}^4He \rightarrow (pp)^3H,$$ etc.

The experiment consists simply in measuring the energy spectrum and the angular distribution of the recoil proton, triton, or $^3He$ nucleus, and looking for a peak in the energy spectrum which would point to the formation of $\bar{p}N$ states with isospin equal to 0 or 1.

It will also be possible to study reactions such as $\bar{p}A \rightarrow \Lambda \Lambda + KK + X$ ($A \geq 3$). In the framework of the MIT bag model it was predicted (JAF 77) that there should exist the H dihyperon with a mass of 80 MeV below the $\Lambda\Lambda$ threshold ($m_H = 2.15$ GeV). The existence of the H particle would give clear evidence of the quark degrees of freedom in nuclei. It would be the simplest configuration of six quarks (2s, 2u, 2d), all in relative S states, in a colour singlet. It
would be the analogue of the $\alpha$ particle in traditional nuclear physics. Recently, the possible existence of the $H$ particle has been invoked (BAY 85; KHR 85) in order to explain the experimental data coming from the pulsar Cygnus X-3. However, there are very big theoretical uncertainties concerning the prediction of $m_H$. In some models it is predicted to lie above the $AA$ threshold. For example, in the quark model with a non-universal bag constant $B$, $m_H$ is predicted to be 150-200 MeV above the $AA$ threshold (2.23 GeV) (L.A. Kondratyuk et al, private communication). With OBELIX it is also possible to look for a $AA$ resonance above the $AA$ threshold. Searches for the double $A$ events in the reaction $\bar{p}A + AA + X$ with a low-intensity beam have given an upper limit of $\gamma \leq (4.5) \times 10^{-4}$ (CON 84). The existence of the $H$ particle and the measurement of its mass are crucial for many quark models and for hadron physics in general.

Owing to the high efficiency of OBELIX for detecting slow protons and mesons, it will also be possible to study the production of low-energy dibaryon resonances. Recently, several experimental groups observed narrow structures in pp mass spectra when investigating the reactions np + (pp) + X, pA + (pp) + X, and πA + (pp) + X. Proton-proton resonances were reported (KVA 84) with masses of 1.96, 2.02, and 2.14 GeV. However, the statistics of these data are not high enough and confirmation is needed. There are also interesting predictions, in the framework of the quark model, on the possible existence of dibaryon resonances with quantum numbers $I = 0$, $J^P = 0^+$ and $J^P = 2^-$. Such resonances cannot decay into np, and because their main decay channel is $\pi NN$ they could be rather narrow. These resonances were first discussed in the framework of a stretched rotating bag model (MUL 80) and the mass was predicted to be 2.11 GeV. Taking also into account the spin-orbit interaction it has been calculated that the lowest state should be $d'$ ($2^-$ with a mass of 2.05 GeV). For two other states of this family, the expectation is $m = 2.09$ GeV for $d'' (2^-)$ and 2.13 GeV for $d''' (0^-)$. The $d'$ ($2^-$) state would then be very near the $\pi NN$ threshold and presumably it could be very narrow (2-5 MeV). It is possible to search for this $d$-state in the $\pi^* pp$ invariant mass spectrum in the reaction $\bar{p}A + (\pi^* pp) + X$.

A thorough investigation of low-energy $\bar{p}$ annihilation on various nuclei, which could provide information as to whether the antinucleon interaction with a nucleus is of a collective nature and whether new states of matter can be produced, requires much higher statistics than are so far available, together with reliable detection and identification of all emitted particles (including kaons and gammas) as well as the possibility of studying rare channels. OBELIX will detect all $NN$ annihilation products, and its central detector will provide
nearly the same kind of information on nuclear fragments as that available from streamer chamber experiments, but with an enormous increase in statistics and trigger possibilities.

2.3.5 Reaction channels and rates

In view of the motivations mentioned above, our plans are to proceed with the following studies:

i) General survey of $\bar{p}$ annihilation

We intend to study the multiplicity distribution and energy spectra of the emitted particles and fragments as a function of the mass number $A$ and of the $\bar{p}$ momenta. The nuclear targets will be $^2$H, $^3$He, $^4$He, Ne, Ar, Kr, Xe; the $\bar{p}$ beam momenta will be three, chosen in the regions: 100-200 MeV/c, 400-600 MeV/c, 1000-2000 MeV/c. The event rate is higher than one event per $10^3 \bar{p}$, and about $10^5$ events per nucleus and per energy are needed.

ii) Pionless annihilation: $\bar{p}A \to p(A-2)N$

We will search for evidence of the reaction $^3$He + pn. The rate is estimated to be one event per $10^5 - 10^6 \bar{p}$ annihilations; the trigger is given by a proton of high momentum (1.7 GeV/c).

iii) Single-pion annihilation: $\bar{p}A \to \pi(A-1)N$

We will look for $^2$H + pn (a$_d$ = 3 µb at 600 MeV/c, at rest about one event per $10^5 \bar{p}$ annihilations) and also the quasi-deuteron $\bar{p}$ absorption in the nuclei, $\bar{p}(NN) \to \pi N$, with one pion and one nucleon in the final state and with high momentum (about 1.2 GeV/c). For neon the cross-section has been estimated to be about 100 µb at 600 MeV.

iv) Quasi-deuteron absorption of $\omega$ or $n$ produced in $\bar{p}$ annihilation at rest on the surface of nuclei: $\bar{p}A \to (NN)\pi$

Two nucleons are emitted nearly back-to-back at high momentum (~ 800 MeV/c for $n$ absorption and ~ 950 MeV/c for $\omega$ absorption). The rate is estimated to be $10^{-4} - 10^{-5}$ per $\bar{p}$ annihilation for nucleons emitted with energy higher than 200 MeV.

v) $\Lambda$ and $K_S^0$ production: $\bar{p}A \to V^0 X$ ($V^0 = \Lambda$, $\bar{\Lambda}$ or $K_S^0$)

This search will exploit the capability of the detector to trigger on $V^0$ topologies (efficiency > 30%). The rate of $\Lambda$ production in light nuclei is about $0.36 \times 10^{-2}$ $\bar{p}$ annihilations at rest and ~ $2 \times 10^{-2}$ $\bar{p}$ annihilations for the heavier nuclei. The $K_S^0$ production in light nuclei is higher than that of $\Lambda$'s, the opposite in heavier nuclei.

vi) Search for multiquark resonances:

$\bar{p}^2$H + (pn)p, $\bar{p}^2$He + (pn)$^3$He, $\bar{p}^4$He + (pp)$^3$H.
These reactions have a cross-section lower by a factor of 10 than those induced by protons.

vii) \( \bar{p}A + AA \rightarrow KK + X \) \((A \geq 3)\).

In the search for bound (N particle) or unbound \( AA \) states, the trigger could be given by an \( S = 2 \) trigger (two \( K^+ \) or a \( X^0K^0 \)) for the bound states, with a further condition for triggering on the decay of the two \( \Lambda \)'s when searching for unbound states.
3. **THE DETECTOR**

3.1 **General layout**

The general layout of OBELIX is shown in Fig. 1.1 and 1.2. The three projected views of the apparatus are shown in Figs. 3.1 to 3.3. Moving out from the centre of the detector, one finds the following components:

- a target (H₂, D₂, or other gas);
- a spiral projection chamber (SPC) [imaging vertex detector with three-dimensional readout for charged tracks and X-rays, similar to the ASTERIX central detector (AST 80; GAS 78, 81, 86)];
- a thin layer of 30 time-of-flight scintillators (TOF);
- AFS jet drift chamber (pictorial drift chamber from the CERN experiment R807, with large-size (Ø ~ 1.6 m), high resolution (σ ~ 200 µm), three-dimensional readout, and dE/dx measurements with up to 42 points per track (AFS 78-82));
- a layer of 90 time-of-flight scintillators (TOF);
- a high angular resolution gamma detector (HARGD) (four moduli made of layers of 3 x 4 m² converter foils enclosed by planes of drift tubes parallel to the beam axis, and of limited streamer tubes in the transverse direction); the tubes come from the CHARM I experiment (CHA 78-83);
- two high-density spiral projection chambers (HDSPCs) (GAS 85b) are positioned upstream and downstream of the vertex detector inside the AFS jet chambers; they complete the solid angle for gamma and prong detection in the end-caps.

The detector components are installed between and around the poles of the Open Axial Field Magnet (OAFM). The proposed configuration permits charged particles to be detected over ~ 4π and to have high-resolution momentum, dE/dx, and TOF over > 2π (with the SPC + AFS jet chambers and the scintillators) owing to the large size of the volume instrumented in the radial direction. Gamma detection is made over nearly 4π with high efficiency and granularity, excellent angular resolution, and three-dimensional reconstruction of the showers. The overall geometry makes it possible to have easy access to the internal components, and good light collection for the TOF scintillators in the magnet cones where the magnetic field is low, and not to have the SPC and AFS jet chamber structural components and front-end electronics in front of the gamma detectors.

3.2 **Design criteria**

We propose a complete large-acceptance and high-resolution spectrometer, relying on the availability of the drift chambers and of the magnet of the AFS spectrometer, and of the drift and streamer tubes from CHARM I.

We have optimized the detection of charged particles (very low momentum threshold, high momentum resolution, both in modulus and in direction; complete imaging of prongs over 97% of the full solid angle with a very high number of
points per track -- from > 20 points per track in the end-caps to 80 points for tracks traversing the HARGD -- so as to be able to observe decays in flight.

We will identify charged particles by $dE/dx$ and TOF in the region away from the magnet axis, and by $dE/dx$ and range in the end-caps.

Our TOF measurement with two layers of scintillators is autonomous (it does not rely on the measurement or the calculation of the annihilation time, and it is not contaminated by decays of particles in flight). This feature is essential to $ar{n}$ physics as it allows the $ar{n}$ momentum to be measured in conjunction with the measurement of the time when the $\bar{p}$ entered the charge-exchange production target. TOF scintillators are necessary in connection with gas targets and drift chambers in order to measure the absolute drift-time directly and to provide a fast-multiplicity trigger in annihilation at rest. The TOF enables identification of charged kaons up to 1 GeV/c and of protons from annihilations in nuclei up to 1.7 GeV/c. The central detector measures nearly all nuclear fragments and recoil protons.

The large detector size imposed by the need for good K/\pi identification and momentum measurement makes it prohibitively expensive to have a gamma detector with high energy and high angular resolution. By taking advantage of the availability of the CHARM I tubes, we have designed a $\gamma$ calorimeter with excellent angular resolution and very high segmentation, both longitudinal and transverse. Consequently, our $\gamma$ detector features very good $\gamma$ identification and $\gamma/\pi^0$ discrimination, and little confusion in high-multiplicity events. We will then have very high energy resolution for $\pi^0$'s in events with only one $\pi^0$ and very high energy resolution for single $\gamma$'s converting in the layer of tof scintillators with $e^+e^-$ conversion pairs well measured in the AFS jet chamber.

The solid-angle coverage for protonium X-rays is about 90%.

The energy resolution for protonium spectroscopy with the $\bar{p}H^+$ co-rotating beam option is $(A_p/p)_{LEAN} \leq 10^{-3}$.

3.3 Detector components

3.3.1 The magnet

The Axial Field Magnet (Figs. 3.4 and 3.5) provides a large unobstructed volume ($L = 1.5$ m; 2.5 m distance from beam axis to bottom yoke) with a central field of 0.5 T. The side access to this volume is completely free. Conical holes inside the two poles with 15° angle to the beam leave, upstream and downstream of the poles, an aperture with $\theta = 48$ cm through which can be inserted the SPC plus the two end-cap HDSPCs. The photomultipliers of the inner tof array can be operated in the low field of the cones.

The coils are made of copper, and the total power consumption is 0.7 MW. The magnet is operated with either polarity at a single nominal field level.
Over the volume of the drift chamber the field is azimuthally symmetric to better than 1%, and the field component transverse to the trajectory of the particles, integrated over the radial dimension of the drift chamber, is approximately constant for polar angles in the range $45^\circ < \theta < 135^\circ$ (see Fig. 3.6). As a consequence, within $\Omega/4\pi = 70\%$ a constant momentum resolution is achieved for particles of a given transverse momentum. The field map has been accurately measured, and a sample of the measurements is reproduced in Table 3.1. Field lines are shown in Fig. 3.7. The yoke weighs 300 tons, and it is composed of 60- and 30-ton elements. It has been dismantled and carefully stored. Both the installation in the South Hall and the control system will be taken care of by the Frascati component of the Collaboration with the help of the Technical Support Group of the Frascati Laboratory, who formerly installed the Streamer Chamber magnet at LEAR.

3.3.2 The Spiral Projection Chamber (SPC) central detector

3.3.2.1 Operation principles

Our central detector will be a Spiral Projection Chamber (SPC) (GAS 81). This type of imaging chamber (shown in Figs. 3.8 and 3.9) has cylindrical symmetry, radial drift electric field, and FADC multihit pulse sampling and digitizing electronics. The active volume is completely empty apart from the gas mixture, and it occupies the space between sense wires stretched parallel to the axis at the periphery of the detector and an internal cylindrical cathode. The sense wires give a three-dimensional image of the ionization deposited in the active volume (by prongs or by X-rays) by drift-time, charge division, and hit-wire measurement. The cathode can have any diameter internal to the sense wires and act as the container of a gas target. The drift cells are directed radially in the absence of magnetic field; when a magnetic field is applied along the detector axis, they take a spiral shape because of the $E \propto 1/r$ dependence of the drift electric field (see Figs. 3.10 and 3.11).

The main characteristics of this detector are its constant granularity down to low radii near to the vertex, the extremely low mass of the active part, and the concentration of massive parts (structural and electronics) in the periphery of the two end-cap support rings. The SPC can be used to detect X-rays, localizing their absorption point, to image and measure the direction, momentum, and $dE/dx$ of charged particles, and to trigger on isolated clusters in space and on hit multiplicities at various radii. The SPC gives a clean X-ray identification, the location -- inside or outside the active volume -- of an X-ray line source; and the determination of the energy of soft X-rays by the usual amplitude and by mean-free-path measurements [X-ray drift chamber technique (GAS 78)].
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3.3.2.2 Characteristics and functions

Our central detector surrounds the gas target, as shown in Fig. 3.12. It will be a shortened and improved version of the Spiral Projection Chamber/X-ray Drift Chamber in use at ASTERIX since 1983 [see Fig. 3.9 (GAS 86)]. The target gas and the counter gas are separated by a thin tube of aluminized Mylar.

A 6 µm thick Mylar tube is currently in use at ASTERIX. An even thinner membrane (2 µm thick) has been developed, but it has not yet been tested in operation. The thin entrance window is transparent to soft X-rays and to low-momentum recoil protons and nuclear fragments.

