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The OBELIX Collaboration

OBELIX Status Report and further Activities (LEAR experiment PS 201)

1 The OBELIX experiment

Meson spectroscopy is not an end in itself, it must be rather considered a tool for the study of Quantum Chromo Dynamics (QCD) in the non-perturbative sector. The mathematical techniques of perturbation theory, so successful in QED, can be applied with success to short distance phenomena (very high energy), where QCD and QED are similar in manifestations. But we do not yet know how to describe the long range confinement properties from first principles. This is a frustrating aspect of QCD. The depth of our ignorance can be illustrated by the fact that although it is widely accepted that hadrons are either baryons ($3q$ objects) or mesons ($\bar{q}q$ objects), we cannot explain this using QCD. Moreover, an unvindicated expectation from QCD, is the existence of a new form of matter, the glueballs (gg or ggg) and the hybrids ($qg\bar{q}$).

A rather established consensus in the theoretical/phenomenological activity concerns the prediction of the mass region which should be populated by gluonium and hybrids states. These mesonic resonances are expected in the low mass region of the hadron spectrum (between 1.0 and 2.5 GeV/c^2). Since this region is overpopulate by the standard $\bar{q}q$ mesons and their radial excitations, and a non-$\bar{q}q$ object may have allowed $\bar{q}q$ quantum numbers, the task of identifying exotic states is not simple.
The strategy developed in the last few years is to use reactions and processes which can tag the flavor content or the quantum numbers of the produced states and then to compare the production properties of a given new state in different reactions.

OBELIX has focussed its search on the mass region (below 1.8 GeV/c^2), with the aim of comparing different type of reactions, specifically with final states containing kaons, taking also advantage of the possibility to change the distribution of the protonium initial states by varying the target density, and, with the $\bar{n}$ beam, to have a pure isospin $I = 1$ in the initial state.

Another important field of research of OBELIX is the study of the annihilation dynamics through the measurement of two-body annihilation frequencies at rest and of the annihilation cross sections in flight at low energy. The possibility to extract from these data the hadronic branching ratios offers the possibility of a direct comparison with the theoretical predictions on quark dynamics.

The exploration of the validity of the OZI rule has suggested to OBELIX a systematic study of antinucleon annihilations in the channels $\phi\pi^{\pm}$ and $\omega\pi^{\pm}$, using both antiproton and antineutron beams. The dramatic OZI violation experimentally observed and the development of the analyses in progress will allow to check the correctness of the hypothesis of the intrinsic strangeness content of the nucleon.

2 The OBELIX detector

The OBELIX spectrometer was conceived as a general purpose, large acceptance ($\sim 3\pi$) and high resolution detector, aimed to the systematic study of antinucleon annihilation. In fact the apparatus is capable of detecting all the products, both charged and neutral, following the interaction of antinucleons on nucleons and nuclei.

Nowadays OBELIX has practically been turned into a facility, allowing a wide spectrum of different measurements, ranging from the atomic to the particle physics, and producing a large amount of original and interesting results. This has been made possible thank to the high versatility of the apparatus and, especially, to the possibility of changing the probe and/or the target without modifying the overall experimental set-up.

OBELIX can be regarded as an ensemble of four sub-detectors (whose detailed description can be found in Ref. [1]) arranged between and around the poles of the CERN *open axial field magnet* (OAFM) [2]. Fig. 1 gives a sketch of the detector complex, characterized by a cylindrical geometry.

Moving out from the axis of the apparatus one finds at first the target, whose

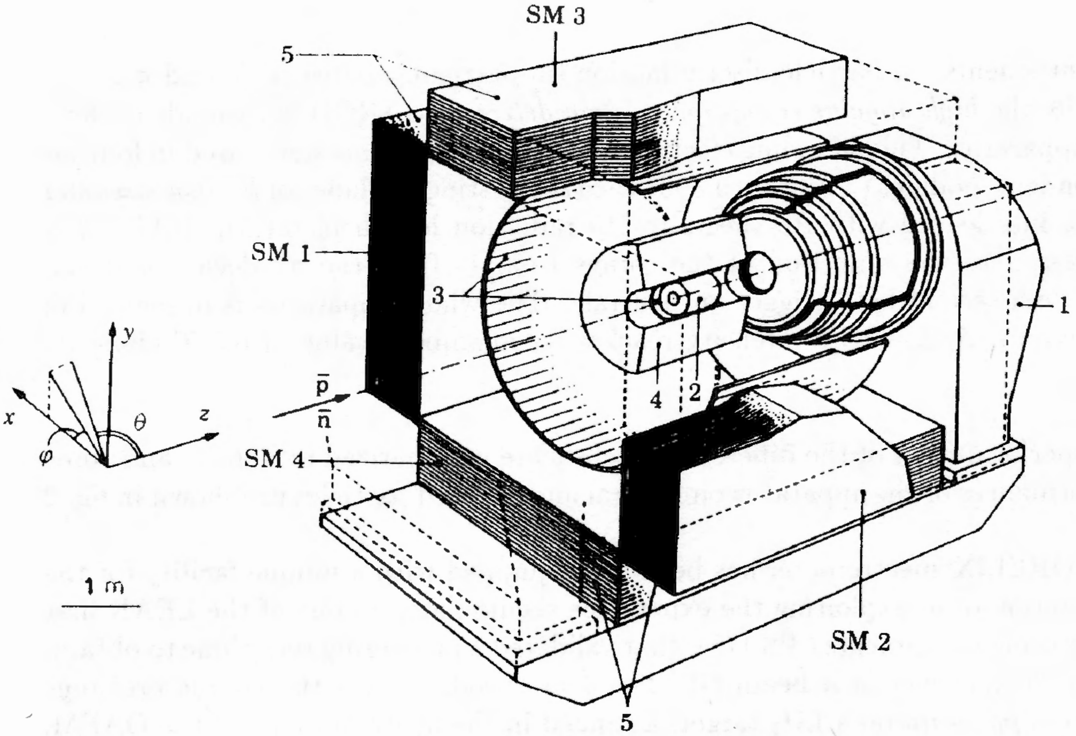

Figure 1: The OBELIX spectrometer: 1) Open Axial Field Magnet; 2) Spiral Projection Chamber; 3) Time-Of-Flight System; 4) Jet Drift Chamber; 5) HARGD (SM1–SM4: Left, Right, Top and Bottom Modules).

nature (gaseous H_2, D_2, ^3He, ^4He, liquid H_2, D_2, solid, ...) depends on the measurement one wishes to perform. A *spiral projection chamber* (SPC), allows the the determination of the interaction vertex and for the recognition of the annihilation prongs. In addition it allows the detection of the the X-rays following the de-excitation of the $\bar{p}p$ atom. Then a first layer of 30 thin (1 *cm*) plastic scintillators (nicknamed *tofino*), arranged as the staves of a barrel, provides the annihilation times to the OBELIX time-of-flight system (TOF). The outer *jet drift chamber* (JDC) is devoted to the tracking of particles. It allows the measurements of the particle momentum and of their dE/dx and contributes to the determination of the interaction vertex and of the topology of the event. The JDC consists of two semicylindrical "bicycle-wheel" drift chambers, 1.4 m long, radius 0.2-0.8 m, operating at atmospheric pressure with a 50/50 Argon/ethan mixture. The chambers are equipped with 3444 sense wires arranged in 4^0 sectors; each wire is instrumented with 8-bit FAD at both ends.
The JDC is, in turn, surrounded by a second barrel of 90 scintillators (nicknamed *tofone*), 4 *cm* thick. The tofino and tofone segmentation is exploited to provide the first level trigger based on the multiplicity of the charged annihilation products, on some selected topologies and, thank to precise time-of-flight

measurements, on particle discrimination (in particular between K and π). Finally the *high angular resolution gamma detector* (HARGD) surrounds ($\sim 3\pi$), the apparatus. This sampling electromagnetic calorimeter is structured in four independent modules ($4.0\times3.0\times0.8\ m^3$ each) consisting of planes of *limited streamer tubes*, interleaved with Pb sheets ($\sim$ 10 radiation length in total). HARGD is addressed to the detection of the γ-rays (mainly from the π^0 decay) and can provide a second level trigger on neutrals. The whole apparatus is immersed in a magnetic field, whose intensity reaches its maximum value of 0.5 T along its axis.

The performances of the different detectors are summarized in Tab. 1, and some performances of the apparatus on neutral and charged particles are shown in fig. 2

The OBELIX spectrometer has been also equipped with a unique facility for the production of $\bar{n}$, exploiting the experience accumulated in one of the LEAR first generation experiments (PS 178), that validated a pioneering technique to obtain, in an efficient way, a $\bar{n}$ beam [3]. The $\bar{n}$ are produced via the *charge exchange reaction* $\bar{p}p \rightarrow \bar{n}n$ on a LH_2 target, arranged in the upstream pole of the OAFM. A complete description of the set-up and of the method used to reconstruct the momentum of *each* annihilating $\bar{n}$ is reported in Ref. [6].

3 The OBELIX strategy

The $\bar{N}N$ annihilation process is characterized by ambiguities on the quantum numbers of the initial state from which the annihilation occurs, and by a great variety of possible multi-particle final states that have to be detected and identified by the experimental apparatus.

In annihilations at rest, the partition among the possible ${}^{2S+1}L_J\,(J^{PC})$ quantum numbers of the protonium six initial states:

$$^1S_0\,(0^{-+}),\quad ^3S_1\,(1^{--}),\quad ^1P_1\,(1^{+-}),\quad ^3P_0\,(0^{++}),\quad ^3P_1\,(1^{++}),\quad ^3P_2\,(2^{++}),$$

is influenced by the target density.

In a LH_2 target the Stark-mixing effect works strongly in favour of S-wave annihilation from the $^1S_0$ and $^3S_1$ states; on the other hand, in a low density gaseous H_2 target, P-wave annihilation should become the dominant process.

The idea of providing the OBELIX apparatus with GH_2 targets with a selectable density (just varying the gas pressure from a few bar down to 1 mbar) and with

SPC	pattern recognition efficiency	95%
	spatial resolution	$\sigma_{r\varphi} = 500\ \mu m$ $\sigma_z = 1\ cm$
	spatial resolution for vertex reconstruction	$\sigma_{r\varphi} = 1\ mm$ $\sigma_z = 5\ mm$
	X-rays detection efficiency	90%
	X-rays energy resolution σ_E/E ($\bar{p}p$ atom)	18% at 1.7 KeV (L_α) 10% at 3.0 KeV ($\mathrm{L}_\beta - \mathrm{L}_\infty$) 7.5% at 5.5 KeV (^{54}Mn)
	dE/dx	34% (FWHM)
JDC	pattern recognition efficiency	97%
	spatial resolution	$\sigma_{r\varphi} = 160\ \mu m$ $\sigma_z = 1.2\ cm$ (0.8%)
	double hit separation	$1\ mm$ (90% of the hits)
	momentum resolution	$\sigma_p/p \sim 3.2\%$ at 930 MeV$/c$
	spatial resolution for vertex reconstruction	$\sigma_x = \sigma_y \sim 3\ mm$ $\sigma_z = 7\ mm$
	dE/dx	22% (FWHM)
TOF	intrinsic resolution of internal/external slabs	400 ps (FWHM)
	precision on the alignment in each barrel	200 ps (FWHM)
	total resolution in the timing of the full array	1 ns (FWHM)
HARGD	solid angle	$\Omega/4\pi \sim 70\%$
	efficiency ($E > 0.15$ GeV)	$> 90\%$
	energy resolution	$\sigma_E/E \sim 18\%/\sqrt{E}$
	angular resolution (vertex known)	$\sim 5\ mrad$

Table 1: Performances of the OBELIX spectrometer four sub-detectors. SPC: drift chamber vertex detector; JDC: jet drift chamber for particle tracking; TOF: inner and outer scintillator barrels for time-of-flight measurements; HARGD: electromagnetic calorimeter.

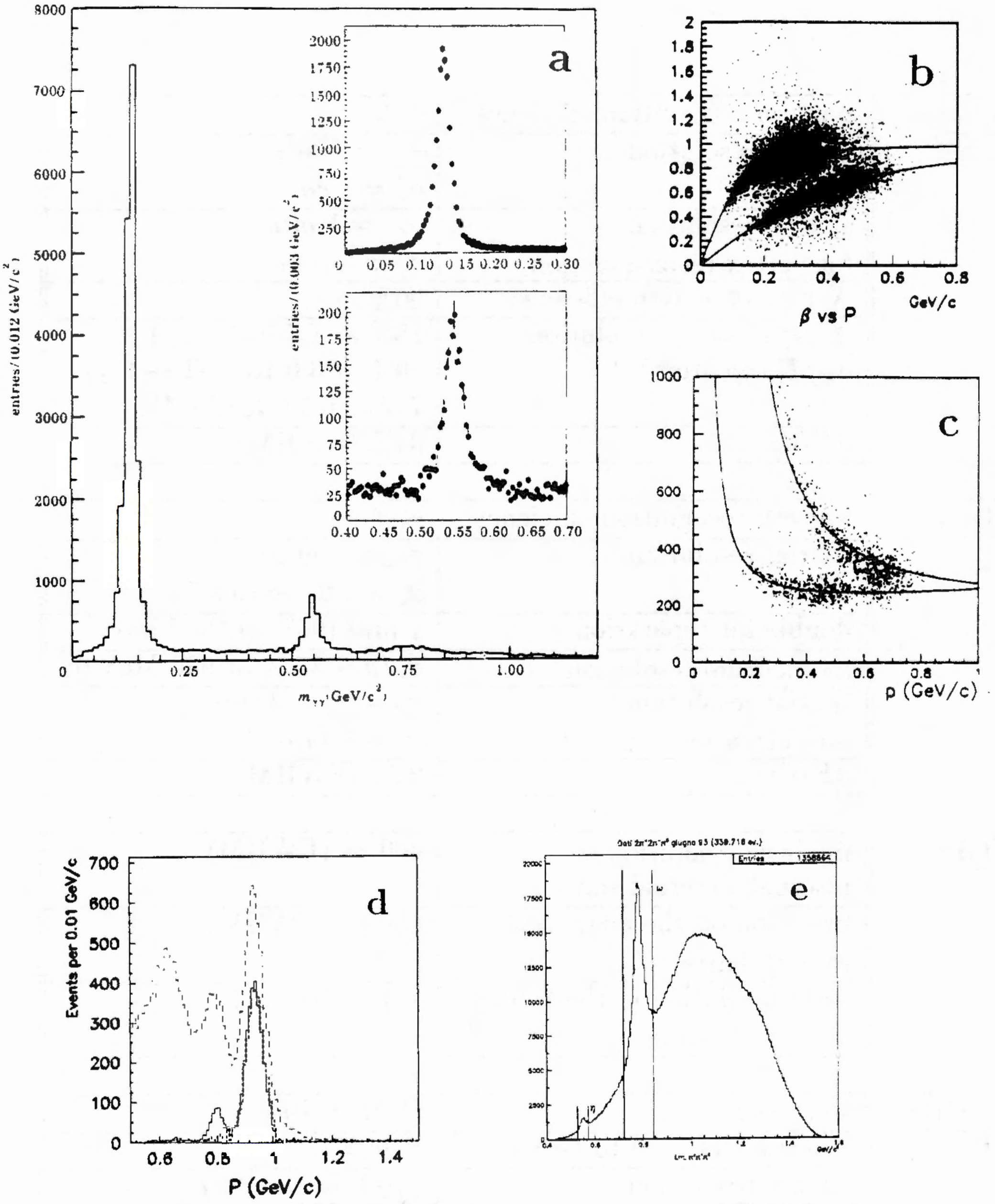

Figure 2: (a) distribution of the $\gamma\gamma$ invariant mass selected by a kinematical fit to the reaction $\bar{p}p \rightarrow \pi^+\pi^-\gamma\gamma$. The fit to the distributions around the π^0 and η masses (shown in the insets) gives: $m(\pi^0) = 134\,MeV/c^2$, $\sigma(\pi^0) = 10\,MeV/c^2$; $m(\eta) = 547\,MeV/c^2$, $\sigma(\eta) = 15MeV/c^2$; (b) pion-kaon separation by means of time of flight and (c) of dE/dx from the JDC chamber; (d) final state particle average momentum after kinematical fit selection for the $\bar{p}p \rightarrow K^+K^-$ and $\bar{p}p \rightarrow \pi^+\pi^-$ reactions, showing two separated peaks at 793 MeV/c and 923 MeV/c and a resolution of about 70 MeV/c FWHM; (e) invariant mass $\pi^+\pi^-\pi^0$ from the reaction $\bar{p}p \rightarrow 2\pi^+2\pi^-\pi^0$, showing the η and ω peaks with a width of $\approx 15MeV/c^2$ sigma.