The functions of the OBELIX SPC will be to

- image and count the multiplicity of all prongs produced in one annihilation in the target gas with high angular acceptance (θ/4π > 90%);
- accurately measure the momentum direction of charged particles very near to the annihilation vertex, with no structural material causing multiple scattering;
- accurately reconstruct the annihilation vertex;
- accurately reconstruct K^0_s and Λ decay vertices;
- measure the absorption point and the energy of X-rays emitted by antiprotonic atoms;
- measure the dE/dx, the direction, the momentum, and/or the range of low-energy nuclear fragments;
- provide fast triggers, based on the hit multiplicity at different radii inside the active volume, on
  - total prong multiplicity,
  - total X-ray multiplicity,
  - K^0_s (jump by two in multiplicity),
  - Λ, Λ̅ (jump by two in multiplicity),
  - γ (jump by two in SPC and AFS jet chamber multiplicity).

3.3.2.3 Detector structure

The basic structural part of the SPC is a can made of a thin aluminium cylinder terminated at the two extremities by two rings that support the wires and the front-end connectors (see Fig. 3.12a). The wires are organized in three concentric layers at the three radii: r_d = 150 mm, r_s = 155 mm, r_c = 160 mm. The wires are fixed to the support rings with crimping pins, as in the AFS chambers.

There are 90 resistive sense wires (dia. 30 µm) stretched at r_s = 155 mm, alternating with 90 field wires (dia. 100 µm) stretched at r_f = 155 mm. There are 180 drift and field wires (dia. 100 µm) at r_d = 150 mm and cathode wires (dia. 150 µm) at r_c = 160 mm. Cathode, field, and drift wires define an amplification cell around each sense wire. The sense wires are at ground potential and the
gain is determined by the voltages $V_c$, $V_f$, and $V_d$ applied to the surrounding wires. An improved version of the connection system of the ASTERIX SPC will make it possible not only to avoid touching the crimping pins but also to avoid exerting force on them when inserting the connectors.

The SPC basic structure is common also to the two end-cap high-density SPCs, and we plan to produce four so as to have one as a spare.

Two field-shaping disks are positioned inside the end-cap rings and support the aluminized Mylar window, which is set at high voltage (see Fig. 3.12b). The drift electric field in the centre of the active volume of the SPC is naturally that of a cylindrical condenser, and is defined by the voltage settings of the Mylar tube and of the drift wires. Because of the presence of the drift wires, the drift and the amplification region in the OBEIX SPC are decoupled, ensuring more flexibility and reliability than in the ASTERIX SPC, where the layer of drift-field wires is not present. We are studying the optimal disposition of the drift wires (number and angular positioning with respect to the sense wires), using drift chamber simulation programs adapted to a cylindrical geometry. The field shaping has to provide a radial electric field with intensity $E \propto 1/r$ also at the extremities of the active volume. The field shaping in the end-caps is provided by a uniform layer of highly resistive coating deposited on insulating disks. High and low voltages are applied to the coating in correspondence with the diameter of the Mylar tube and of the ring, respectively. The current flowing out radially onto the highly resistive coating finds a resistance inversely proportional to the radius, and provides a radial field $E \propto 1/r$ everywhere on the field-shaping ring. The voltage setting of the drift-field wires and at the extreme radius of the field-shaping ring are coupled to ensure the $1/r$ dependence. In ASTERIX the field shaping is given by a printed-circuit board with conducting rings and a chain of lumped resistors sunk into Araldite for isolation. The new field shaping we plan to use is more reliable and requires much less material in the end-cap of the SPC. This makes the detector very transparent both to $\gamma$'s going out to the two end-cap $\gamma$ detectors and to those going to the azimuthal $\gamma$ detectors. At both extremities, fast low-loss signal cables connect the sense wires to preamplifiers located in the cones of the magnet poles, so that the end-cap gamma detectors can be placed against the extremities of the SPC in order to maximize their solid-angle acceptance.

3.3.2.6 Chamber gas

The chamber operates at NTP. An overpressure $\delta p$ of less than 1 Torr stabilized to better than 0.1 Torr is given to the target gas in order to ensure that the Mylar tube has a nice cylindrical shape.
We plan to use a mixture of argon (50%) + C\textsubscript{2}H\textsubscript{6} (50%), as in the AFS chambers and in the ASTERIX SPC. There are other mixtures that permit higher spatial resolution, but their ageing effects and acceptable rates are not yet so well known. Should a mixture that is better than Ar/C\textsubscript{2}H\textsubscript{6} in all respects be usable but require special operation, then the easy access to the chamber would enable the necessary installation for thermal stabilization.

The gas mixture also affects the geometry of the drift cells, as the drift angle and velocity depend on the gas mixture and on the intensities of the electric and magnetic fields.

3.3.2.5 Electronics

The electronics for readout and triggering associated with the SPC will be similar in conception to those used in the ASTERIX SPC. A larger dynamical range would be advantageous so as to avoid pulse amplitude saturation in tracks of heavy nuclear fragments.

Figure 3.13 shows the scheme of the ASTERIX SPC readout electronics, which is of the CERN UA1 type (UA1 80), and of the ASTERIX SPC/KDC trigger electronics (KAL 84).

After preamplification, the charge signals of both wire ends, Q\textsubscript{R}(t) and Q\textsubscript{L}(t), are sent to 2 of the 24 inputs of a charge and time digitizer (CTD) module via twisted-pair cables. Here Q\textsubscript{L}(t) and Q(t) = Q\textsubscript{L}(t) + Q\textsubscript{R}(t) are continuously integrated over 32 ns; then a first 6-bit 31.25 MHz FADC directly digitizes I(t) = Q\textsubscript{L}(t)/Q(t), whilst a second FADC with non-linear response function, yielding an effective dynamic range of 8 bits, converts Q(t), thus supplying dE/dx samples.

The drift time within 32 ns is measured by a 3-bit TDC interpolator with an accuracy of 4 ns; an additional bit, the time tag, flags the sample corresponding to the start of pulse.

The digitizations are stored in a circular 128 × 16-bit buffer memory containing the last 4 μs of wire information. To obtain the best accuracy and the same performances from all channels, two gains and four offsets per channel are adjustable by means of six digital-to-analog converters (DACs). The gap time modules (GTMs) of Fig. 3.13 (KAL 84) are used for fast X-ray triggering with discrimination against charged particles.

A GTM handles 12±2 wires and provides a signal for each 'hit' wire lying between two adjacent wires, with no hit in a preselected drift-time window. The drift-time window is defined by two strobe pulses supplied by a programmable strobe module. This serves for the identification of low-energy X-rays, which have typically long drift times (GAS 78).
When a pretrigger (e.g. p stop) occurs, the CTDs are stopped after 4 μs. Then, if a first-level trigger is verified (e.g. one gap condition), a Read signal starts the readout of CTD buffer memories and the data reduction and formatting under the control of the readout processor (ROP). The results are stored in 1 word FIFO memory and read out by the data-acquisition host computer. For each hit the ROP gives: wire number, drift time, the total charge (sum of the linearized $dE/dx = E_1$, samples), the averaged $<z>$ coordinate ($<z> = \frac{\sum E_1 z_1/\sqrt{\sum E_1}}{1}$), and pulse length (obtained by comparing $dE/dx$ samples with a given threshold). This information is grouped in three 16-bit words. Optionally, all the $dE/dx$ samples above a threshold may be sent to the host computer with a pre-selected number of samples preceding the time-tag bin for the control of the electronics pedestal. Typically, 10 16-bit words are generated per X-ray, and between 10 and 30 per charged particle.

The readout electronics of the ASTERIX XDC consists of four crates, each one containing one time-stop interpolator, two CTDs (12 wires each), two GTMs, one strobe module, and one ROP. The ROP also performs sophisticated functions for monitoring and calibrating the XDC electronics.

Another possibility for the digitizing electronics under evaluation is to use electronics similar to that of the OPAL jet chamber, which has better design performances in time resolution (2 ns corresponding to 100 μm spatial resolution) and in double track resolution (2.5 mm).

The cost of the SPC readout electronics ranges from SF 1500 to SF 3000 per sense wire. Besides using the same basic mechanical structure for the SPC and the two HSPCs, we will use the same electronics and software. This standardization will minimize the work and the number of necessary spare parts. We have evaluated the possibility of using these electronics also for the AFS jet chamber, but this turns out to be too expensive and not necessary.

3.3.2.6 Performances

The OBEILIX SPC is an improved version of the ASTERIX SPC.

The design of the ASTERIX SPC/XDC, started in 1978 (GAS 78a), was based on previous experience (GAS 78c). It evolved (AST 80) and improved during construction (GAS 81). It took advantage of the UA1 development for its electronics (UA1 80), and required dedicated development for the trigger (KAL 84). The ASTERIX SPC/XDC has been in operation at LEAR since 1983. More than $3 \times 10^7$ pp annihilation events have been recorded, and the performance of the detector has been better than was expected from the design specification. The cylindrical geometry of the SPC requires dedicated efforts at the software level with the non-straightforward extrapolation from planar geometry usually adopted in imaging chambers. The software developed in the ASTERIX Collaboration for the
SPC/XDC is very satisfactory for event imaging (DUC 84), measurement of X-ray energy, and track dE/dx (LAN 85). However, the track reconstruction routines do not aim at measuring directions and curvature; and the systematic work needed to produce the exact map of drift-lines and equidrift time-lines has not yet been done. However, it has been started by one of the OBELIX software groups, and the results will also be of use for the analysis of ASTERIX data.

Under these circumstances we can estimate the performances of the OBELIX SPC, taking those of the ASTERIX SPS as pessimistic.

i) X-ray detection efficiency

Figure 3.14 shows the absolute detection versus energy for X-rays emitted from the centre of the ASTERIX XDC. We will have better efficiency at high energies because of the thicker active volume (target radius r_t \leq 3 cm instead of 8 cm) and at low energies because of the thinner Mylar window (6 \mu m or less Mylar instead of 12 \mu m).

ii) X-ray identification and energy resolution

Figure 3.15 shows one event with one X-ray emitted by a \( p\bar{p} \) atom detected in the presence of four prongs produced in the annihilation.

The X-ray spectrum with a \( ^{57}\text{Co} \) source positioned on the axis of the ASTERIX SPC is shown in Fig. 3.16. The X-ray energy resolution is \( \sigma_{E}/E = 10\% \sqrt{5.5/E \text{ (keV)}} \).

iii) Charged particle identification by dE/dx

Figure 3.17 shows one ASTERIX event with two charged pions and a \( K^+K^- \) pair.

Figure 3.18 is the scattergram dE/dx versus momentum, indicating a clear K/\pi separation up to 400 MeV/c (LAN 85). The performance of the OBELIX SPC will be enhanced because of the doubling of the thickness of the active volume due to the reduced target diameter.

In ASTERIX the dE/dx resolution is \( \sigma_{dE/dx} = 33\% \). In OBELIX it should be about 25%.

iv) Imaging of complex events

Figures 3.19a and 3.19b give example of the capability of the ASTERIX SPC to visualize high-prong multiplicity events and events with splash-back particles.
v) Double-track separation
The double-track separation is already about 1 cm with the ASTERIX UA1-type electronics. One example of two tracks 1 cm apart from each other is given in Fig. 3.20.

vi) $K^0$ imaging and triggering
Figure 3.21 shows the visualization of one event with a $K^0_S \rightarrow \pi^+\pi^-$ in the SPC. A $K^0_S$ trigger based on the variation of multiplicity by 2 along the SPC radius has been tested at ASTERIX (BAy 86). The electronic trigger efficiency exceeds 50% and the rejection effect is around $10^3$.

The physical trigger efficiency on $K^0_S$ and $\Lambda^0$ is given by the probability to observe the $K^0_S \rightarrow \pi^+\pi^-$ (cr = 2.67 cm) and $\Lambda^0 \rightarrow p\pi^-$ (cr = 7.89 cm) decays is given by the probability to observe their vertices in the SPC. In Fig. 3.22a these probabilities are given versus the $K^0_S$ and $\Lambda^0$ momentum. The percentage of decays outside the SPC is negligible for kaons and less than 5% for hyperons in the momentum range considered.

In Fig. 3.22b is plotted the $K^0_S \rightarrow \pi^+\pi^-$ decay probability $P$ inside the SPC versus the gas target radius for pp annihilation at rest. The curve has been obtained using the $K^0_S$ inclusive momentum spectrum obtained by fitting pp annihilation data at rest (ARM 69). For in-flight annihilation, distributed uniformly along the target, the probabilities are only 3% lower than at rest.

vii) Direction measurement and vertex reconstruction
The SPC measures the direction of prongs emitted from the annihilation vertex with no scattering material apart from the target gas, the active gas, and the (negligible) Mylar window. The direction of the prongs can then be measured precisely before they can get a kink due to multiple scattering in containers and structural material, after which their momentum is measured accurately in the AFS jet chamber. This results in small errors in the reconstruction of the invariant mass of objects decaying into prongs.

The crossing-point of a track with the edge of one cell of the SPC can be measured with an accuracy $\sigma_r \sim 300$ μm, $\sigma_r^x \sim 300$, and $\sigma_z \sim 4$ mm at all radii. Notice also that the cell width reduces from 5 mm at the sense-wire radius down to 1 mm at the Mylar radius. Under these circumstances the error on the direction of one track is controlled in the $r^+$ plane by multiple scattering in the active gas and in the $z$ direction, by the $\sigma_z/z - 1\%$ of the charge division. Typical errors would be 5 mrad in the $r^+$ plane and 30 mrad in $z$. The vertex will be reconstructed in the $r^+$ plane to about 0.5 mm.
viii) Heavy-prong detection (protons and nuclear fragments)

Our calculations of the SPC detection efficiency for charged particles
($\pi$, $p$, d, t, $^3$He) coming from $\bar{p}^4$He annihilation are based on a sample of
$\bar{p}^4$He annihilation data obtained with the streamer chamber. These data show that
the gross structure of $\pi$, p, d, t, and $^3$He momentum spectra can be reproduced by
Maxwellian distributions with mean momenta of 300 MeV/c and 200 MeV/c for $\pi$ and
heavy-charged particles (p, d, t, $^3$He), respectively. On the basis of this in-
formation, we show in Table 3.2 the threshold $T_0$ of the kinetic energy neces-
sary to enter the SPC, and the fraction $\varepsilon$ of particles in the spectrum with $T > T_0$.

**Table 3.2**

Kinetic energy threshold $T_0$ for detection in the SPC,
and percentage $\varepsilon$ of particles with $T > T_0$ for annihilations in $^4$He and Ne.
The numbers refer to a path of 4 cm in gas and 6 $\mu$m in Mylar
before entering the SPC.

<table>
<thead>
<tr>
<th>Particle</th>
<th>$^4$He</th>
<th></th>
<th>Ne</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\varepsilon$ (%)</td>
<td>$T_0$ (MeV)</td>
<td>$\varepsilon$ (%)</td>
</tr>
<tr>
<td>$\pi^\pm$</td>
<td>100</td>
<td>0.4</td>
<td>100</td>
</tr>
<tr>
<td>p</td>
<td>$&gt; 99$</td>
<td>1.0</td>
<td>$&gt; 99$</td>
</tr>
<tr>
<td>d</td>
<td>75</td>
<td>1.1</td>
<td>55</td>
</tr>
<tr>
<td>t</td>
<td>70</td>
<td>1.3</td>
<td>60</td>
</tr>
<tr>
<td>$^3$He</td>
<td>65</td>
<td>3.0</td>
<td>60</td>
</tr>
</tbody>
</table>

The SPC efficiency could be deduced from these data by a Monte Carlo cal-
ulation. However, in this case we again prefer to use a sample of reaction
products of $\bar{p}^4$He annihilation measured in the streamer chamber. In this sample,
1016 mesons ($\pi^\pm$ with a small percentage of $K^\pm$) and 419 heavy prongs (p, d, t,
$^3$He) -- 44 of which (d, t, $^3$He only) stopping with 9 cm of gas at MTP -- have
been identified.

Since 9 cm of $^4$He = 4 cm of $^4$He + 6 $\mu$m of Mylar, this situation corresponds
to the working conditions of OBELIX with a $^4$He gas target.

Taking into account the geometrical correction due to the cylindrical
geometry, we find that out of a total of 1435 tracks, 55 should have stopped
before entering the SPC. Hence for the case of $\bar{p}^4$He annihilation we obtain the
following efficiencies:
96% of all tracks,
87% of heavy prongs.

We note that we lose only the particles that are heavier than the proton with kinetic energy $\leq 2.5\text{ MeV}$. These low-energy heavy particles may be considered as spectators in the annihilation process, and their detection is not critical for most of our nuclear physics program.

ix) Momentum measurements

The curvature of low $p_T$ tracks can be seen inside the SPC from the ASTERIX on-line events displayed in Figs. 3.23a and 3.23b. However, momentum measurements have yet been attempted in ASTERIX in spite of the obvious interest of measuring low-momentum pions in the search for baryonium states near threshold.

In order to measure a curvature in the SPC the absolute position in space of track points must be determined accurately. This requires a full mapping of drift-lines and equidrift time-lines in order to associate track points with points in space. For this the behaviour of the detector and the electronics (drift velocity and drift angle -- $E$, $B$, and gas-dependent; clustering and diffusion; rise-time and clipping-time of the signals) must be taken into account.

We have started this work (BBS 85). Figure 3.24 gives the SPC momentum resolution evaluated for tracks that intercept at least four drift-cell boundaries.

For heavy fragments stopping in the SPC the energy will be determined by measuring their range in the SPC gas.

3.3.3 The AFS jet drift chamber

We shall employ the cylindrical drift chamber of the Axial Field Spectrometer of the ISR. This chamber was built in the years 1978-80, and operated successfully at high luminosities in the AFS until the closure of the ISR. The chamber is made of two independent equal moduli (see Fig. 3.25). A spare one is also available, and it is brand new as it was never necessary to use it. The ageing of the chambers is well under control. These chambers can continue operation for years. The AFS jet chambers feature

- low mass to minimize interference with surrounding detectors;
- good momentum resolution;
- powerful pattern recognition for high track densities and event rates;
- particle identification in the non-relativistic region by the $dE/dx$. 
3.3.3.1 The chamber

The detector consists of two half cylinders, each containing 41 azimuthal sectors of 4° each (Fig. 3.26). The wires are sensitive over 1.28 m. The chamber is made of three crowns of 14, 18, and 10 wires, grouped radially so that there are 42 sense wires in each azimuthal sector. The total number of sense wires is 3444.

The sense wires are staggered by ±0.4 mm to resolve the left-right ambiguity (Fig. 3.27) and spaced by 8 mm radially. Cross-talk between sense wires is reduced by alternating them with potential wires, which are coupled to ground. Each sector of ±2° is bounded by drift- and field-shaping wires, producing a flat potential distribution parallel to the corresponding sense-wire plane. The sense wires are made of non-magnetic Ni-Cu alloy, with a diameter of 30 μm and a high resistance (1.8 kΩ/m) suitable for charge division. The resistance of all the sense wires is constant to ±2 % r.m.s. The potential and field-shaping wires are made of Be-Cu alloy, with a diameter of 100 μm.

The mean radius of the three crowns are
\[
\begin{align*}
\bar{r}_1 &= 260 \text{ mm}, \\
\bar{r}_2 &= 510 \text{ mm}, \\
\bar{r}_3 &= 760 \text{ mm},
\end{align*}
\]
and the chamber dimensions are
\[
\begin{align*}
\varphi_{\text{int}} &= 40 \text{ cm}, \\
\varphi_{\text{ext}} &= 160 \text{ cm}.
\end{align*}
\]
The inner walls of the cylinder are made of 1 cm of Rohacell sandwiched between two Vetrotene layers, 1 mm each.

The end-plates are made of 1 cm of Stesalit. All wires are crimped in tubes which are located in holes in the end-plates. The holes were drilled with high precision (a < 15 μm), and the crimping permits wire positioning inside the tube with α < 10 μm vertically to the wire plane. Owing to the gravity, the sagittae for the sense wires and the potential wires are 20 μm and 120 μm, respectively; the sagitta due to electrostatic forces is typically 150 μm for the sense wires. The potential wires and the drift wires are decoupled to ground with capacitors of 3.6 nF and 2 nF, respectively, distributed over the two end-plates. Apart from a few support bars at the outer diameter, the chamber is then quite transparent to γ-rays.

3.3.3.2 The chamber gas

The gas employed will be a mixture of argon (50%) + C₂H₆ (50%). The gas must be recirculated through the chamber at 6 l/min and passed through a purifier for oxygen and water absorption. The working pressure of the gas will
be 1 atm (atmospheric pressure). It is foreseen to monitor the gas gain at the input and the output of each half cylinder of the detector.

3.3.3.3 \textit{Voltage}

The voltage distribution of the drift wires and the potential wires provides a gas amplification of \((3.6) \times 10^4\) and a drift field of about \(E = 1.25\) kV/cm. The choice of gas amplification represents a compromise between reasonable \(z\)-resolution from charge division on the one hand, and gain saturation and gas ageing on the other.

With a gas amplification of \(3 \times 10^4\) and \(E_d = 1.25\) kV/cm, a drift velocity of 51 mm/\(\mu\)s and a drift angle \(\Theta_d = 16^\circ\) have been measured at the ISR in the central region of the magnet, with \(B = 0.5\) T. The drift-cell path length of each radial sector increases with radius: it varies from 7.4 mm to 27.0 mm. The maximum drift times vary between \(t_{d_{\text{min}}} = 140\) ns and \(t_{d_{\text{max}}} = 530\) ns. This difference is relevant to the gating specifications of the chamber electronics.

3.3.3.4 \textit{Electronics}

The original electronics of the chambers are not available. We have therefore to instrument the 3444 wires with 6888 channels of ADCs and 3444 channels of TDCs, or with 3444 multihit FADC electronics channels.

We have investigated several types of electronics suitable for the AFS jet chamber and compared performances, prices, commissioning work, and the needs of our experiment (BICE 85; PAN 85; TOS 85). The azimuthal segmentation of the AFS jet chamber (82 sectors) is three times higher than the segmentation of all other existing or planned jet chambers, and the prong multiplicity we have to cope with is typically below 15. Under these conditions, single-hit electronics can handle the multiplicity without confusion. The spatial resolution for drift times as long as the maximum drift time in the AFS jet is as good with leading-edge techniques as with fast-pulse sampling and digitization techniques. Therefore we have decided to employ a standard technique making use of traditional ADCs and TDCs; in this field there are various possibilities available on the market. We are investigating the opportunity of employing FASTBUS Standard ADCs and TDCs (as some LEP experiments plan to do) or the usual CAMAC standard. The total cost is in the range of SF 350-500 per wire.

3.3.3.5 \textit{Performances}

The performances expected for this detector in our experiment are the ones measured during the data-taking of the AFS at the ISR. The chambers were in operation at the ISR for several months, at luminosities around \(1.4 \times 10^{31}\) cm\(^{-2}\) s\(^{-1}\) (and up to \(2 \times 10^{32}\)), and beam momentum of 31 GeV/c. This
luminosity produced typically $4 \times 10^5$ hits per wire per second, including background.

a) Drift time

The results have been obtained with CERN Drift-Time Recorder (DTR) units; the electronics contributes $\sigma = 60 \mu m$ to the space resolution. A point resolution with $\sigma_r = 200 \mu m$ has been obtained for all tracks visible radially over $\gtrsim 50 cm$, averaging over the full azimuth and all points with valid $z$ information. Near to the sense wires and the sector boundaries the resolution is worse; in between these zones it is better. This performance could be slightly improved in our case, as we will employ more recent electronics with better specifications than those of the DTR.

b) Charge division

The $z$ position information (the position along the wire direction) is obtained by charge division. For a gas amplification of $5 \times 10^4$, the measured average resolution for all reconstructed tracks was $\sigma_z = 1.4 cm$, i.e. 1% of the wire length.

c) $dE/dx$

The truncated mean of the 60% lowest pulse heights, averaging over all tracks containing $> 30$ time digitizations and $z$ measurements, gave a $\sigma_E/E = 10\%$. Figure 4.1 in the next section shows the separation between $\pi$, $K$, $p$. Protons are fully identified up to 1.0 GeV/c, pions and kaons up to 0.6 GeV/c.

d) Momentum resolution

The momentum resolution measured by averaging over all tracks measured in the AFS chamber is well fitted by the expression

$$\sigma_p/p = \left[ (0.025p)^2 + 0.01^2 \right]^{1/2}.$$  

The momentum resolution versus deep angle is given in Fig. 3.28 for a few momenta. The momentum resolution versus momentum will be given in Fig. 4.3.

e) Tracking

We plan to use the AFS tracking programs. The track reconstruction efficiency of the analysis program is greater than 95% even at multiplicities $N_c > 20$. Figure 3.29 shows a high-multiplicity event from $\alpha\alpha$ collisions at the ISR as seen by the event reconstruction program. The tracking program reconstructed 45 tracks in this event.
<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal radius (cm)</td>
<td>20</td>
</tr>
<tr>
<td>External radius (cm)</td>
<td>80</td>
</tr>
<tr>
<td>No. of sectors</td>
<td>82</td>
</tr>
<tr>
<td>No. of crowns of wires</td>
<td>3</td>
</tr>
<tr>
<td>Sense wire diameter (µm)</td>
<td>30</td>
</tr>
<tr>
<td>Field wire diameter (µm)</td>
<td>100</td>
</tr>
<tr>
<td>No. of sense wires</td>
<td>3444</td>
</tr>
<tr>
<td>Drift path (mm)</td>
<td>7-27</td>
</tr>
<tr>
<td>Drift time (ns)</td>
<td>137-530</td>
</tr>
<tr>
<td>$E_d$ (kV/cm)</td>
<td>1.25</td>
</tr>
<tr>
<td>$v_d$ (mm/µs)</td>
<td>51</td>
</tr>
<tr>
<td>Gas: Ar (%)</td>
<td>50</td>
</tr>
<tr>
<td>C$_2$H$_4$ (%)</td>
<td>50</td>
</tr>
<tr>
<td>Flux (1/m)</td>
<td>6</td>
</tr>
<tr>
<td>Pressure (atm)</td>
<td>1</td>
</tr>
<tr>
<td>$\sigma_r$ (µm)</td>
<td>±200</td>
</tr>
<tr>
<td>$\sigma_z$ (%)</td>
<td>1</td>
</tr>
<tr>
<td>$\sigma_p/p$ (cm)</td>
<td>1.4</td>
</tr>
<tr>
<td>$\sigma_{dE/dx}$ (%)</td>
<td>$\sqrt{(0.025)^2 + 0.01^2}$</td>
</tr>
<tr>
<td>$\sigma_{dE/dx}$ (%)</td>
<td>10</td>
</tr>
</tbody>
</table>
Table 3.3 summarizes the main characteristics and performances of the AFS jet chamber.

3.3.4 The time-of-flight system

The main function of the time-of-flight system is identification of charged particles at momenta higher than 600 MeV/c. It will make it possible to tell a $K^\pm$ from a $\pi^\pm$ up to 1 GeV/c, and $p$ from a $\pi^+$ up to 1.7 GeV/c.

The TOF system will allow a fast triggering on $K^\pm$ with momenta up to 300 MeV/c and a slower triggering on $K^\mp$ of higher momentum, and will give a fast timing for the SPC and AFS drift chambers.

It will measure the time-of-flight of $\bar{p}$ produced by charge exchange and annihilating in the target. This system will also be very useful for selecting cosmics of various directions at the debugging and calibration stage of the experiment.

3.3.4.1 Detector characteristics

The TOF system will consists of two cylindrical arrays of scintillator strips coaxial with the $\bar{p}$ beam. The dimension foreseen are given in Table 3.4.

<table>
<thead>
<tr>
<th></th>
<th>Radius (cm)</th>
<th>No. of strips</th>
<th>Strip Width (cm)</th>
<th>Strip Thickness (cm)</th>
<th>Strip Length (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer detector (TOF)</td>
<td>135</td>
<td>90</td>
<td>9</td>
<td>3</td>
<td>350</td>
</tr>
<tr>
<td>Inner detector (tof)</td>
<td>18</td>
<td>30</td>
<td>3</td>
<td>1</td>
<td>50</td>
</tr>
</tbody>
</table>

Fast photomultipliers (PMs) view each strip at both ends through suitably shaped light-guides whose geometry is chosen to optimize light collection time and to minimize magnetic field effects.

The inner detector (tof) is made up of two parts, each part comprising 15 scintillator strips that are fixed to the inner wall of the AFS jet chamber. These strips also act as converters for $\gamma$'s in the '2\pi pair spectrometer' trigger mode.

The outer detector (TOF) is also made in two parts, each comprising 45 scintillators. These two parts are movable for access to the AFS jet chamber.
We plan to use XP 2020 PMs and NE 110 scintillator. We expect on the basis of experience (BRE 84b) and looking at the performances of other similar systems (COS 85), a time-of-flight resolution \( \sigma_{\text{TOF}} \leq 200 \) ps.

The system will be completely new; its cost, including electronics is estimated to be SF 0.7 \( \times 10^6 \) (SER 85).

3.3.4.2 Performances

The TOF system covers 75\% of the solid angle.