LH_2 target, is a simple and effective way to change the relative weights of the initial state quantum numbers of the detected annihilation channels, leaving the detector practically in the same conditions.

Another technique developed by OBELIX is the annihilations in flight at very low $\bar{p}$ incident momentum (≤ 50 MeV/c). In these conditions annihilation should predominantly occur form S-wave state in a statistical mixture of singlet and triplet. Such low momenta can be tagged by a simple timing procedure, calibrated on the $\bar{p}$ slowing-down process into the target [5].

Finally, when using an $\bar{n}$ beam, the isospin of the $\bar{n}p$ state is fixed to $\mathrm{I}=1$, as for the $\bar{p}n$ state in deuterium, but without any complication due to the "spectator" proton.

These five different experimental arrangements ($\bar{p}$ at rest on liquid, NTP and low pressure hydrogen targets, $\bar{p}$ in flight at low momentum, $\bar{n}$ in flight) are at present used extensively to collect data on meson spectroscopy and annihilation dynamics.

For what concerns the selection of specific final states, an extended use of specialized triggers has been made.

The first level trigger is based on the TOF system and can operate in less than 200 ns. At first level, the multiplicity of hits on the inner and outer barrels slabs can be fixed, thus choosing the event topology to be selected. The kaons can be roughly selected in real time by requiring a TOF larger than a programmable minimal value. Simple topological conditions may also be required and activated in the inner tof barrel (*tofino*) to select particular channels like back-to-back two charged prong annihilations (enrichment factor > 10), or $\phi \to K^+K^-$ (enrichment factor > 50).

At the second level, there exist also the possibility to correlate each internal slab to a subset of external slabs in order to increase the efficiency of the *pattern recognition trigger*, when triggering on back-to-back configuration. This technical facility allows also a momentum selection of the charged products through their curvature radius. At this level, it is also possible to trigger on particular shower topologies with the HARGD calorimeter, to improve the detection efficiency on the channel containing neutrals.

4 Meson spectroscopy (spin-parity analyses)

In this section we present our most recent results on the search of exotic mesons. The technique used is the spin-parity analysis of the spectra of the mesons produced in the $\bar{N}N$ annihilation.

4.1 The $\bar{N}N$ annihilation into three pions

The experimental investigation in the channel $p\bar{p} \rightarrow \pi^+\pi^-\pi^0$ begun in the sixties with the bubble chamber experiments that were able to collect statistics of few thousands of data from annihilation in liquid hydrogen.

Generally speaking, the three pions final state is the most simple channel in which is possible to produce resonant states; moreover, its branching ratio allows the collection of high statistic samples.

In the bubble chamber data interesting details of the channel were weakened by the low statistics collected and by the strong ρ production. The experiments of the LEAR generation, by measuring with high statistics and also in gaseous hydrogen, put in evidence the existence of new resonant states.

Up to now OBELIX has analyzed data in the channel $p\bar{p} \rightarrow \pi^+\pi^-\pi^0$ at three different densities: 5 mbar (120.000 events over the Dalitz-plot), 1 Atm (85.000 events) and 3 Atm (70.000 events), obtained by reconstructing the π^0 with a 1C kinematical fit. The sub-samples obtained with a 3C kinematical fit, using the π^0 reconstructed by the calorimeter, are also available with a statistics five times lower.

In Fig. 3 we show the Dalitz-plots (and their projections) of the NTP and 5 mbar samples. At first glance the two Dalitz-plots look like very similar; this is due to the fact that almost all the resonances can be produced both in S-wave and in P-wave, so that it is impossible to appreciate by eye the different angular momentum modulations of the S-wave and P-wave contributions. To obtain samples with a different initial partial wave mixture, we collected in 1994 a large statistics at NTP and in liquid hydrogen, and a significative sample of annihilation in flight at low $\bar{p}$ momentum, where the S-wave, in a statistical mixture, is totally dominant.

The actual version of the spin-parity program represents the different isobars by Breit-Wigner forms and Zemach angular momentum tensors while the $\pi\pi$ interaction in S-wave is parameterized following the Au, Morgan and Pennington prescriptions. The fit can adapt the percentage of initial partial waves, relative phases, amplitudes, masses and widths of the different resonances. We are employing also a new version based on the K-matrix formalism. The analysis of the different samples is in progress; the 1C larger samples and the 3C sub-samples, obtained with the reconstructed π^0 by the calorimeter, are fitted simultaneously.

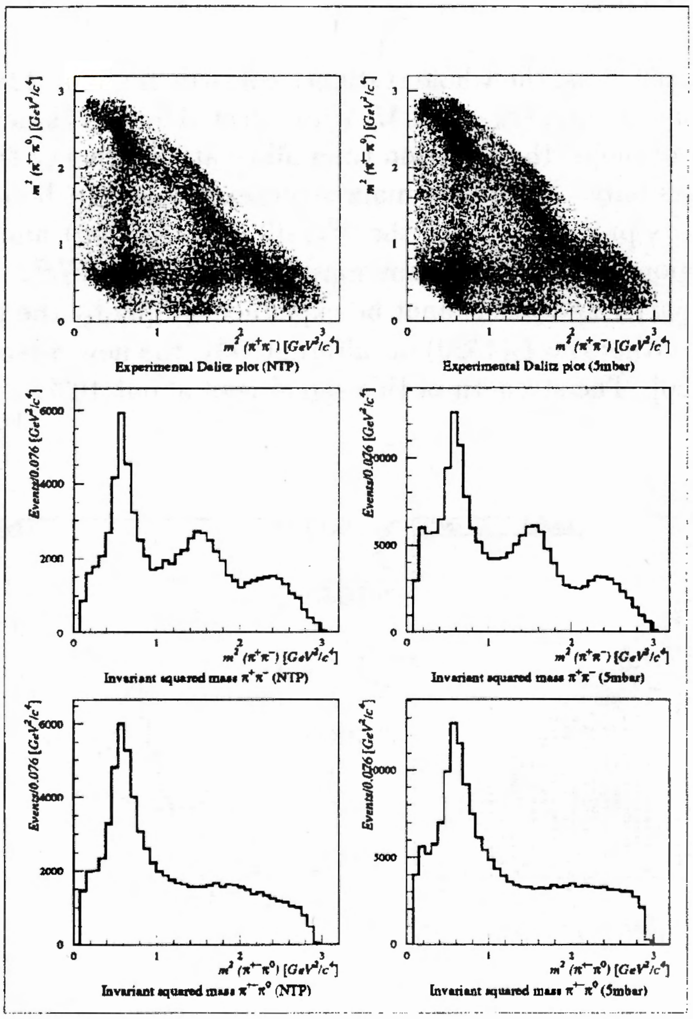

Figure 3: Dalitz plot, $\pi^+\pi^-$ and $\pi^+\pi^0$ squared invariant masses for the reaction $\bar{p}p \to \pi^+\pi^-\pi^0$ in gas at NTP (left) and at a pressure of 5 mbar (right).