The useful path length for time-of-flight determination depends on the vertex position and the emission angle of the annihilation products. Neglecting the track curvature in the \( r^+ \) plane in the presence of the magnetic field, the path length varies from 120 cm to 200 cm for a polar angle \( \theta \) between 90\° and 40\° (130\°) for annihilations in the centre of the detector. Figure 3.30 shows the time-of-flight bands of pions and kaons emitted from \( \theta = 90\° \) to \( \theta = 40\° \) (130\°). The bands are separated up to 300 MeV/c. A very fast trigger on \( K^\pm \) with momentum below 300 MeV/c is feasible on the basis of this simple information. With proper treatment of the signals from the two PM's looking at the same scintillator strip, the 3 coordinate of the detected particle can be determined within 5 cm FWHM (BRE 84b). By using the information from the AFS jet chamber and from the HARGD, the z coordinate will eventually be measured to better than 1 cm in the off-line analysis. Figure 4.2 (see next section) gives the time-of-flight differences for \( e/\pi, \pi/K, \) and \( K/p \) pairs in the most difficult case \( \theta = 90\°; \) flight-path (120 cm). Our design resolution (\( \sigma_{\text{TOF}} \leq 200 \) ps) can be compared with the time-of-flight differences in the curve; \( K/\pi \) separation is then feasible up to 1 GeV/c and \( K/p \) up to 1.7 GeV/c.

High-momentum tracks are easily recognizable as they fire only one 4\° sector of the AFS jet chamber. Neglecting their curvature, the error on the flight path is then negligible, as is the error on the position along the scintillator determined from the two associated PM's. The TOF information can then be used at a relatively fast trigger level to select high-momentum kaons and heavier prongs.

3.3.5 The HARGD (High Angular Resolution Gamma Detector)

_\text{azimuthal calorimeter}_

The HARGD (see Figs. 3.31 to 3.33) is the largest of the two types of shower counters. It covers a solid angle of 0.7 \( \times 4\pi \) to a depth of 0.5 r.l. It serves to: i) measure the coordinates of a \( \gamma \) conversion point; ii) measure the energy of \( \gamma \)-rays; iii) determine the direction of high-momentum \( \gamma \) (shower direction); iv) provide 21 dE/dx and 28 range samples for a redundancy in the
measurement of high-momentum charged prongs, thus allowing a π/κ discrimination up to about 500 MeV/c; ν) detect scattered antineutrons and neutrons from nuclear reactions.

The HARGD is completely unobstructed by other components of the OBELIX detector; it has a granularity of 384 cells in azimuth and 384 cells along the beam axis; furthermore, it is segmented in the longitudinal direction in 28 layers positioned at a larger distance from the interaction vertex than in the MARK III detector (MAR 84). It allows for a good three-dimensional reconstruction of showers.

The angular segmentation is better than 20 mrad in the rφ plane and 6 mrad in θ. The angular resolution σθ is better than 1 mrad for prongs and better than 3 mrad for γ conversion points in the rφ plane, and σφ is less than 3 mrad. Owing to the high number of dE/dx samples in the longitudinal direction of shower development, the HARGD provides single-γ identification against high-energy π0's also for π0's with decay opening angle smaller than the 10 mrad granularity of the detector.

3.3.5.1 Detector structure

The detector consists of four large supermodules (4 × 3 × 1.1) m³ built with converter foils and active elements [11,000 proportional drift tubes (PDTs) and 14,000 limited streamer tubes (LSTs)] that are available, together with their electronics, from the CHARM I experiment. The minimum distance of the supermodules from the beam axis is 1.4 m. The bottom supermodule is supported by the yoke of the OAPS magnet. It is mounted on rails and can be extracted (see Fig. 3.33) in order to have access to its electronics. The two lateral supermodules are suspended from an overhead structure, thus enabling them to be slid along parallel to the magnet (Fig. 3.33) for giving access to the centre of the detector and for the installation and maintenance of the supermodules themselves.

Figure 3.34 shows the structure foreseen for suspending the supermodule above the magnet (GUA 85). The module is assembled on a platform suspended from a support fixed on the two vertical parts of the magnet yoke. The platform is suspended by means of pods positioned in between the active elements of the calorimeter. The dead areas of this arrangement do not point to the interaction region.

Each supermodule is subdivided into two sections, each composed of seven equal active layers. The inner section (conversion region) is designed to measure the conversion points accurately. It is made of modules composed of one plane of LSTs orthogonal to the beam axis (z-measurement) and two planes of PDTs parallel to the beam axis. Lead converter foils are sandwiched between the
planes of active elements. No converter is put before the first (internal) modulus, which acts as veto for prongs and helps in the measurement of high-momentum prongs. The external section (shower containment region) is made of seven planes of PDTs parallel to the detector axis, each providing a dE/dx sample. Again, lead converter foils are sandwiched between the PDT planes. Each PDT layer is thermally insulated with two 5 mm thick sheets of polyurethane foam in order to minimize the gain dependence on room temperature (ΔT = 1°C → ΔG/G = 4%). There are 13 layers of lead interspersed between the active planes; the inner six are 3 mm thick and the outer seven are 6 mm thick, for a total of 10 r.l.

3.3.5.2 Detector components

a) Proportional drift tubes

The PDTs have 29 x 29 mm² internal cross-section, 2 mm aluminium wall thickness, and 4 m length. Sixteen tubes are aligned and glued together to form a unit (wire material: stainless steel, 50 µm diameter; wire spacing: 31 mm; effective width, taking into account the gluing of tubes the spacing between two units, and the insulating sheets: 500 mm; thickness: 43 mm; length: 4 m). The units are flat over a 4 m length to within 2 mm, and deviate from straightness along the width by less than 1 mm. The wire positions are known to within 0.2 mm. Six units are mounted together to form one plane of 3 x 4 m² sensitive area. The tubes are operated at 1.5 kV and are flushed with a mixture of Ar (95%) + C₃H₈ (5%). Variation of amplification with the gas pressure (30 mbar above the atmospheric pressure; ΔP = 50 mbar → ΔG/G = 60%) can be compensated by regulating the high voltage. The charge collected on the wire is integrated over 800 ns after the signal leading edge and converted by an 8-bit ADC (CHA 78). An 8-bit 20 MHz TDC measures the drift time. The process of encoding the drift time and charge can last up to 26 µs and can be terminated by an external signal derived from slow decision logic in order to reduce the dead-time of the system. Only non-zero data from the front-end electronics are transferred at a rate of up to 2 MHz, into a buffer memory housing 256 charge and time measurements.

b) Limited streamer tube characteristics

Each LST has 9 x 9 mm² internal cross-section, 1 mm thick aluminium walls, and 2.85 m length (CHA 83b). They are organized in units of 16 LSTs.

A single unit is built by gluing together two aluminium profiles of eight cells each (wire material: stainless steel, 50 µm diameter; wire spacing: 10 mm; effective width, taking into account the gluing and spacing between two units: 165.5 mm; thickness: 12 mm; length 2.85 m).
Twenty-four units are assembled together to form a plane of 4 x 2.85 m² sensitive area.

The tubes are filled with a 1:3 argon-isobutane mixture and work at 3.7 kV. Owing to the uncritical conditions the gas system can be kept simple and standard. The logic interconnections in the front-end electronics are based on a three-level hierarchical system. The minimum time between the readout of two events is 10 µs.

3.3.5.3 Detector performances

The performances of the active elements of the HARP are well known from the measurements made by the CHARM I Collaboration (CHA 78, 83b). In the following we give a summary of their results.

a) PDT performances

Measurements of the drift path as a function of drift time show a linear dependence (see Fig. 3.35a), corresponding to an average drift velocity of 3.56 cm/µs for drift distances up to 18 mm.

The observed resolution in track position in a single tube as a function of drift path is shown in Fig. 3.35b.

The space resolution averaged over a unit of 16 PDTs was measured using muons. The deviation from a track determined by a best fit to 15 tubes is shown in Fig. 3.35c. Its r.m.s. width is 0.73 mm.

The pulse-height distribution on a sense wire (see Fig. 3.36a) observed for minimum-ionizing muons has a FWHM of 58% for a mean charge of 4.3 pC, corresponding to a gas amplification factor of 7.5 x 10⁴. The long tail clearly shows the wide dynamic range available. Figure 3.36b shows the distribution of deviations from the mean pulse height in 80 points distributed along the 4 m length of one PDT and measured for 420 16-PDT units. The average deviation is 5% as would be expected from the variation in thickness of the sense wire. The constancy of pulse height over these long chambers is rather remarkable.

b) Limited streamer tube performances

The efficiency curve for an LST unit is shown in Fig. 3.37a. The band in the rising part represents the total spread over the whole population of units tested, and includes differences due to constructional details, uncertainties in the gas mixture setting, etc.

A charge spectrum at the working voltage is shown in Fig. 3.37b; the mean charge is ≈ 30 pC for an integration time of 500 ns.

The spurious hit probability was checked in events containing only a single traversing muon and was found to be lower than 10⁻⁴ per tube.
c) HARGD general performances

The organization of the HARGD is quite similar to that of the barrel shower counter for the MARK III detector at SPEAR, for which experimental figures are available (MAR 84). This is a unimodular cylindrical detector placed inside the MARK III solenoid. It consists of 24 radial layers of finely segmented proportional resistive wire chambers, interspersed with 23 layers of 0.5 r.l. of lead supported by an aluminium spool (3.85 m length, 2.52 m diameter). The MARK III shower detector has 320 cells per radial layer (radial height 12.7 mm, width 32.2 mm for the outermost layer cell). The drift time is not measured, and consequently the angular resolution is not better than the detector azimuthal segmentation. The $z$ coordinate is measured by charge division with $\sigma_z = 4.4$ cm.

The HARGD specifications for angular resolution are based on measured performances of the existing active elements and are better by a factor of 3 than those of the MARK III shower detector, as shown in Table 3.5.

<table>
<thead>
<tr>
<th></th>
<th>$\sigma_{\phi}$ (prong) (mrad)</th>
<th>$\sigma_{\phi}$ ((\gamma) conversion point) (mrad)</th>
<th>$\sigma_{\theta}$ (mrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HARGD</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>MARK III</td>
<td>7</td>
<td>7</td>
<td>20</td>
</tr>
</tbody>
</table>

The HARGD measures the energy released by $\gamma$ showers, using a number of independent $dE/dx$ samples comparable to the 24 samples of MARK III, as we have up to 21 PDTs and 7 LSTs in the shower direction.

In the Mark III detector, the photon detection efficiency has been measured as a function of photon energy. For this purpose the final-state $\psi(3095) \rightarrow \pi^+\pi^-\pi^0$ was used. Employing the drift chamber to measure the momenta of the two charged pions, the momentum of the $\pi^0$ was determined. Then, using the $\pi^0$ momentum and detecting one photon from its decay and therefore knowing its position and angle, the position and angle of the second photon could be predicted. The efficiency at a given photon energy was determined as the ratio between the number of photons detected and the total number of predicted photons at the same energy. The results are shown in Fig. 3.38. The efficiency is $\approx 100\%$ above 200 MeV and $\approx 70\%$ at 100 MeV.

The energy resolution and energy scale linearity have been determined in MARK III by using Bhabha events, and also from energy-constrained $\pi^0$ photons. In
the latter case, locating one photon predicts the energy and direction of the
other. Figure 3.39 shows the distribution of measured photon energy versus pre-
dicted energy. The data scale quite well from 800 MeV down to 50 MeV.

For the energy resolution determination, a plot of the energy spread at
the $\psi(3095)$ for Bhabha-scattered electron events shows that the data are well
fitted by an energy resolution of $17.5\% /E \text{ (GeV)}$.

The energy resolution expected for single $\gamma$'s detected in the HARGD is
plotted in Fig. 3.40.

We take the performances of the MARK III shower detector as HARGD specifi-
cations for detection efficiency, energy resolution, and energy scale linearity.
This assumption has been confirmed by Monte Carlo simulations of the HARGD per-
formances, which have been made (DAG 85) by producing Monte Carlo events in the
HARGD structure (see Fig. 3.41).

Figure 3.42 shows the performance of MARK III when reconstructing invariant
masses of particles decaying into two $\gamma$'s in multigamma events that produce com-
binatorial background. The $\pi^0$ and $\eta$ peaks are very well identified over a smooth
background in the reaction $J/\psi \rightarrow \pi^+\pi^-3\gamma$. Owing to the better angular resolution
of the HARGD, we expect a better performance than in MARK III.

In reactions where monochromatic $\pi^0$'s or $\eta$'s are produced, the decay opening angle of the two associated gammas has a Jacobian distribution, with the
minimum opening angle given by

$$
\theta_{\min} = 2 \arcsin \left( \frac{M}{E} \right)
$$

where $M$ is the invariant mass of the decaying particle, and $E$ is its total
energy. The minimum opening angle for $\pi^0$ and $\eta$ versus $E$ is given in Fig. 4.6 of
the next section, where Fig. 4.7 shows the decay opening angle distributions for
monochromatic $\pi^0$'s of different energies. Under these circumstances the energy
of the $\pi^0$ is determined by the value of the minimum opening angle, and the
energy resolution is controlled by the error on the opening angle $\alpha$:

$$
\frac{\Delta E}{E} = \frac{p}{2m} |\Delta \alpha|
$$

where $E$ is the total energy, $p$ is the momentum, and $m$ is the mass of the mother
particle. With our angular resolution, $\sigma_{E}/E$ is at the 1% level.

In reactions where the total energy of a particle decaying into two $\gamma$'s is
fixed by the kinematics, the error on the invariant mass is determined by the
opening angle error by the
\[ \sigma_M = \frac{1}{2} \frac{\beta}{M} \sigma_\alpha. \]

Beautiful results in the reaction $J/\psi \rightarrow \gamma\gamma\gamma$ measured in the DM 2 detector with angular resolution worse than the one expected in OBELIX can be seen in Fig. 4.8.

The expected $\sigma_M/M$ versus the momentum of the decaying particle is shown in Fig. 4.9. The invariant mass resolution $\sigma_M$ varies from 0 to 3 MeV for momenta from 0 to 1.5 GeV/c with $\Delta \alpha = 4$ mrad.

Figure 3.43 compares the Dalitz plots for the reaction $J/\psi \rightarrow 3\gamma$ in two detectors, of which one, DM 2, has good angular resolution, and the other, XB (Crystal Ball), good energy resolution. The advantage of high angular resolution in reactions of this type is evident. Notice that our specifications for angular resolution are better than those of DM 2 (cf. Table 4.1).

3.3.6 The HDSPC (High-Density Spiral Projection Chamber) end-cap calorimeters

In the end-caps we plan to employ a shower detector with a new geometry, the High-Density Spiral Projection Chamber (GAS 85b).

The two HDSPCs will cover 12\% of the total solid angle and will image the showers of $\gamma$'s and the tracks of prongs emitted forward and backward to the interaction volume.

The HDSPCs give a very good $\gamma$ identification with a three-dimensional sampling of the shower; a good measurement of the conversion point ($\sigma_r \sim 300 \mu m$, $\sigma_\phi \sim 25$ mrad, $\sigma_\theta \sim 1$ cm), resulting in high angular accuracy ($\sigma_\theta < 2$ mrad, $\theta_\phi \sim 25$ mrad) at all emission angles; a calorimetric measurement of a $\gamma$ energy ($\sigma_\gamma/E \sim 18\% E^{1/2}$); and the shower direction of high-energy $\gamma$'s.

Prongs are scattered and lose energy in the radiators. The HDSPCs image their trajectory (and that of the secondary particles emitted in the interaction with the radiator), sample their energy loss, and measure the range of those prongs that stop inside the radiator.

3.3.6.1 Detector-structure-and-operation

The general layout of an HDSPC is shown in Fig. 3.44a. A radiator (shown in Fig. 3.44b) is inserted into the peripheral part of an SPC modulus (Fig. 3.12a) and the electric potentials are arranged so that the electric field distribution in the drift spaces is the same as in the SPC. The principles of operation are also the same as for the SPC; consequently the detector provides a three-dimensional image of all the ionization deposited in the drift space in between the disks of the radiator, and so visualizes the track of a prong that traverses
the radiators, and also the electrons and positrons produced by a $\gamma$ converting
in a plate.

The radiator is made of equally spaced disks supported by a metallic tube
with an internal diameter of 6 cm. These disks, which are all equal in size, are
made of lead plates sandwiched between aluminium plates. Each disk is coated
with a layer of Araldite, onto which a uniform coating of highly resistive
material is deposited. The disks are spaced by means of metallic rings which
ensure electrical contact between the support tube and the high-resistance
coating. These rings constitute the internal cathode of the HDSPC. There are
20 disks per radiator. We plan to use 3 mm thick Pb radiator plates (~ 0.5 r.l.).
The full radiator will have 10 r.l.; it will, however, be possible to have
thicker places in the shower containment region. Once the radiator disks are
assembled and fixed onto the support tube, a grid (called a drift grid) made of
100 $\mu$m Cu wires parallel to the tube axis will be fixed with conductive glue at
the periphery of the radiator. The radiator is plugged into an SPC modulus, and
negative high-voltage is applied to the support tube and negative voltage to the
drift grid. Current flows from the centre of the disks out to the edges and
finds a resistance which reduces with the radius with a $1/r$ dependence. Conse-
quently, the electric field has $1/r$ dependence on the surface of the radiator
plates as well as in the drift regions. The voltages of the drift grid and the
drift wires of the SPC modulus are adjusted appropriately. The drift wires could
even be used for gating purposes once we have required some experience and if
really needed at very high reaction rates.

3.3.6.2 Electronics

The electronics will be exactly the same as for the SPC, and with the same
number of channels per HDSPC (90 wires).

3.3.6.3 Performance

Each HDSPC covers 7% and 9%, respectively, for $\gamma$ and prong detection, with
$\gamma$-detection efficiency of about 100% above 200 MeV.

The specifications of the HDSPC's are listed in Table 3.5.
Table 3.6
HDSPC specifications

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of sense wires</td>
<td>90</td>
</tr>
<tr>
<td>Wire length (cm)</td>
<td>40</td>
</tr>
<tr>
<td>Minimum distance from detector centre (cm)</td>
<td>26</td>
</tr>
<tr>
<td>Radiator radius (cm)</td>
<td>13</td>
</tr>
<tr>
<td>Sense wire radius (cm)</td>
<td>15.5</td>
</tr>
<tr>
<td>Solid angle for p (%)</td>
<td>6</td>
</tr>
<tr>
<td>Solid angle for prongs (%)</td>
<td>8</td>
</tr>
<tr>
<td>$\gamma$-detection efficiency</td>
<td>$\sim 100%$, above 200 MeV/c</td>
</tr>
<tr>
<td></td>
<td>$\sim 70%$, at 100 MeV/c</td>
</tr>
<tr>
<td>Energy resolution $\sigma_E/E$ (%)</td>
<td>18% $E^{-1/2}$</td>
</tr>
<tr>
<td>Position resolution $\sigma_r$ ($\mu$m)</td>
<td>300</td>
</tr>
<tr>
<td>$\sigma_z$ (mm)</td>
<td>4   (disk spacing 2 cm)</td>
</tr>
<tr>
<td>$\sigma_\phi$ (mrad)</td>
<td>$\leq 25$</td>
</tr>
<tr>
<td>Angular resolution $\sigma_\theta$ (mrad)</td>
<td>$&lt; 2$</td>
</tr>
<tr>
<td>$\sigma_\phi$ (mrad)</td>
<td>$\leq 25$ at all $\theta$'s</td>
</tr>
</tbody>
</table>

The maximum momenta of charged particles that stop in the HDSPC are given in Table 3.7. The energy uncertainty quoted is the maximum energy that can be lost in the plate where the prong stops.

Table 3.7
Maximum energy and ranges of prongs in the HDSPC

<table>
<thead>
<tr>
<th></th>
<th>$\pi^-$</th>
<th>$K^+$</th>
<th>$p^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum (MeV/c)</td>
<td>212</td>
<td>450</td>
<td>684</td>
</tr>
<tr>
<td>Kinetic energy (MeV)</td>
<td>114</td>
<td>174</td>
<td>223</td>
</tr>
<tr>
<td>Max. energy loss in the last plate (MeV)</td>
<td>17</td>
<td>29</td>
<td>37</td>
</tr>
</tbody>
</table>

Charged kaons can then be identified in the HDSPC up to 450 MeV/c by $dE/dx$ and range measurements.
3.4 Trigger

The detector can stand high beam rates without damage, and up to 200,000 annihilations per second without confusion between events. It will require moderate beam intensity in a first phase and high Ω beam intensities in several cases:

i) for Ω production for Ω physics,
ii) to search for rare reactions,
iii) for annihilation in flight,
iv) increase, with selective triggers, the statistics of channels where structures will have been discovered in the analysis of high-statistics, low-bias data samples.

We foresee a number of parallel on-line triggers that can be combined to increase the trigger selectivity. Some possibilities are listed below:

- X-ray trigger (isolated single-ionization cluster in the XDC/SPC) to select p-wave annihilations;
- K⁺ₜ trigger (increase of the hit multiplicity with increasing radius in the XDC/SPC);
- nuclear products' multiplicity (XDC/SPC multiplicity near to the Mylar);
- annihilation prong multiplicity (multiplicity in the tof and TOF scintillators and in the HDSPC);
- K⁺ trigger (by TOF and fast-transverse-momentum reconstruction);
- high-transverse-momentum particles (by a drift-chamber hit row contained in a 4° sector);
- γ/π⁺ triggers (cluster multiplicity in the HARGD and HDSPC γ detectors).

The architecture of the trigger system is shown in Fig. 3.45.

Event triggers can be divided into two categories:

i) fast (nanosecond),
ii) slow (microsecond).

3.4.1 Fast triggers

These triggers arise from the detection of the incident reacting particle by the beam telescope or in a fast time-of-flight selection of a particle produced in the reaction. The fast pulses from the scintillators tof and TOF can be used to trigger on kaons and hadrons.

We will use a thin (50 μm) silicon surface barrier counter in the incident antiproton beam to define the arrival of an antiproton in the target. Such a counter is capable of nanosecond time resolution.

Further fast triggers can be produced by a multiplicity measurement in the fast logic system. An increase in the multiplicity of the charged tracks in the
ASTERIX SPC has been used to select $K_S^0$ events in which the $K_S^0$ conversion occurs in the SPC and, as a result, the number of charged prongs increases by two (Fig. 3.45). Such a trigger gives a spectacular trigger-rate reduction.

3.4.2 Slow triggers

Triggering on events in which either the energy or the momentum of the emerging particle is measured is of necessity slower than when only a fast timing signal is required. Drift times in the SPC and AFS may take up to a microsecond, whereas the reduction of the data by a rudimentary tracking program requires several hundred microseconds. If parallel processors are used to define such tracks, the process can be speeded up dramatically. Such a processor (KOP) has been developed and tested at CERN for the UA2 experiment and will be used for triggering in reactions in which momentum cuts are required.

The HARGD data can be processed much more quickly, as the production of showers from the converted gamma-rays is a fast process and fast gamma-ray triggers will be implemented by using data from these detectors at the logic level.

The HDSPC will require microprocessor calculations of the shower and range data, and cannot be used in the fast trigger system.

Finally, reactions in which the incident particle is an antineutron will require special triggering. The antineutrons are produced by charge exchange of an antiproton in an hydrogen target. The incident antiproton will produce a timing signal which can be related to the flight time of the antineutron by measuring the event time of the reaction products in the tof. Such a trigger already reduces the rate to such an extent that further rate-reducing triggers are not necessary.

3.5 Data acquisition

The data-acquisition system for the ASTERIX experiment was CAMAC-based, with some fast processors (Supercaviars) for the data organization before the data were transmitted to the PDP11-60 HOST computer. The OBEIX system will be more complicated owing to the increased number of functions that have to be performed when reading out the data from

- 270 spiral projection cells,
- 3444 drift chamber anodes,
- 120 double-ended scintillator strips,
- 11,000 drift tubes,
- 14,000 streamer tubes.

The system requires amplitude measurement in every channel except the streamer tubes. It requires the measurement of the drift times in all the drift tubes and in the SPC and the HDSPCs. It also requires fast logic signals from
the scintillators for the TOF timing so as to separate the pions from the kaons. Some fast analysis has to be done to limit the data flow to the interesting events and to prevent saturation of the system.

The general data-acquisition scheme is shown in Fig. 3.46. In order to permit fast data reduction, microprocessors will be used on the various detector modules of the system. No firm decision has yet been taken regarding the system architecture. Both FASTBUS and VMEbus are under consideration. The use of personal computers as local terminals in the VMEbus system give this option certain cost advantages. The host computer will be a VAX 780.

3.6 On-line monitoring

The data that is being written on tape will be sampled for on-line analysis in the VAX. It will be transmitted to the monitors, where it will be displayed along with the system parameters that will be collected in its own personal microprocessor-controlled channel. Intelligent terminals will be used to display and histogram data.

3.7 Detector simulation and event reconstruction

Because of the scale and complexity of the detector, we will use modular software. The choice is also motivated by the fact that software already exists for certain components of the system. Modular software will allow us to test and remove certain parts without affecting the overall performance of the program. Independent software development can proceed for the various components that will be assembled at the different home institutes.

For program exchange and data communication the Collaboration will take advantage of the network connections between the host computers of the different groups in the collaboration and with the CERN computer centre. The viability of such a link has already been established in the ASTERIX experiment in which the Canadian group has done significant program development and data reduction on the computer at the University of British Columbia. The French component of the Collaboration has requested time on the IBM 3090 at the new National Computer Centre at Lyon. The Italian institutes have VAX computers that are linked together via INFNET. A VAX has been chosen as the host computer for our data-acquisition system.

We will require the use of the CERN central computing facility for the development of the data-acquisition routines and for the processing and analysis of data samples. The mass data reduction will be done at the computers at the various participating institutes.
3.7.1 Detector simulation

The aim of the detector simulation program is to produce Monte Carlo data files with the same format and characteristics as those of the expected experimental data. The simulated data will provide

i) optimization of the detector performances for the experimental set-up and the measurement of the system efficiencies;

ii) the checking of different trigger strategies;

iii) input to the data analysis programs to test track reconstruction programs.

iv) aid in the interpretation of the experimental data.

The detector simulation program will be written in the GEANT 3 framework, which provides a complete system of detector description and particle-tracking tools.

3.7.2 Event reconstruction

As is the case for the detector simulation, the track reconstruction programs rely on the existence of programs for certain components of the existing hardware packages. These packages exist for the SPC, the AFS jet chamber, HARGD, and the HDSPC.

The most complex of these is that for the AFS drift chamber, and we are thankful that the collaboration has provided us with a complete package for this.

For the SPC and HDSPC we plan to improve on the ASTERIX programs.

For the SPC a sophisticated drift-chamber simulation program has already been adapted to our special cylindrical geometry (BUS 85).
4. DETECTOR PERFORMANCES

In this section we will summarize the main characteristics and the overall performance of our apparatus for measuring single charged and neutral particles and intermediate-state resonances decaying into charged particles and gammas. In Table 4.1 the characteristics of OBELEX are compared with those of similar equipment in operation at e+e− machines.

4.1 Charged particles

As far as the detection of single charged particles is concerned, OBELEX is equipped with the SPC, the AFS jet chamber, TOF, HDSPCs, end-caps, and HARCD. The SPC makes it possible to reach a very low threshold in detecting low-momenta particles, as already indicated in Table 3.2. In particular, we can detect recoil protons down to 30 MeV/c and the 70% of the nuclear fragments. Charged particles are detected over 98% of the total solid angle.

Identification of charged prongs is obtained from measurements of dE/dx in the SPC and AFS chambers, from time of flight, and from range measurements in the HDSPCs and the HARCD. Figure 4.1 shows the π/K/p separation in the non-relativistic region obtained from dE/dx measurements by means of the AFS drift chambers. Figure 4.2 shows the features of the TOF system which enables π/K separation up to 1 GeV/c, e/π up to 400 MeV/c, and K/p up to 1.7 GeV/c over 70% of the total solid angle.

The momentum resolution of the SPC and AFS jet chamber is plotted in Fig. 4.3. The combined use of the SPC and the AFS drift chambers results in remarkable momentum resolution in a range from 30 MeV/c to 2 GeV/c. The direction resolution is σφ = 3 mrad and σθ < 15 mrad. The annihilation vertex is reconstructed to ±500 μm in the rθ plane.