The preliminary results show a strong deviation of the fit in the ρ^0 region which is due probably to the parameterization derived from the diffusion data. The study of a new ρ^0 parameterization for the production process by using experimental annihilation data is in progress. We have verified that the deviation in the ρ^0

region doesn't affect the sensitivity to the other resonances. We verified also, by Monte Carlo simulations, that the sensitivity of our fit to the 2^{++} and 0^{++} signals is good, because signals of the order of few percent in each partial wave are detected unambiguously by the fit program.

The data require a 2^{++} $f_2(1520)$ (AX) production from the $^1S_0$, $^3P_1$ and $^3P_2$ initial states. A resonance 0^{++} $f_0(1525)$ coming from the $^1S_0$ initial state greatly improves the χ^2 of the fit.

Concerning the antineutrons, the whole statistics consists of about 22×10^3 $\bar{n}p \rightarrow \pi^+\pi^+\pi^-$ annihilations in flight ($p_{\bar{n}} < 400 MeV/c$) selected by a 4C kinematical fit. For an odd number of pions, the selection rules allow at this energy the $^1S_0$, $^3P_1$ and $^3P_2$ initial states only. The three main structures that can be seen in the Dalitz Plot and in its projections, are the $\rho^0(770)$, the $f_2(1270)$ and an excess of events in the region of $\pi^+\pi^-$ invariant mass around $1.5\,GeV/c^2$. This "AX signal" in our spin-parity analysis cannot be explained simply by the presence of only one resonance, either the $f_2(1520)$ or, alternatively, the new meson $f_0(1500)$ recently proposed [20]. The strength of this signal is of about 10%.

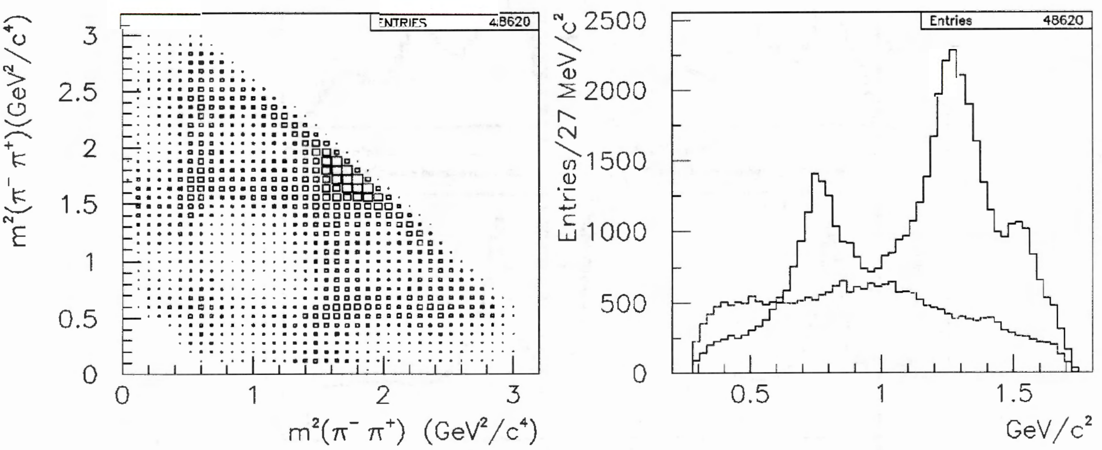

Figure 4: Dalitz-plot and $\pi^+\pi^-$ invariant mass for the reaction $\bar{n}p \rightarrow \pi^+\pi^+\pi^-$.

4.2 The $\bar{N}N$ annihilation into five pions

Here we consider the analysis of the spectra of the reaction $\bar{N}N \rightarrow 5\pi$ after the ω subtraction. This channel is object of studies from long time. Deuterium bubble chamber data, recently reanalyzed [14], showed the existence of a signal in the four pion neutral invariant mass in the channel $\bar{p}n \rightarrow 2\pi^+3\pi^-$, with a spin-parity assignment $J^{PC} = 0^{++}$, $I = 0$, mass and width $M = 1386 \pm 30\, MeV/c^2$ and $\Gamma = 310 \pm 50\, MeV/c^2$. The decay mode was suggested to be $\rho\rho$ and $\sigma\sigma$ in interference, where σ indicates a dipion system in relative S wave. This analysis was performed with 1400 events only, and with the assumption of only the ${}^1S_0$ initial state.

OBELIX [15] performed the spin-parity analysis of a sample of 5394 in flight events (momentum between 100 and 300 MeV/c) in the channel $\bar{n}p \rightarrow 3\pi^+2\pi^-$, by using the antineutron beam facility of the experiment. This analysis of entirely new data confirmed the existence of a signal in the $(2\pi^+2\pi^-)$ invariant mass, the 0^{++} spin-parity assignment and the $(\rho\rho - \sigma\sigma)$ decay mode. The signal saturates completely the channel (no phase space!). The found mass and width values were $M = 1345 \pm 12\, MeV/c^2$ and $\Gamma = 398 \pm 26 MeV/c^2$. Note the larger width found in this new measurement, compared to that of [14].

This result definitely ruled out the (2^{++}) quantum numbers for this state, an assignment made in previous analyses of this channel [16].

The Crystal Barrel Collaboration [18] reported then the observation of the same 0^{++} state in the configuration $(\pi^+\pi^-\pi^0\pi^0)$ at rest in liquid hydrogen in the channel $\bar{p}p \rightarrow \pi^+\pi^-\, 3\pi^0$ with a statistics of 23220 events. The found mass and width values were $M = 1374 \pm 38\, MeV/c^2$ and $\Gamma = 375 \pm 61 MeV/c^2$.

At this point the common belief is to be in the presence of a new $f_0(1400) \rightarrow (\rho\rho), (\sigma\sigma) \rightarrow 4\pi$ meson, named in the last Review of Particle Properties as $f_0(1370)$. The interpretation of this state is currently matter of discussion. Firstly, it could be the known $f_0(1300)$ meson seen in its 4π decay mode. Alternatively, this state could be a $\rho\rho$ molecule bound by one-pion exchange [19] or also an exotic state.

The large width of the $f_0(1370)$ found in this channel ($\Gamma \approx 400 MeV/c^2$) greater than the one found in the other channels ($\Gamma \approx 250 MeV/c^2$), seems to suggest the hypothesis of an overlap of this resonance with the exotic candidates $f_0(1500$ or the $f_2(1525)$ found in the $\bar{p}p \rightarrow 3\pi$ channel [20] and never seen in the four pions decay mode. In the last year OBELIX has undertaken a systematic study of this channel with the aim to investigate this hypothesis .

New data have been taken in four different conditions in order to vary the mixing of the initial states to resolve the ambiguities in the best fit solutions: a)130 000 $p\bar{p} \rightarrow 2\pi^+\, 2\pi^-\, \pi^0$ events in gas at 3 atm, b) 40 000 $p\bar{p} \rightarrow 2\pi^+\, 2\pi^-\, \pi^0$ events in liquid Hydrogen, c) 90 000 $p\bar{p} \rightarrow 2\pi^+\, 2\pi^-\, \pi^0$ events at very low momentum