4.2 K0S and Λ

The SPC will give an efficient trigger and allow visualization of neutral particles decaying into charged particles, as shown in Fig. 3.22. The detection efficiency depends upon the inner radius of the SPC and on particle momenta. With the planned inner radius of 3 cm for the SPC, we will be able to detect 17% of K0S and from 30% to 60% of Λ's decaying into charged particles. Measurement of the invariant mass is obtained from SPC and AFS chamber data, and the mass resolution ranges from 4 to 15 MeV for K0S, with momenta from rest to 1 GeV/c, as shown in Fig. 4.4.
## Table 4.1
Summary of OBELIX characteristics and comparison with DM 2, MARK III, and CLEO experiments

<table>
<thead>
<tr>
<th>Component</th>
<th>DM 2</th>
<th>MARK III</th>
<th>CLEO</th>
<th>OBELIX</th>
<th>ASTERIX</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Magnet</strong></td>
<td>Solenoid (internal coil)</td>
<td>Solenoid (external coil)</td>
<td>Superconducting solenoid</td>
<td>DAAP</td>
<td></td>
</tr>
<tr>
<td>Gap (mm)</td>
<td>3000</td>
<td>3500</td>
<td>3150</td>
<td>1500</td>
<td></td>
</tr>
<tr>
<td>Height from bottom yoke (mm)</td>
<td>1000</td>
<td>1715</td>
<td>2057</td>
<td>2500</td>
<td></td>
</tr>
<tr>
<td>Nominal axial field (T)</td>
<td>0.5</td>
<td>0.4</td>
<td>1</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Radial field homogeneity (%)</td>
<td>≤ 1</td>
<td>≤ 1</td>
<td>≤ 1</td>
<td>≤ 1</td>
<td></td>
</tr>
<tr>
<td>Power (MW)</td>
<td>2.3</td>
<td></td>
<td></td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>Current (A)</td>
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<td></td>
<td></td>
<td>1500</td>
<td></td>
</tr>
<tr>
<td>Total weight (t)</td>
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<td></td>
<td></td>
<td>300</td>
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</tr>
<tr>
<td><strong>Central detector</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of readouts</td>
<td>MWPC 2240</td>
<td>Drift 128</td>
<td>MWPC 720</td>
<td>SPC/EDC 30</td>
<td>SPC/EDC 30</td>
</tr>
<tr>
<td>Points per track</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thickness of active volume (mm)</td>
<td>90</td>
<td>98</td>
<td>97</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>Ψ/4π (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>≤ 100</td>
<td>100</td>
<td>≤ 100</td>
<td>≤ 100</td>
<td></td>
</tr>
<tr>
<td>e(dE/dx) (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Tracking devices</strong></td>
<td>Drift chamber</td>
<td>Drift chamber</td>
<td>Drift chamber</td>
<td>AFS drift chamber</td>
<td>MWPC</td>
</tr>
<tr>
<td>Total No. of wires</td>
<td>2040</td>
<td>2544</td>
<td>5304</td>
<td>3444</td>
<td></td>
</tr>
<tr>
<td>Points per track</td>
<td>13</td>
<td>38</td>
<td>17</td>
<td>42</td>
<td></td>
</tr>
<tr>
<td>Ψ_3 (%)</td>
<td>207</td>
<td>220</td>
<td>180</td>
<td>200</td>
<td>600</td>
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<tr>
<td>Ψ/4π (%)</td>
<td>82</td>
<td>93</td>
<td>73-97</td>
<td>75</td>
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<tr>
<td>Ψ/4π (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>≤ 100</td>
<td>97</td>
<td>≤ 100</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>e(dE/dx) (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>σ(p)/p</td>
<td>0.014(p^2+1)^{1/2}</td>
<td>[0.015]^2</td>
<td>[(0.47pe sin θ/θ)^2 (0.0688 sin θ/θ) + (0.0438 cos θ/θ) sin θ/θ)^1/2</td>
<td>800 MeV/c</td>
<td></td>
</tr>
<tr>
<td><strong>Time of flight</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inner TOF distance (mm)</td>
<td>970</td>
<td>1180</td>
<td>2350</td>
<td>180</td>
<td></td>
</tr>
<tr>
<td>Outer TOF distance (mm)</td>
<td>56</td>
<td>48</td>
<td>55</td>
<td>30 + 90</td>
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</tr>
<tr>
<td>Number of scintillators</td>
<td>20</td>
<td>50</td>
<td>25</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Inner TOF thickness (mm)</td>
<td>56</td>
<td>48</td>
<td>55</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Outer TOF thickness (mm)</td>
<td>20</td>
<td>50</td>
<td>25</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>G/4π (%)</td>
<td>79</td>
<td>60</td>
<td>66</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>σ(t) (ps)</td>
<td>800</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>σ/K separation (GeV/c)</td>
<td>0.8</td>
<td>1</td>
<td>0.8</td>
<td>30</td>
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Table 4.1 (Cont.)
Summary of OBELIX characteristics and comparison with DM 2, MARK III, and CLEO experiments

2) GAMMAS

<table>
<thead>
<tr>
<th>Aramid detector</th>
<th>DM 2</th>
<th>MARK III</th>
<th>CLEO</th>
<th>OBELIX</th>
<th>ARTEMIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum distance from target (mm)</td>
<td>1500</td>
<td>1260</td>
<td>2350</td>
<td>1400</td>
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<tr>
<td>Number of shower samples</td>
<td>19</td>
<td>24</td>
<td>44</td>
<td>25</td>
<td>??</td>
</tr>
<tr>
<td>0/4w (%)</td>
<td>70</td>
<td>76</td>
<td>47</td>
<td>70</td>
<td>50</td>
</tr>
<tr>
<td>Efficiency (%) (E \geq 200 MeV/c)</td>
<td>-100</td>
<td>100</td>
<td>-100</td>
<td>-100</td>
<td>\leq 40</td>
</tr>
<tr>
<td>E/E (%)</td>
<td>15/10</td>
<td>17/10</td>
<td>17/10</td>
<td>18/10</td>
<td></td>
</tr>
<tr>
<td>Total rad. length (X/X_0)</td>
<td>5</td>
<td>11</td>
<td>12</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>\sigma_0 for shower protons (mm)</td>
<td>6</td>
<td>15</td>
<td>15</td>
<td>1</td>
<td>0.6</td>
</tr>
<tr>
<td>\sigma_2 for shower protons (mm)</td>
<td>3</td>
<td>27</td>
<td>15</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>\sigma_0 (rad) (y direction)</td>
<td>10</td>
<td>7</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>\sigma_2 (rad) (y direction)</td>
<td>7</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

End-cap detectors

| Minimum distance from detector centre (mm) | 1380 | 1390 | 1140-1640 | 250 | 600 |
| Number of shower samples | 12 | 24 | 20 | 25 | |
| 0/4w (%) | 12 | 30 | 22 | 12 | -25 |
| E/E (%) (for y) | 17/10 | 17 (9 GeV) | 18/10 | |
| Efficiency (%) (E \geq 200 MeV/c) | 100 | 100 | 100 | 100 | -40 |
| Total rad. length (X/X_0) | 5 | 12 | |
| \sigma_0 (\mu m) | |
| \sigma_2 (\mu m) | 4 |
| \sigma(E) (MeV) (for \mu) | 7 |
| \sigma(E) (MeV) (for \pi) | 12 |
| \sigma(E) (MeV) (for \rho) | 16 |
4.3 Single-$\gamma$ detection

OBELIX detects gammas mainly by means of the HARGD and the HDSPCs (10 r.l.), which are highly segmented and permit a three-dimensional reconstruction of showers and excellent angular resolution. The solid angle covered is 82%. The overall detection efficiency is: 100% above 200 MeV/c and 70% at 100 MeV/c. The calorimetric energy resolution $\sigma_E/E$ is $18%/E$.

In order to measure the energy of single $\gamma$'s we will trigger on those that convert in the SPC container and in the inner TOF array. This trigger has been tested in ASTERIX (see Fig. 4.5). A very good energy resolution, $\sigma_E/E < 2.5%$ at all energies, will be achieved by using the AFS chambers as a $2\pi$ pair spectrometer. The trigger on these is made by requiring a jump in the multiplicities in the SPC and in the AFS jet chambers.

4.4 $\pi^0$, $\eta$, and other particles decaying into two gammas

In reactions where monochromatic $\pi^0$ or $\eta$ are produced, the decay opening angle of the two associated gammas follows a Jacobian distribution.

The minimum decay opening angle versus total energy for $\pi^0$ and $\eta$ is given in Fig. 4.6, whilst Fig. 4.7 shows the decay opening angle distributions for monochromatic $\pi^0$'s of different energies. The energy of $\pi^0$'s and $\eta$'s identified by missing mass can be deduced with high accuracy from the measurement of the opening angle [see Fig. 4.8 (AST 80)]. For $\pi^0$'s up to 1 GeV/c the energy resolution will be better than 2%.

In reactions where the total energy of a particle decaying into 2$\gamma$'s is fixed by kinematical constraints, the error on the invariant mass is determined only by the opening angle error. Figure 4.9 shows the beautiful 2$\gamma$ invariant mass results in the reaction $J/\psi \rightarrow 3\gamma$ obtained with the DM 2 detector, which has $\sigma_\Theta = 7$ mrad and $\sigma_\phi = 10$ mrad. OBELIX has an angular resolution which is three times better in $\Theta$ and two times better in $\phi$.

The expected resolution on the invariant mass versus the momentum of the decaying particle is shown in Fig. 4.10. The invariant mass resolution varies from 0 to 3 MeV for momenta from 0 to 1.5 GeV/c, with an opening angle resolution $\sigma_\alpha = 6$ mrad.

4.5 Resonances

Figure 4.11 shows examples of $\omega$ and $\eta$ decays in $\pi^+\pi^-\pi^0$ from bubble chamber and ASTERIX data, with the $\eta/\omega$ recoiling against a $\pi^+\pi^-$ or a $K\bar{K}$ pair. It is easy to see the impressive background reduction achievable when studying decay channels with kaons, thanks to the absence of combinatorial background. OBELIX has a factor of 2-3 better resolution than ASTERIX, plus the capability of triggering on channels with neutral and charged kaons.
4.6 X-rays

OBELIX will have higher detection efficiency than ASTERIX for protonium X-rays owing to the reduction of the target diameter and to the associated increase of active volume for absorbing higher energy X-rays. We will also be able to measure the X-ray energy by mean free path measurement, owing to the better vertex reconstruction and the rigorous mapping of the drift-cell geometry. The detection efficiency will be typically 50% in the L- and K-line region.
5. **EXAMPLES OF SENSITIVITIES**

We anticipate that in the ACOL era much will remain to be done in the study of $p\bar{p}$ annihilation no matter how successful the analysis of the large amount of data already taken with the ASTERIX detector may turn out to be.

Although a better knowledge of interesting channels (as yet undetermined) could come from increased statistics obtained with specific on-line triggers, the use of a detector with characteristics much superior to those of ASTERIX will in any case be required. The properties of the different components of the detector proposed here have been summarized in Table 4.1, where those of ASTERIX are also given.

It is important to emphasize again that the values quoted for the different parameters are not design values but measured ones.

Indeed for charged particles, the central detector is an improved version of the one used in ASTERIX, whilst the tracking drift chamber is the one used in extensive experiments at the ISR.

For gamma detection, the proposed detector is very similar to detectors used in experiments by the MARK III Collaboration at SLAC or the DM 2 Collaboration at LAL.

We believe that the well-known properties of our detector will allow us to quote its expected performance with confidence, although due care must be exercised to take into account that the range of gamma energies is different.

In Section 2 we elaborated on the physics objectives we would like to pursue. Briefly, they may be summarized as follows:

a) Resonance production

i) Study of the light $(q\bar{q})$ mesons

Here the classification is far from complete or satisfactory. Are the $\delta$, $\pi'$, $\eta$, $\kappa$ the SU(3) scalars, or should they be interpreted at $q^2\bar{q}^2$ states?; which are the actual members of the $J^{PC} = 1^{++}$ and $1^{--}$ nonets? In particular, what is the $E$ meson? These are some of the obvious questions which as yet have not received a satisfactory answer and which $p\bar{p}$ annihilations (in which some of the states were first observed) could help to solve.

ii) Are there exotic states -- baryonium, glueballs, hybrids?

Accepting QCD as the correct theory of strong interactions implies the existence of these exotic states. Although a consensus from different models is gradually emerging on the $J^{PC}$ and masses of members of the ground levels, the same cannot be said about their widths or decay modes.
b) Study of quark and gluon dynamics

Here we would like to establish how the quarks, antiquarks, and gluons in a \( p\bar{p} \) system with fixed quantum numbers (isospin, spin parity, and charge conjugation -- \( I^J_{PC} \)) transform into different final states formed by particles (resonances) with well-defined quantum numbers. Because of the difficulties inherent in the analysis of three-body production, we will concentrate attention on quasi-two-body channels only.

The above considerations indicate the need to attempt a study of all possible \( p\bar{p} \) annihilation channels with good statistics. This, in turn, implies first the determination of all possible final states, e.g., to establish the final state \( \pi^+\pi^-\pi^0 \) as a first step towards measuring the contributions of channels such as \( \varphi(\pi^+\pi^-)\pi^0 \), \( f((\pi^+\pi^-)\pi^0 \), \( X^0(\pi^+\pi^-)\pi^0 \), \( \pi^+\pi^-\pi^0 \) (phase space), etc.

In the following we present qualitative arguments to show that the proposed detector can contribute greatly to reaching the indicated goals. More elaborate Monte Carlo studies are in progress to verify quantitatively the claims now made.

We will limit ourselves to annihilation either into pions only, or into kaon pairs with and without accompanying pions. These constitute the bulk of the annihilations. Extension of the arguments to much rarer radiative processes should often be fairly straightforward.

A convenient starting point is provided by Table 5.1, which illustrates the requirements for fulfilling point (b) of our program. It shows the different associated productions of members of \( SU(3) \) nonets available to \( p\bar{p} \) annihilations at rest. Besides the quasi-two-body annihilations forbidden by strangeness conservation (S) or phase-space limitations (E), we indicate with an 'A' those susceptible to analysis with the ASTERIX data, and with a 'D', those undetectable with ASTERIX.

The 'D' annihilations arise basically from the very limited \( 4\gamma \) detection possibilities of ASTERIX, where the product of the geometric \( (Q/4\pi) \) times the single-\( \gamma \) detection probability \( \epsilon \) is

\[
\left( \frac{Q}{4\pi} \epsilon \right) = 0.7 \times 0.3 = 0.21.
\]

For OBELIX, although the same number is \( 0.8 \times 1 = 0.8 \), in the following we will take it as \( 0.8 \times 0.9 = 0.72 \). This reduced probability of \( \gamma \)-ray materialization in the detector tries, somewhat arbitrarily, to take into account the inevitable cuts which are often needed for selecting reliable information.

In the following we examine, sector by sector, how OBELIX could establish the 'missing' D-entries and how they could establish the original \( p\bar{p} \) state.
Table 5.1
The associated production of members of SU(3) nonets available to $p\bar{p}$ annihilation at rest

<table>
<thead>
<tr>
<th></th>
<th>$\pi$</th>
<th>$\eta$</th>
<th>$\eta'$</th>
<th>$K$</th>
<th>$\phi$</th>
<th>$K^*$</th>
<th>$\delta$</th>
<th>$\epsilon$</th>
<th>$S^*$</th>
<th>$\kappa$</th>
<th>$\Delta^+$</th>
<th>$\Delta^-$</th>
<th>$T$</th>
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<tbody>
<tr>
<td>$\pi$</td>
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<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\eta$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\eta'$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The table shows the associated production of members of SU(3) nonets available to $p\bar{p}$ annihilation at rest.
5.1 Pseudoscalar-pseudoscalar sector

We will look at the \( \pi^0 \pi^0, \pi^0 \eta, \pi^0 \eta' \), and \( \eta \eta \) channels allowed by phase space, and which we considered as being inaccessible to ASTERIX (hereafter referred to as 'missing' channels). They require the observation of four \( \gamma \)'s. In OBELIX the probability of detecting them is \( 0.8^4 \times 0.9^4 = 26.9\% \) \((\text{geometric factor})^4 \times (\text{single-\( \gamma \) detection efficiency})^4\). This to be compared with \( 0.8^4 \times 0.3^4 = 0.33\% \) in ASTERIX.

In each channel we would have the following information:
- the momenta of the two particles are known by hypothesis -- they are equal and opposite in direction;
- the directions \((\theta, \phi)\) of each of the four \( \gamma \)'s are measured although their energies are not well known.

A kinematic fit with two constraints (2C fit) is therefore possible in each channel.

The expected contamination would come from \( 3\pi^0 \) events in which only four out of the six decay \( \gamma \)'s have been detected. The probability that four out of the six decay \( \gamma \)'s are detected is 32%.

The bubble chamber results show that 3% of all annihilations go into all neutrals. If we pessimistically assume that they are all \( 3\pi^0 \) events, \( 10^6 \bar{p}p \) annihilations will give

\[
10^6 \times 30 \times 10^{-2} \times 32 \times 10^{-2} = 10^4
\]

spurious \( 4\gamma \) events.

The boundary of the \( 3\pi^0 \) Dalitz plot is sketched in Fig. 5.1. The zones indicated by A, B, and C are those where two of the three \( \pi^0 \)'s are collinear and could therefore be confused with \( \pi^0 \pi^0 \) events, but having a momentum of 850 MeV/c instead of the 930 MeV/c of real \( \pi^0 \pi^0 \) events.

If we assume that only 10% of the Dalitz plot is occupied by collinear \( 3\pi^0 \) events and that 33% of these are not rejected by the kinematic fit, then the \( 3\pi^0 \) background would be

\[
10^4 \times 10^{-1} \times 33 \times 10^{-2} = 330 \text{ events}.
\]

If we require the \( \pi^0 \pi^0 \) signal to have an 8\sigma statistical significance, then

\[
8 \times \sqrt{330} = 145 \text{ events} \quad \text{must be observed, i.e. a branching ratio of}
\]

\[
\frac{10^{-6} \times 145}{(0.8)^4 (0.9)^4} = 5 \times 10^{-4}/\bar{p}
\]

would result.
For the annihilations $\pi^0\eta$ and $\eta\eta$ the $3\pi^0$ background would be lessened owing to the lower monochromatic momenta in these two channels.

Because of the very low rate $\eta' \rightarrow \gamma\gamma$ of $2\%$, the channels $\pi^0\eta'$ and $\eta\eta'$ should be better studied in the final states $\pi^0(\pi^+\pi^-\eta)$, and $\eta(\pi^+\pi^-\eta)$, which will be considered later.

These channels come from the ($p\bar{p}$) isotopic state $I = 0$ with $J^{PC} = 0^{++}$ (3$^2P_0$ state) and orbital angular momentum $l = 1$, or from the $1^{++}$ (3$^2P_2$) state with $l = 1$.

The easily observable $\pi^+\pi^-$ channel can come, in addition, from the $I = 1$, $1^-$ (3$^1S_1$) state, so that from the $\pi^0\eta^0$ and $\pi^+\pi^-$ rates the relative contributions of S- and P-states to $\eta\eta$ annihilations would be established. Note that the contribution obtained in this way with s- and p-wave contributions established from the X-ray information.

### 5.2 Pseudoscalar-vector sector

The 'missing' annihilations are

$$\pi^0 \omega \quad p^* = 775 \text{ MeV}/c,$$

$$\eta\omega \quad p^* = 650 \text{ MeV}/c,$$

$$\eta'\omega \quad p^* = 525 \text{ MeV}/c,$$

leading to the final state: $(\gamma\gamma)[\pi^+\pi^-(\gamma\gamma)]$. The resonances being narrow, the common momenta $p^*$ may be assumed to be monochromatic.

As a global fit with three constraints is possible, the channels are well determined.

The annihilation $\pi^+\pi^-3\pi^0$ is estimated (GHE 84) to occur with a branching ratio of $(23.3 \pm 3) \times 10^{-2}$.

The probability that $3\pi^0$ events lead to the observation of four $\gamma$'s being $32 \times 10^{-2}$, the effective branching ratio becomes

$$23 \times 32 \times 10^{-4} = 7.5 \times 10^{-2}$$

In the single-pion momentum observed by bubble chambers in the annihilation $2\pi^+2\pi^-\pi^0$, momenta greater than 600 MeV/c occur with a frequency of $\sim 3 \times 10^{-2}$. Therefore, at most 10% of the $\pi^0$'s in $\pi^+\pi^-3\pi^0$ could contribute to the background. If we assume that the fit can gain a factor of 5, we end up with a $3\pi^0$ background of

$$7.5 \times 10^{-2} \times 5 \times 10^{-2} = 1.5 \times 10^{-3}/p.$$
A branching ratio of $2 \times 10^{-3}$ would then be observed at the 6σ with $10^6 \bar{p}\bar{p}$ annihilations.

It has to be observed again that the annihilation $\eta'\eta$ would have to be looked for in the final state ($\pi^+\pi^-\eta$) ($\pi^+\pi^0\eta^0$), because of the low $\eta' + \gamma\gamma$ rate.

Both the $\eta\eta$ and $\eta\eta$ can come from the $J^{PC}(1^{-})^3S_1$ and $(1^{++})^1P_1$ initial $\bar{p}\bar{p}$ states, the first in the $I = 1$ ($\bar{p}\bar{p}$) and the second in the $I = 0$ states.

With X-ray information from the XDC, the S- and P-state contributions may be determined through the association of events with I X-rays observed.

5.3 Vector-vector sector

Only the $\eta\eta$ channel is 'missing'. It should appear in the final state

$$2\pi^+2\pi^-\eta^0(\gamma\gamma)\pi^0(\gamma\gamma) \quad p^* = 500 \text{ MeV/c}.$$ 

With the four $\gamma$'s observed, the annihilation is again susceptible to a 4C fit.

The $3\pi^02\pi^+2\pi^-$ rate is only 4% (GHE 84). Compared with the previous case, this contamination should now be very small and it would appear reasonable to assert that a 6σ deviation signal with a branching ratio of $\sim 10^{-3}$ is attainable with $10^6 \bar{p}\bar{p}$ annihilations.

The allowed initial $\bar{p}\bar{p}$ states have $I = 0$ and $J^{PC}: 0^{++}(1^1S_0); 0^{++}(3^5P_0); 1^{++}(3^3P_1); 2^{++}(3^3P_2)$.

Coincidence studies with X-rays would separate the S and P contributions.

5.4 Pseudoscalar-Axial Vectors sectors

Accessibility to the 'missing' channels:

$$\eta(A_1), \eta(D) \text{ and } \eta(B), \eta(H)$$

will be difficult because of a combination of

i) phase-space limitations,

ii) fairly large widths of the resonances which, together with

iii) low $\pi^0$ momenta, will lead to a very wide range of $\gamma$ energies for which the detector accuracy may be variable and poorly understood.

A more basic difficulty is that although the D and B mesons have well-established properties (mass, width, $J^{PC}$), the same is not true for other assumed members of the nonets; the mass and width of the $A_1$ are poorly established; the $E$ is not yet established as the $I = 0$ ($s\bar{s}$) member; whilst the $H$ has been seen in only one experiment and the H' not at all.
As should appear clear from the following subsections, the channels 
\( \pi^+(A) \to \pi^+ (\rho \pi^+) \) (with \( \rho \to \pi^- \pi^+ \)) and, for instance, \( \eta (D) \to \eta (\pi^+ \pi^-) \) or \( \eta (E) \to \eta (\pi^+ \pi^- + \rho) \) would offer no difficulties if occurring with branching ratios 
\( \gtrsim 10^{-3} \).

To complete the study of the dynamics in these sectors, the essential requirement is, therefore, to detect the not yet established members.

The general question of how well can be established the multipion final states where these and other resonances may occur is dealt with in the next subsection.

5.5 Multipion annihilations

Given the good accuracy with which the four-momenta of charged particles can be measured, the final states \( \pi^+ \pi^- X^0 \), \( 2\pi^+ 2\pi^- \), \( 2\pi^+ 2\pi^- \pi^0 \), \( 3\pi^+ 3\pi^- \), ..., where \( X^0 = \rho, \eta, \) or \( \eta' \), should be determined with very small backgrounds through kinematic fits with one or four constraints, depending on whether one or no \( X^0 \) accompanies the charged particles. The two \( \gamma \)'s for the \( X^0 \) decay will be detected in \( \approx 40\% \) of the events, allowing a 3C fit. They would provide a good check on the reliability of the fitting procedures.

Neutral multipion events or events with three or more \( \pi^0 \)'s will be very poorly detected or will have large backgrounds if they do not occur, as was the case in earlier subsections, in well-defined channels involving narrow resonances.

However, an isotopic spin decomposition of the \( I = 0 \) and \( I = 1 \) initial \( pp \) system into different isotopic spin groupings of pions [e.g. \( (5\pi) \to (\pi)(4\pi) \) or \( \to (2\pi)(3\pi) \) and the further decomposition e.g. \( (4\pi) \to (\pi)(3\pi) \) or \( \to (2\pi)(2\pi) \)] shows that with rare exceptions the isospin information contained in the easily accessible channels such as \( 2\pi^+ 2\pi^- \pi^0 \) is more complete than that contained in final states with a given number of pions when an even number of charged pions with total charged \( 0 \) are replaced by an even number of \( \pi^0 \)'s.

Nevertheless, the disentangling of isospin and the narrowing down -- if not the complete determination -- of other quantum numbers require the analysis of events where \( \pi^0 \)'s replace charged pions. As already pointed out, with OBELIX there is a good probability of detecting and fitting four \( \gamma \) events to the \( 2\pi^0 \) hypothesis, and thus observing events of the general type:

\[ \pi^+ \pi^- \pi^0 \pi^0 . \]

How the events from the two samples would be analysed is illustrated with the following example. Suppose that in the final state \( 2\pi^+ 2\pi^- \) an enhancement in the \( (\pi^+ \pi^-) \) mass distribution is seen, and one wants to see if it also occurs in the final state \( \pi^+ \pi^- \pi^0 \pi^0 \).
Events $\pi^+ \pi^-$ with four associated $\gamma$'s are then selected with a missing mass to the $(\pi^+ \pi^-)$ system embracing the region of the previously observed $(\pi^+ \pi^-)$ enhancement. These events are then subject to a 2C kinematic fit. If $I(\pi^+ \pi^-) = 0$, an enhancement with relative weight $1/2$ (after detection efficiency corrections) should appear in the $(3\pi^0)$ mass spectrum, whilst no enhancement would be observed if $I(\pi^0) = 1$.

Further progress in establishing the other quantum numbers would be made using the conservation rules: $G = C(-1)^I$ and $C = P = (-1)^J$, where $J$ is the spin of the $(\pi^0)$ enhancement.

Although similar arguments could be made comparing the $2\pi^+ 2\pi^- \pi^0$ and $\pi^+ \pi^- 3\pi^0$ final states [3$\pi^0$ detection probability = 14% and $I(3\pi^0) = 1$], we do not dare to make them without a Monte Carlo study of the combinatorial problem of assigning the six $\gamma$'s to the three $\pi^0$'s.

5.6 A sensitivity estimate

Without preconceived ideas it is difficult to give estimates of the branching ratio attainable for a given effect. The example given below may help to get at least a feeling for the orders of magnitude involved.

Assume that a $(\pi^+ \pi^- \pi^0)$ enhancement is being looked for in the reaction $\bar{p}p \rightarrow 2\pi^+ 2\pi^- \pi^0$. The bubble chamber result is that its branching ratio is $20 \times 10^{-2}$. Phase-space limits the $3\pi$ masses to occur between 0.5-1.5 GeV with the distribution sketched in Fig. 5.2.

The attainable branching ratio sensitivity would clearly depend on the mass at which the enhancement occurs and on its width. To be quite general we assume a flat mass distribution between the two mass limits.

The branching ratio per 10 MeV mass band $= 2 \times 10^{-3}/\bar{p}$. For $10^6 \bar{p}$ annihilations this gives $2 \times 10^3$ events per 10 MeV produced, of which $2 \times 10^3 \times 25 \times 10^{-2} = 500$ would be observed. A 6$\sigma$ enhancement would then correspond to

$$6 \times (500)^{1/2} = 135 \text{ observed events},$$

i.e. a $BR = 5.4 \times 10^{-4}/\bar{p}$. But both the number of events and the signal-to-background ratio $(S/B)$ are too small to make meaningful a determination of the quantum numbers of the enhancement.

If we require $S/B \geq 1$ and at least $10^3$ events, the branching ratio would have to be $\geq 1 \times 10^{-2}$ -- this for a resonance with a width $\sim 10$ MeV. If instead the width were 100 MeV, then the branching ratio would drop to $1 \times 10^{-2}$.
In our example these limits would apply at masses near 800 and 1200 MeV; they would be a factor of $\sqrt{2}$ worse at the top of phase space and decrease quickly for masses outside the limits inside the two mass values.

5.7 Proton-antiproton annihilations at rest into $K\bar{K}$, $n\pi$ ($n = 0, 1, 2, \ldots$)

Knowledge of the $p\bar{p}$ annihilation process into final states containing a kaon pair is still very limited owing to their low probability: $\approx 10\%$ of all annihilations. Bubble chamber experiments, because of the difficulty in measuring the specific ionization of charged tracks, could study only the annihilations giving rise to a visible $K_S^0 + \pi^+\pi^-$ decay, whilst counter experiments (e.g. ASTERIX) have not, as yet, had the possibility to make an unbiased selection of final states containing neutral or charged kaons.

Two unique properties of the proposed detector make a high-statistics study of the annihilation $p\bar{p} \rightarrow K\bar{K} +$ anything look very promising:
- the unambiguous off-line separation of pions and kaons over the full momentum range ($\gtrsim 1$ GeV/c) by a combination of TOF and dE/dx measurements;
- the possibility to trigger on charged kaons with little ambiguity and no bias over the full momentum range using TOF information.

Signalling a charged kaon in the trigger makes it possible to accumulate, for the first time, very large data samples containing kaon pairs in the final state without drowning in the multipion background. In addition, the accuracy in the determination of the momentum and the trajectory of the charged particles is much superior to previous experiments, allowing more precise studies of $K_S^0$ production and decay.

Before we proceed to a more detailed discussion of the detector performance for specific kaonic final states, we want to point out some of the physics arguments in favour of a high-statistics study of kaonic final annihilation states.

Apart from the lack of information about this process, which is an experimental challenge in itself, neither the study of quark-gluon dynamics nor the search for resonances can be completed without the analysis of annihilations involving kaon pairs accompanied or not by pions. Strange particles in the final state indicate the production of a $\pi\bar{\pi}$ quark pair during the annihilation and hence provide a window for looking at quark degrees of freedom.