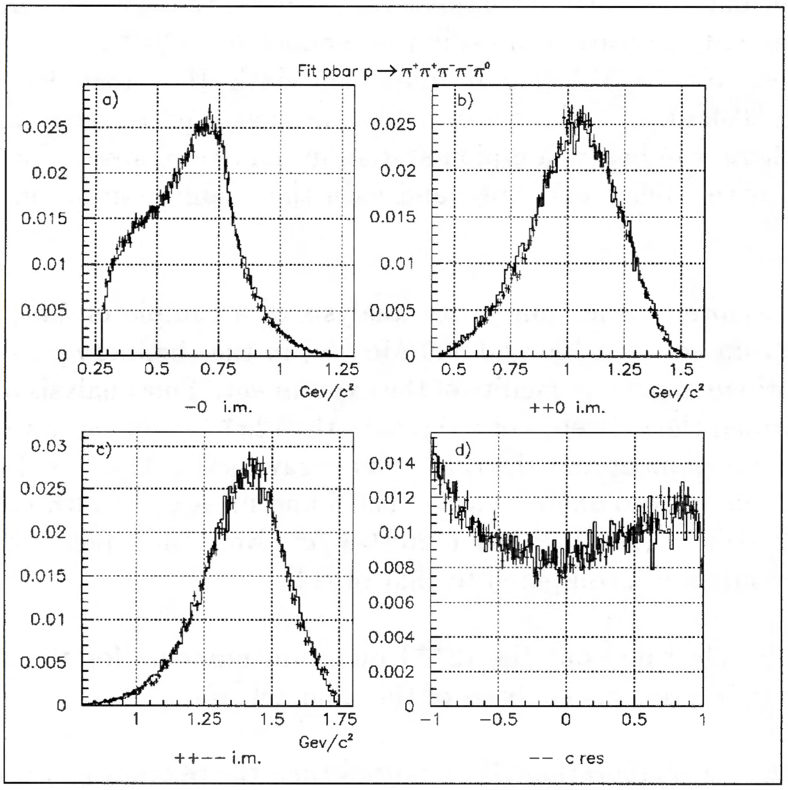

Figure 5: (a) $(\pi^{\pm}\pi^{0})$, (b) $(\pi^{\pm}\pi^{\pm}\pi^{0})$, (c) $(2\pi^{+}\,2\pi^{-})$ invariant masses and (d) angle between the two charged pions in the $p\bar{p} \to 2\pi^{+}\,2\pi^{-}\,\pi^{0}$ annihilation at rest in gas (after ω subtraction). The continuous line is the fit result.

($p < 50$ MeV/c), d) 20 000 $p\bar{n} \to 3\pi^{+}\,2\pi^{-}$ events in flight ($p_{\bar{p}} < 400 MeV/c$) with the antineutron beam. The collected statistics is more than 7 times greater than the sum of the previously published data.

Concerning the antiproton data, in gas an acceptable fit has been obtained with the overlap of the $f_0(1370)$ resonance and of a non resonant $\rho\sigma$ state. The mass and width of the resonance are $M = 1335 \pm 50\, MeV/c^2$ and $\Gamma = 394 \pm\, 10 MeV/c^2$, in agreement with the previous results of OBELIX and Crystal Barrel. The agreement between theory and data, although acceptable (see fig. 5), is not completely satisfactory ($\chi^2 = 1.5$): it seems that the amplitudes used up to now, when applied to high statistics data, are not completely correct.
The data in liquid give fits equivalent to those in gas, both starting from initial S states only and using S and P initial states. We hope to solve this ambiguity by analyzing the data in flight at very low momentum, where S wave dominates.

We observed no significant improvements by using an overlap of the $f_0(1370)$

and $f_2(1520)$ resonances with variable width. The fit assigns to the 2^{++} signal a weight $< 10\%$, without improving the fit. Also the overlap of the $f_0(1370)$ and the $f_0(1500)$ 0^{++} resonances, done in terms of Breit-Wigner functions, does not improve the fit. However, this overlap requires a reformulation of the amplitude in terms of unitary scattering matrices; the work on this point is in progress.

Concerning the most recent antineutron data (about $20 \cdot 10^3$ events taken at 100-400 MeV/c $\bar{n}$ incident momentum), the $(\pi^+\pi^+\pi^-\pi^-)$ invariant mass, after a scan on the $\bar{n}$ momentum, shows the following feature: the $f_0(1370)$ resonance is present in any case and doesn't seem to suffer any partial distortion in the different slices chosen for $\bar{n}$ momentum. The presence of a shoulder towards the end of the $(\pi^+\pi^+\pi^-\pi^-)$ spectrum seems, in any case, rather evident, but the difference spectrum doesn't show a well separated structure for higher $\bar{n}$ momenta, as could be seen in the previous analysis with less statistics [6]. Whether this effect has to be attributed to a worsening of the invariant mass resolution for high $\bar{n}$ momenta or to a statistical fluctuation is still under study.

4.3 Research of exotic mesons in the E/ι region

The first evidence for a possible non-$q\bar{q}$ state came in 1963, with the discovery from the CERN-College de France group of a resonance at 1400 MeV/c^2 in the $K\bar{K}\pi$ system [7], which they named the E-meson. It was seen in the annihilation at rest $p\bar{p} \rightarrow K^{\pm}K^0_S\pi^{\pm}\pi^+\pi^-$ with a spin-parity analysis favoring 0^{-+} [8]. The decay modes into $K^*\bar{K}$ and $a_0\pi$ were found to be equally strong.

In more than thirty years, despite the contribution of many experiments, the number of resonances in the 1400-1500 MeV region, their quantum numbers and decay modes are still controversial. This situation has been referred to as "the E/ι puzzle". The most recent results, in J/ψ radiative decays [9, 10], claim for the presence of three objects: two pseudoscalars and an axial vector. Among them, at least two have a high score for not being ordinary $q\bar{q}$ states.

The OBELIX strategy for the search of the E/ι mesons is based on a program of high statistics data collection, with dedicated triggers, under different initial $p\bar{p}$ angular momentum states.

So far, three data sets at three different target densities have been collected from November 1993 to October 1994: $6 \cdot 10^6$ events at 5 mbar pressure Hydrogen (P-wave dominance), $18 \cdot 10^6$ events in liquid Hydrogen (LH2) (S-wave dominance), $26 \cdot 10^6$ events in gaseous Hydrogen at NTP (about 50 % S and P waves).

A comparison of the three data sets indicates a decreasing of the signal from LH2 to 5 mbar, consistent with the hypothesis that in $p\bar{p}$ annihilation at rest the pseudoscalar states proceed from the $^1S_0$ initial state and the production of the axial vector appears to be weak. The sample of data at 5 mbar are not statistically sufficient for a spin-parity analysis. The data at NTP (taken in October 1994) have been almost completely processed and their analysis has started. Fig. 6 shows the $KK\pi$ invariant mass for the three data sets after the subtraction of the combinatorial background. For the NTP the figure refers to about 80% of the overall statistics.

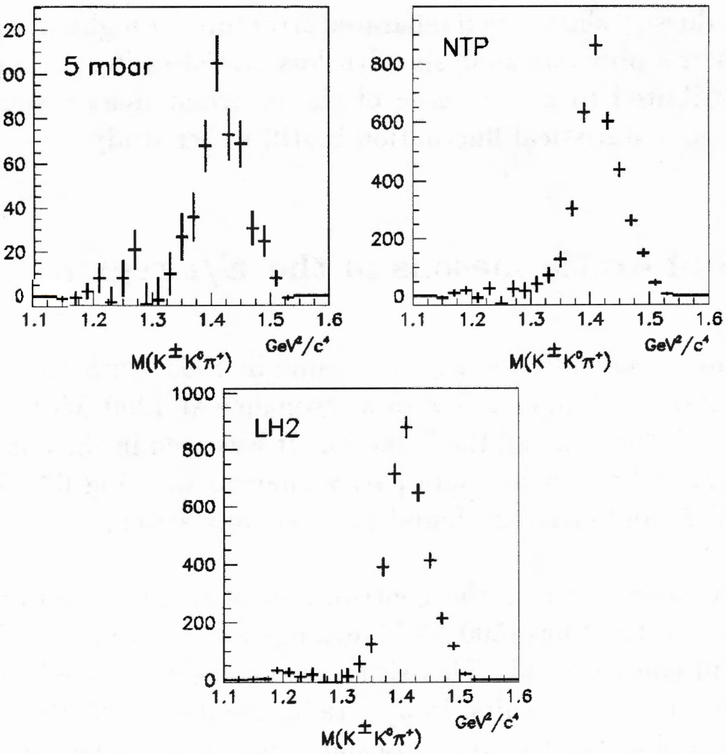

Figure 6: $K\bar{K}\pi$ invariant mass from $\bar{p}p \to K^{\pm}\,\pi^{\mp}\,(K^0)_{miss}\,\pi^+\pi^-$ events with (a) 5 mbar, (b) NTP, and (c) LH2 targets.