If four quark states exist, their decay width is probably large (50-500 MeV/c). Four quark states containing only non-strange quarks will preferably decay into multipion final states, and their signature may be difficult to disentangle from the background. Four quark states of the type $qq\bar{q}\bar{q}$ will have a kaon pair in the final state, helping to reduce combinatorial and background problems. The study of the decay of 'glueball' candidates into as many final
states as possible, including the kaonic ones, tests the hypothesis of 'flavour blindness'. The E(1420), which in spite of all efforts is still subject to controversial discussions, decays mainly into \(K\bar{K}\) final states. All non-strange members of the scalar monet also decay into \(K\bar{K}\) pairs.

Naturally the question arises as to how well these states can be measured and separated from the background. In general, the pion multiplicity accompanying \(K\bar{K}\) production is lower than in pion annihilations. Consequently, the number of \(\pi^0\)'s that have to be detected is now smaller, and any given final state will be less affected by background problems than in the pion case.

We start now with the discussion of the detector performance for specific final states. Again the annihilation dynamics is closely linked to the measurement of the two-body or quasi-two-body annihilation branching ratios, whereas the search for resonances takes place in three- and more-body final states. Although most of the remarks made earlier on the detection efficiencies for multipion annihilations apply also for kaonic final states, kaon pairs present special characteristics that are worth recalling:

\[
K\bar{K}: K^+K^-, \ K^0\bar{K}^0, \ \bar{K}^0K^0
\]

Here all estimates made for \(\pi^+\pi^-\), \(\pi^+\pi^-\pi^0\), and \(\pi^+\pi^-+\) (missing mass) states apply. The \(K^+K^-\) channel can be easily separated from the background by kinematics and TOF + dE/dx measurements. The \(K^0\bar{K}^0\) channel, only accessible from the p-wave, has been seen in ASTERIX with a branching ratio of \(\approx 2 \times 10^{-5}/p\) annihilation. This channel can be examined with higher accuracy by means of a 6C fit; a better vertex determination allowing sharper cuts on the vertex separation and hence an increased number of \(K^0\bar{K}^0\) events in the final spectrum, and a better momentum resolution leading to a smaller background. The \(K^0\bar{K}^0\) (K^0 missing) channel -- giving a clear signal in the ASTERIX data over a relatively small background -- is also more easily accessible because of the better momentum resolution. The higher \(\gamma\) detection efficiency as well as the determination of the nature of the missing \(K^0\) reduces the background from \(\pi^+\pi^-\pi^0\).

\[
K\bar{K}: K^+K^-\pi^0, \ K^+\bar{K}^-\pi^+, \ K^0\bar{K}^0\pi^0, \ K^0\bar{K}^0\pi^0
\]

The \(K^+K^-\pi^0\) channel offers very interesting features:
- the possibility to trigger on two charged kaons yields a low background trigger rate;
- all events can at least be submitted to a 1C fit; if the two \(\gamma\)'s from the \(\pi^0\) decay are detected \([D.E. = (0.72)^9 \geq 50\%\ of\ the\ events]\), a 3C fit is possible.

The \(K^+K^-\) system may be in an \(I = 0\) or \(I = 1\) state. Any enhancement seen in \(K^+K^-\) will be visible in the \(K^+\bar{K}^0\) system if it has \(I = 1\), and it will disappear if \(I = 0\). The selection rule \(C = P = (-1)^I\), together with the fact that \(K^0\bar{K}^0\) and \(K^0\bar{K}^0\) are in \(C = +1\) and \(C = -1\) states, respectively, helps to determine \(I, C, P\) of a state and tells us if its angular momentum is even or odd.
Proper identification of the $K_S^0 K_S^0 \pi^0$ state requires the detection of four $\pi$'s and two $\gamma$'s ($0.8^4 \times 0.72^2 = 21\%$), but allows a 5C fit. This is useful for reducing the serious background in this final state.

**KK + 2 or more pions**

The number of possible intermediate resonant states increases rapidly with increasing pion multiplicity, but at the expense of the available phase space. Although there are many highly interesting channels contained in the accessible final states, we restrict ourselves to two examples: $K^+ K^- \pi^+ \pi^-$ and $K^+ K^- \pi^+ \pi^- \pi^0$. A strongly enriched sample containing these two final states can be achieved by requiring two charged kaons in the TOF trigger and a multiplicity of 4. The kaon momentum spectrum is known to end at $p \approx 400$ MeV/c, and hence the trigger efficiency is very good. The off-line analysis guarantees the unambiguous identification of all particles, and allows a 4C and a 1C fit, respectively. The latter can be improved to a 3C fit by detecting the two $\gamma$'s from the $\pi^0$ decay.

The $K^+ K^- \pi^+ \pi^-$ final state contains interesting information on two-body branching ratios such as $K^+ K^0, \phi, K\rho$, etc. There is $\pi^+ \pi^- (A_2 \rightarrow K^+ K^-)$ as well as the decay $\pi^0 (B^+ \rightarrow \pi^+ + K^+ K^- \pi^0)$, which is Zweig-forbidden but should exist because of $\omega\rightarrow \pi$ mixing. A complete analysis of the $\pi^+ \pi^- \pi^0$ Dalitz plot with high statistics could reveal the existence of $q\bar{q}s\bar{s}$ four-quark states.

The $K^+ K^- \pi^+ \pi^- \pi^0$ final state comprises two-body annihilations such as $(S^+, S^+, \phi) + \eta$, $(S^+, S^+, \phi) + \eta$, and also the $\pi^+ \pi^- (E + K^+ K^- \pi^0)$ and $\pi^+ \pi^- (D + K^+ K^- \pi^0)$. To give an idea of the expected rates, we assume a branching ratio of $pp \rightarrow \pi^+ \pi^- (E + K^+ K^- \pi^0) = 5 \times 10^{-7}$ (ASTERIX proposal), and of all annihilations $pp \rightarrow K^+ K^- \pi^+ \pi^- +$ neutrals of $10^{-2}$. With a trigger efficiency of 50%, a detection efficiency for four prongs of $(0.8)^4 = 40\%$, and a $pp$ stop rate of $10^8$ per second, one gets $10^5 \times 0.4 \times 10^{-2} / 0.5 \approx 800$ trigger per second, out of which $6 \times 10^{-7} / 2 \times 10^{-2} = 3\%$ would be $\pi^+ \pi^- (E + K^+ K^- \pi^0)$ events. The trigger rate will saturate the data-acquisition system, and, if one writes with a maximum tape-writing speed of 50 events per second, after one hour of data-taking there will be 180,000 events on tape, and of these, 5400 will be $\pi^+ \pi^- E$ events. This is a factor of 5 more (per hour!) than the present world statistics for $pp$ annihilation at rest.
6. **BEAM AND DETECTOR INSTALLATION**

6.1 **General remarks**

We plan to install the apparatus in the extreme top right-hand corner of the South Hall (Fig. 6.1). The magnet should be mounted in the place where at present the hut of the ASTERIX experiment is located. This arrangement optimizes the use of the experimental floor in the South Area, leaving maximum space for the beam transport lines, for installation of other experiments upstream of OBELIX, and for access from the South Hall extension. This layout is also essential in order to allow us to use the neutral p̅ beam line, which has to be a direct prolongation of the SL1 straight section of the LEAR machine. Space is necessary behind our magnet so as to have room for shifting the lateral HARGD supermodules.

During installation, our area can be isolated from the area in front. This would allow operation of other experiments which could be installed in the area actually occupied by the ASTERIX spectrometer. This scenario, which has been worked out jointly with the PS Experimental Area Group (SIM 85a), would also permit continuation of experiments sitting in the N1 beam without major changes, as they could keep their present electronics hut and cabling.

We plan to request beam starting from the second half of the 1988 after having completed the debugging of our detector with cosmics. Before requiring p̅ beam we will run tests with cosmics of the behaviour of all the detector components plus their calibration -- to the extent that the cosmics and sources are sufficient -- and report to the Committee.

6.2 **Antiproton beam**

The p̅ line envisaged for us and for the upstream experiments will have characteristics comparable with those of the present N1 line (SIM 85a, b) (good focus, achromatic beam, full energy swing), and will completely fulfil our needs.

6.3 **Antineutron beam**

The n̅ beam will be produced by charge exchange in a liquid H₂ target placed inside the upstream yoke of the magnet (Fig. 6.2). Antiprotons of 300 MeV/c are brought at rest into a 15 cm long target, and n̅ forward-produced by charge exchange will enter the experiment. The main characteristics of the n̅ beam have been computed with a Monte carlo simulation program, developed for PS178. The Monte Carlo takes into account geometry effects, energy loss of p̅ in the target, multiple scattering, and energy dependence of the differential cross-section for charge exchange reaction. The total n̅ rate at 0° for 10⁶ incoming p̅ is 1.58 x 10⁹. n̅ of all momenta between 100 and 300 MeV/c will be simultaneously
produced (Fig. 6.3). The energy of each annihilating \( \bar{n} \) will be determined by a TOF measurement. An overall resolution of less than 1 MeV and an angular uncertainty of 1° can be obtained (Fig. 6.4). The Monte Carlo data are confirmed by the first results of the ANTIN PS178 (PS 178 85) experiment. Figure 6.5 shows a TOF distribution with the \( \gamma \) and \( \bar{n} \) peaks clearly separated, performed by PS 178. Subject to proposed experimental verifications, in the future it would be interesting to expose our apparatus to a beam of polarized antineutrons.

6.4 Beam of \( \bar{p} \) atoms

Antiproton atoms emerge from the direct prolongation of the first straight section (SS1) of LEAR. The beam emittances are those of the circulating \( \bar{p} \) beam, or smaller.

The intensity varies from \( 10^3 \) to \( 10^5 \), depending on the working point of the machine and on the cooling of the \( \bar{p} \) beam (MÖH 85). A number of tests will be necessary in order to assess the final parameters of the beam. We will use this beam in an advanced stage of the experiment. The critical point is not to have mechanical obstructions in the straight line between SS1 in LEAR and our experiment.

6.5 Detector installation, debugging, calibration and maintenance

The installation of the magnet in the South Hall needs a hole about 2.5 m high \( \times \) 4 m wide \( \times \) 8 m long.

The feasibility and cost of this hole, together with the time schedule, have been studied with the PS EA Group and the SB Division.

It has been assessed that the hole can be made in such a way that it does not weaken the structure of the South Hall. The excavation should begin at the start of the AA shutdown in order to permit the magnet installation in early 1987, and then make free the access to the surroundings of the experimental area for installation of other nearby experiments.

The electronics will be arranged partly near the detector and partly in the data-acquisition room. A convenient place for the electronics hut is above the one of PS172 and PS185.

We plan to perform the debugging of the hardware and the electronics with cosmic rays.

All detector modules will be mounted on sliding supports for maintenance. Particular attention will be devoted to a well-designed cabling, which will also be discussed with the EA Group.
6.6 Safety

Our detector uses flammable gases which are provided by the LEAR gas-distribution facility, and which will be mixed near to the magnet. Each detector will be provided with its own gas distribution and control system.

We plan to have a forced ventilation in the lower part of the hole, and an automatic water-pump in case of water leaks.

The installation and the maintenance require space all around the magnet so as to have access to all the components of the apparatus.
7. **COST, RESOURCES, RESPONSIBILITIES**

The OAF magnet, the AFS jet drift chamber, the proportional drift tubes, and the tubes (and the electronics of the last two items) are available from CERN. All other equipment necessary for the OBELIX detector will be provided by the external participating institutes.

The estimated costs are shown in Table 7.1. The total funds required are balanced by the contributions of the collaborating institutes requested from funding agencies outside CERN.

As pointed out we have reserved at CERN, with the agreement of the former users, of the constructors, and of the division concerned: i) the OAF magnet, ii) the AFS jet drift chamber, iii) the tubes and associated electronics from the CHARM I Collaboration. The institutes outside CERN have requested about 6 million Swiss francs for purchasing the electronics for the drift chambers, and to cover the cost of the rest of the equipment to be built or bought.

Our priorities in the commissioning of the equipment are as follows: magnet, SPC and AFS jet drift chambers, TOF, HARGD, and HDSPEC.

The Aimé Cotton Group from Orsay plans to participate with the LEAR Group in laser tests on the $H^+$ beam. These tests are necessary in order to give the absolute calibration for high-resolution protonium spectroscopy, and also to provide a powerful non-destructive beam monitor for LEAR (COC 85). They will supply the necessary laser instrumentation.
### Table 7.1
Cost of new equipment

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<thead>
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<td>TDCs, preamplifiers</td>
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<td><strong>AFS</strong></td>
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<tr>
<td><strong>TOF</strong></td>
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<td></td>
<td>electronics</td>
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<tr>
<td><strong>SPC + HDSPE</strong></td>
<td>Mechanics</td>
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<td></td>
<td>FADC electronics</td>
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<tr>
<td><strong>HARGD</strong></td>
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<tr>
<td><strong>Trigger</strong></td>
<td>ECL logic</td>
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<tr>
<td><strong>Mechanics</strong></td>
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<tr>
<td><strong>Contingences</strong></td>
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</table>
8. REQUESTS TO CERN

We require the necessary floor space for the experiment along the neutral \( p\bar{p} \) line, and space for the electronics and the hut in the South Hall extension. The Collaboration will take care of the installation of the magnet and of the detector infrastructures.

We require extension to OBELIX of the support being given by the CERN EP Electronics Pool to the groups which are currently working with ASTERIX, ANTIN, and STREAMER.

The collaborating institutes have requested CPU on VAX, IBM 3090, CDC 7600, and IBM-like mainframes in the home institutes for the mass data-processing.

We will need to use the CERN Central Computing facilities for the development of data-acquisition routines and event reconstruction programs, for the analysis of data samples, and for a fraction of the final analysis but not for the mass data-production.

The total CPU time requested from CERN amounts to 600 CDC 7600 equivalent CPU hours during the next four years.

We need a CERNET link to our VAX data-acquisition computer.

Access to the floor will be necessary as from September 1986 in order to start installation work for the magnet.

We request the allocation of \( \bar{p} \) production corresponding to three ACOL days per year for a period of four years, starting at the end of 1988, in order to perform the measurements listed in Table 8.1.

Also, we will need beam at 100, 300, 600, and 1800 MeV/c, and eventually scanning in steps of 40 MeV/c below 400 MeV/c.

We request agreement for LEAR to make the necessary tests of the \( p\bar{p} \) co-rotating beam operation, and for the beam installations in the South Hall, to be compatible with the neutral \( p\bar{p} \) beam line.

A proposal for IDEFIX, with details of the experimental apparatus and beam-time request for the \( p\bar{p} \) operation of LEAR in main user mode, will be presented some years from now.
<table>
<thead>
<tr>
<th>Beam</th>
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<th>Total events on tape</th>
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$pp \rightarrow \pi^+ \pi^- \pi^0$ at rest in gas target

**P-Wave Annihilation**

![P-Wave Annihilation Graph](image)

**S-Wave Annihilation**

![S-Wave Annihilation Graph](image)

**Bubble Chamber Data**

$pp \rightarrow \pi^+ \pi^- \pi^0$ at rest in liquid target

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