At present a spin-parity analysis of the LH2 data is in progress and preliminary results are given here. The fitting procedure is based on the maximization of the likelihood function. The sample consists of 3940 events coming from the reaction:

$$p\bar{p} \to K^{\pm}\pi^{\mp}(K_0)_{miss}\,\pi^+\pi^- \qquad (1)$$

with an estimated background contribution of about 15%. We emphasize that

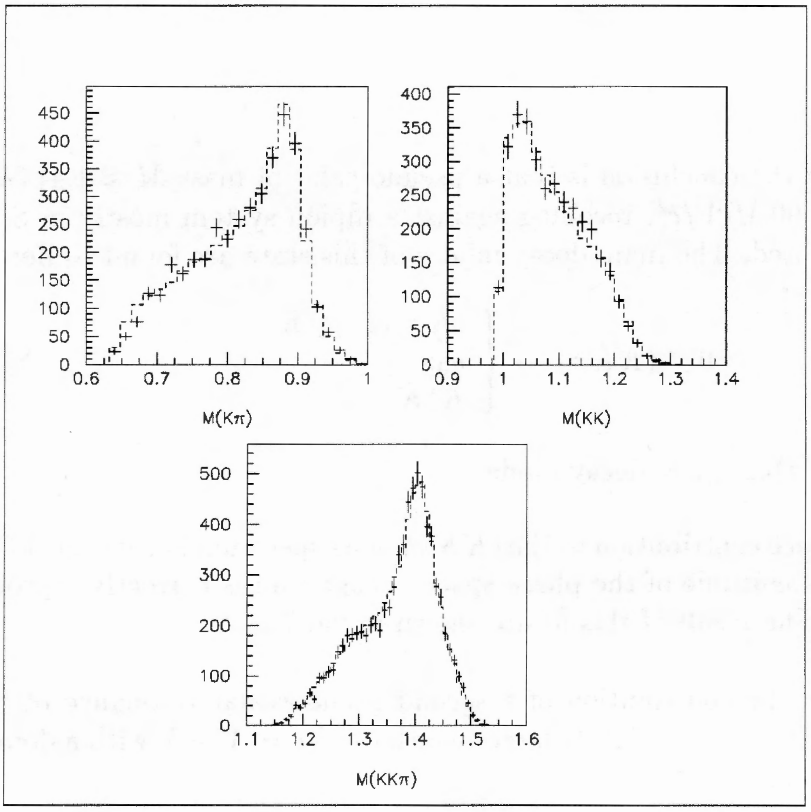

Figure 7: (a) $(K\pi)$, (b) $(K\bar{K})$, and (c) $(K\bar{K}\pi)$ invariant mass distributions from the reaction $\bar{p}p \rightarrow K^{\pm}\,\pi^{\mp}\,(K^0)_{miss}\,\pi^+\pi^-$ The broken line superimposed to the data is the result of the fit.

this statistics, which exceeds by almost an order of magnitude previous data on this channel has been collected in 15 days of run.

The invariant mass spectrum of the $(K\bar{K}\pi)$ system, which has 2 entries per event, has shown a signal in the mass region around 1.4 GeV/c^2. The data show in addition the presence of a neutral K^* signal and of a $K\bar{K}$ threshold enhancement which can be identified with the $a_0(980)$ scalar state.

A spin parity analysis of the final state (1) has been performed in the framework of the isobar model, having as ingredients: a) the K^* and the $(K\bar{K}\pi)$ resonant contributions parameterized with standard relativistic Breit-Wigner formulas, b) the $a_0(980)$, parameterized with a Flattè function; c) the $(K\pi)$ and $(\pi\pi)$ S-wave, parameterized both according to the effective range approximation and to the N/D formalism. Two independent programs based on the helicity and Zemach tensor formalism were used and found in excellent agreement.

A good description of the final state (1) cannot be achieved introducing only 5-body direct production plus background and the non interfering production of the K^* and a_0 resonances. In addition, the data demand the inclusion of a $(K\bar{K}\pi)$ resonant contribution. For this resonance several spin-parity assignments were tested and the conclusion is that a pseudoscalar of mass $M \approx 1.41\,GeV/c^2$ and width $\Gamma \approx 60\,MeV/c^2$, recoiling against a dipion system mostly in S-wave, is strongly favoured. The main decay modes of this state are found to be:

$$0^{-+}\,(K\bar{K}\pi) \rightarrow \left\{ \begin{array}{l} (K\pi)_{S-wave}\,\bar{K} \\ a_0\pi \\ K^*\bar{K} \end{array} \right. ,$$

with a large $(K\pi)_{S-wave}\,\bar{K}$ decay mode.

The 0^{-+} resonance contribution to the $(K\bar{K}\pi)$ mass spectrum is between 45% and 60%, and the magnitude of the phase space background is correctly reproduced (about 15 %). The result of this fit are shown in fig. 7.

The fit requires the contribution of a second pseudoscalar resonance of higher mass ($\approx 1.47\ GeV/c^2$) and slightly larger width ($\approx 90\ MeV/c^2$), with a dominant $(K^*\bar{K})$ decay mode.

The presence of two pseudoscalars under the $\eta(1440)$ (following the last notation of the Particle Data Group) makes more meaningful the debate on their possible exotic nature. Strong arguments in favour of an exotic interpretation of one of the two pseudoscalars do exist [11, 12, 13].

4.4 The annihilation at rest $\bar{p}p \rightarrow K^+K^-\pi^0$

No detailed investigation of the $K^+K^-\pi^0$ system has been made before OBELIX, apart from a very low statistics sample in liquid hydrogen and an ASTERIX analysis of the $\phi\pi^0$ channel only [17].

In spite of the scarcity of available data, this channel is very important because it offers the possibility to observe the K^+K^- decay mode of the new mesons $f_0(1500)$ and $f_2(1525)$ observed at LEAR in their $\pi\pi$, $\eta\eta$, and $\eta\eta'$ decay modes [21, 20, 22] (see also sect. 4.1)

We have obtained for this reaction a preliminary sample of 7218 and 25316 events in Hydrogen targets at NTP and at 5 mb, respectively, with a 20-25 % background percentage coming mainly from the $p\bar{p} \rightarrow \pi^+\pi^-(MM)$ reaction.

These data have been compared with the prediction of a theoretical decay amplitude containing many interfering resonances, parameterized in terms of standard relativistic Breit-Wigner functions and covariant spin tensors.

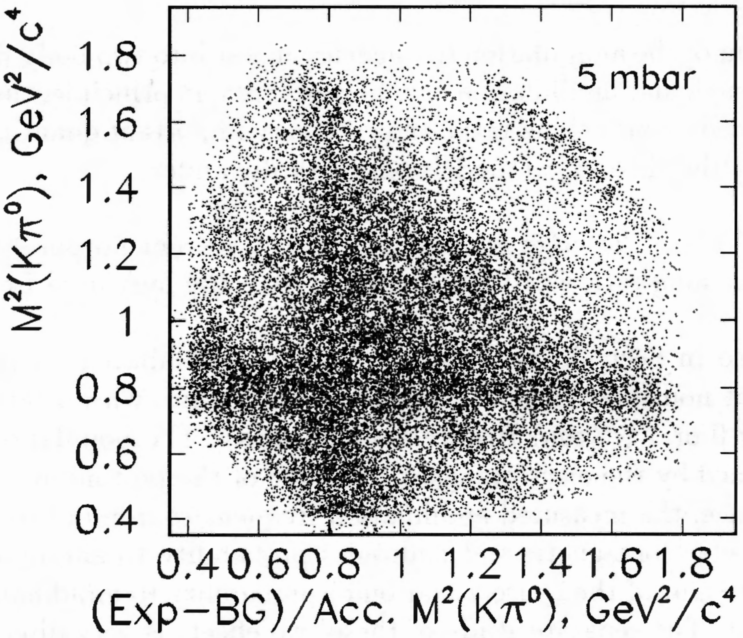

Figure 8: Dalitz-plot of the $\bar{p}p \to K^+K^-\pi^0$ reaction in a hydrogen target at 5 mbar pressure.

Concerning the presence of exotics, the fit was made for two different cases: either with the known $f_2'(1525)$ contribution only or with the $f_0(1500)$ one. At present, both these hypotheses give a good description of the NTP and low pressure data. The analysis of this channel in difficult, and the work is in progress. The statistics has been increased significantly with the last data taken in October 1994.

5 Annihilation dynamics

An important field strictly connected to the underlying quark dynamics in the annihilation process is the determination of the branching ratios at rest of the annihilation channels and the measurement of the annihilation cross sections in flight at low energy. In this section we list the most relevant results obtained by OBELIX during the last two years on these topics.

5.1 Annihilation frequencies

The measurement of the annihilation frequencies at rest into two body final states and into other particular annihilation channels permits, in principle, the determination of the hadronic branching ratio, that is a very important quantity, directly comparable with the theoretical models on quark dynamics.

Unfortunately, despite the large amount of data, at present no purely hadronic annihilation branching ratio has been extracted from the measured frequencies.

As explained also in Sect. 3, the reason is that the annihilation at rest occurs from six different non interfering J^{PC} states of protonium, with orbital angular momentum $L = 0$ or 1 (S and P-wave annihilations). The population of these state is determined by the electromagnetic cascade of the protonium, and is not well known. Hence, the measured annihilation frequencies from a target are the product of the (electromagnetic and hadronic) probability to annihilate from a certain J^{PC} state and of the (purely hadronic) probability to annihilate into the observed channel. The separate study of these two effects is very difficult.

The OBELIX Collaboration is performing systematic measurements of frequencies in different conditions of target density and in flight at low momenta with the aim to disentangle, for some important annihilation channels, the electromagnetic effects from the hadronic ones.

Three goals could be reached with such a systematic job: a) the determination of the hyperfine protonium level widths, b) the determination of the hadronic branching ratios and c) the removal of the ambiguities of the spin-parity analyses due to the ignorance on the distributions of the initial states.

This ambitious programme requires many measurements and can not be performed by only one experiment. The OBELIX contributions to this field are reported in the first part of tab. 2; this study will be improved and completed in the next years. The measured frequencies concerns some $\bar{p}p$ annihilation into two stable mesons at two target densities, NTP and 5mbar. This is only a first important step in the hadronic branching ratio determination. One can note, for example, that the $\pi^+\pi^-$ frequency at 5 mbar has the same value of that at NTP, in contrast with the K^+K^- frequency, which shows, at 5 mbar, a value different from that measured by ASTERIX at NTP (and therefore not reported in the table, which concerns the OBELIX results), which is $(6.9 \pm 0.4)\,10^{-4}$ [30]. The last datum of this group concerns a measurement in deuterium that permitted, for the first time, a model dependent evaluation of the P-wave percentage in the annihilation of a $\bar{p}$ on the proton bound in deuterium ($18 \pm 7\%$) [29].

TARGET or BEAM	REACTION		VALUE	REFERENCE or REMARKS
NTP	$\bar{p}p \to$	$\pi^0\pi^0$	$(1.27 \pm 1.3)\,10^{-3}$	[23]
NTP		$\pi^+\pi^-$	$(4.27 \pm 0.23)\,10^{-3}$	[25]
NTP		$K^+K^-/\pi^+\pi^-$	(0.163 ± 0.011)	[29]
5 mbar		$\pi^+\pi^-$	$(4.26 \pm 0.11)\,10^{-3}$	[24]
5 mbar		K^+K^-	$(4.6 \pm 0.3)\,10^{-4}$	[24]
NTP		$\phi\pi^0$	$(2.04 \pm 0.20)\,10^{-4}$	to be sub.
NTP		$\eta\pi^0$	$(3.4 \pm 0.7)\,10^{-4}$	to be sub.
NTP		$\eta\eta$	$(2.7 \pm 0.7)\,10^{-4}$	to be sub.
NTP	$\bar{p}D \to$	$K^+K^-/\pi^+\pi^-$	(0.27 ± 0.02)	[29]
in flight	$\bar{n}p \to$	$\phi\pi^+/\omega\pi^+$	(0.110 ± 0.016)	[28]
NTP (slow p)	$\bar{p}D \to$	$\phi\pi^-/\omega\pi^-$	(0.133 ± 0.026)	[27]
NTP (fast p)		$\phi\pi^-/\omega\pi^-$	(0.113 ± 0.030)	[27]
NTP	$\bar{p}D \to$	π^-p	$(1.29 \pm 0.09)\,10^{-5}$	[26, 25]

Table 2: Two-body annihilation frequencies measured in various conditions by the OBELIX Collaboration

The study of many other channels is in progress; in particular, we are analyzing the reaction $\bar{p}p \to K_S K_L$, that occurs from the $^3S_1$ state only.

5.2 OZI rule violation

The second group of data of tab. 2 is a ratio of frequencies for the production of a pion associated to the strange and non strange isoscalar members of the vector mesons nonet. This ratio is *purely hadronic*, because the frequencies are measured in the same experimental conditions, so that the ratio drops out all the spurious effects. The value for the antineutron in flight refers to incident momenta $< 300 MeV/c$, whereas that in deuterium is measured by selecting slow ($< 200 MeV/c$) or fast ($> 400 MeV/c$) spectator protons. A new sample of antineutron data is under analysis, and the statistics collected will allow a reduction of the error on the ratio $\phi\pi^+/\omega\pi^+$ of more than 50%. These data show a strong violation of the OZI rule, which predicts for this ratio a value about 40 times lower. This result, found also in different channels by other LEAR experiments [31], is perhaps one of the most interesting results of the studies on the annihilation branching ratios, because it gives information on the possible $\bar{s}s$ quark content in the nucleon (see [28] and references therein).

To test OZI rule violations in Pontecorvo reactions, OBELIX performed the measurement of the $\bar{p}d \to \phi n$ channel, with a dedicated " ϕ trigger": a preliminary final state selection, on about 1/10 of the overall statistics, is shown in fig. 9

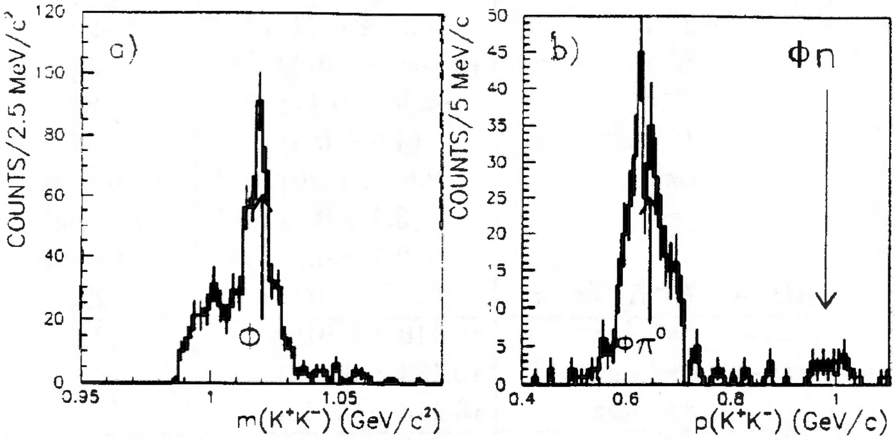

Figure 9: (a) K^+K^- invariant mass distribution of the $\bar{p}p \to K^+K^-n$ reaction, showing a clean ϕ peak and (b) K^+K^- momentum distribution, showing two enhancements corresponding to $\phi\pi^0$ and ϕn final states.

The same data sample shows also the production of Λ^0 with high momenta, which can only be related to the *Pontecorvo-like* channels $\bar{p}D \to \Lambda^0 K^0$, $\Lambda^0 K^{*0}$.

5.3 Low energy $\bar{p}p$ annihilation cross section

During the initial stage of the experiment we verified that the measurement of the $\bar{p}p$ annihilation cross section at very low momenta was feasible [5]. A set of new values of the cross section at 170, 104, 66, 59, 55, 51 and 41 MeV/c has now been obtained and a publication is in preparation. Moreover, a new data sample has been recently recorded with a new technique, that allows the measurement of the cross section to be performed below 35 MeV/c.

The capability of OBELIX to efficiently use beams of very low momentum, coupled to the large acceptance of the spectrometer, provides the possibility to study the partial annihilation cross section for different exclusive channels. Information about the behaviour of these cross sections could be a formidable input for different annihilation models based on meson exchange or quark dynamics. At low energy,in fact, the waves contributing to the annihilation process are few, and the comparison between data and theory is more direct. In this domain, practically no other experimental data are available under 400 MeV/c.

6 Nuclear and Atomic physics

The Collaboration performed also some measurements in fields different from meson spectroscopy and annihilation dynamics. The topics chosen have the common characteristic to be of primary importance in the respective areas of nuclear and atomic physics and to require a very short time for the data taking.

6.1 Nuclear physics

The last measured rate of tab. 2 is a precise measurement of the "prototype" Pontecorvo reaction $\bar{p}D \to \pi^- p$, in which the annihilation involves both nucleons of deuterium. This rate is sensible to the presence of 6-quark bags in nuclei, and its precise measurement is of importance to fix the parameters of many theoretical models dealing with the quark degrees of freedom in nuclear matter.
Along the above lines, a data sample concerning $\bar{p}$ annihilation at rest on ^4He nuclei was collected in 1993. Events having the features expected for the annihilation involving more than one nucleon have been identified both in $2\pi^+2\pi^-$ and in $2\pi^-\pi^+$ channels. The production rate for these events is of the order of 5×10^{-3} [32]

Two sets of data have been taken in 1990 and 1994 concerning the annihilation cross section of antineutrons on nuclei.
The first set (1990) includes $\sim$ 20000 events of antineutron annihilation on C, Al, Cu, Sn and Pb, at three different momenta (180, 240, 281 MeV/c). The results are free from the Coulomb distortion, and show a scaling law of the annihilation cross section with the baryon number to the power 2/3 for all the 3 momenta [33].
The second set of data (1994) has been taken in a "parasitic mode", i.e. with the nuclear target put few centimeters downstream the reaction LH2 target: in such a way the antineutrons non interacting with hydrogen are used as available beam for the nuclei. The nuclear targets were the same as in 1990, with in addition a silver target. The range of momenta was extended up to 400 MeV/c. The amount of data is of the order of 6 millions, the analysis is at the beginning.

6.2 Atomic physics

To test the feasibility of the low pressure target technique, few dedicated runs have been devoted to the measurement of cascade protonium times and widths at

8.2, 4.1, 2.1 mbar pressures. Decreasing the pressure, cascade times of 110 ± 10, 145 ± 15, 210 ± 25 ns and widths of 45 ± 5, 82 ± 9, 125 ± 9 ns have been measured [34]. After this result, spectroscopy data at a pressure of about 5 mb have been collected in many channels.

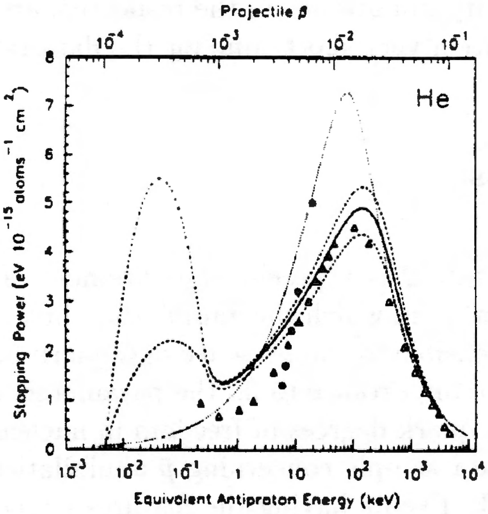

Figure 10: $\bar{p}$ stopping-power best fitting function for He (solid line) and upper- and lower-limiting behaviours down to 0.5 kEV (dashed line); the dotted line is the proton stopping power [35]; •: Golser and Semrad data [36]; △: μ^- in He; dot-dashed and dashed lines below 0.5 keV are, respectively, an acceptable and an unacceptable behaviour for $\bar{p}$ stopping power.

With the above technique used to measure protonium cascade times, data on the delayed annihilation of $\bar{p}$ stopped in a ^4He gas have been also collected. The behaviour of the delay time ($\approx 3 \mu s$) with the pressure and the presence of contaminants has been reported [37].

The simultaneous measurement of the vertex spatial coordinates and of the annihilation times of $\bar{p}$s annihilating at rest in a H_2 and ^4He target at very low pressure, allowed for the first time the measurement of the $\bar{p}$ stopping power at energies below 1.1 MeV. The Barkas effect, i.e., a difference in the stopping power for antiprotons and protons of the same energy in the same material, shows up clearly in either of the gases. Moreover, below ≈ 0.5 keV there is indirect evidence for an increase of the antiproton stopping power. This “nuclear” effect, i.e., energy losses in quasi-molecular interaction, shows up in fair agreement with theoretical predictions. [38, 39].

7 Future plans and requests

To achieve our experimental program on meson spectroscopy and annihilation dynamics we have to complete the statistics on the channels under study for all the different target and beam experimental conditions exploited up to now (see Sect.3)
In addition, we intend to make some new measurements of particularly interesting reactions, that are well within the possibility of the apparatus.
In the following, we list all these items, together with the beam requests for 1996 and beyond.

- *Meson spectroscopy studies at rest*
  We intend to complete our statistics on $\bar{p}p$ annihilation at low incident momenta and at low pressure.
  One of the main topic will be the investigation of the two kaon and of the $\eta\pi$ bound states, in the region of the $a_0(980)$ up to 1.6 GeV/c^2, through the reactions:
  $$\bar{p}p \to K\bar{K}\pi\ , \qquad \bar{p}p \to \pi^+\pi^-\eta\ ,$$
  with two charged kaons, a neutral K missing or decaying into $K_S \to \pi^+\pi^-$, and with the η meson decaying into $\gamma\gamma$ or into $\pi^+\pi^-\pi^0$.
  To this end, a large statistics on 2 and 4 prong channels with dedicated trigger is necessary.
  We plan also to collect high statistics data on $\bar{p}n$ annihilation by filling the target with deuterium. Very slow spectator proton stopping in the gas of the SPC vertex detector ($p_{\bar{p}} < 50 Mev/c$) can be identified to obtain a sample of annihilations on a quasi-free neutron more significant than that obtained in the past with bubble chambers ($p_{\bar{p}} < 150 Mev/c$).
  Concerning the E/ι region, within the large fraction of all the charged modes one can efficiently select the six-prong final state:
  $$\bar{p}p \to (K^0_S K^\pm \pi^\mp)\,\pi^+\pi^-$$
  with the K^0_S selected from its $\pi^+\pi^-$ decay products. The detection of this reaction by a 5C kinematical fit provides additional and more precise information on the nature of the decay $E/\iota \to K\bar{K}\pi$
  Another interesting six-prong channel, which allows an experimental determination of the C (and G) parity of the E/ι, is:
  $$\bar{p}p \to (K^0_S K^0_S \pi^0)\,\pi^+\pi^-$$
  with $K^0_S \to \pi^+\pi^-$.
  An additional interest comes from the possibility to study the channel
  $$\bar{p}p \to (\eta\pi\pi)\pi\pi$$

with the η observed in its $(\pi^+\pi^-\pi^0)$ mode. Preliminary indications on the presence of E/ι in this reaction comes from the analysis of a reduced data sample ($1.2 \cdot 10^6$ events) collected in liquid Hydrogen during the May 94 data taking. These data should allow a coupled channel analysis of $E/\iota \rightarrow (K\bar{K}\pi)$ together with $E/\iota \rightarrow (\eta\pi\pi)$.

Finally, we intend to increment the present 4-prong sample of about 4000 $K\bar{K}\pi$ events taken with a liquid Hydrogen target to study the final states:

$$\bar{p}p \rightarrow K^{\pm}\pi^{\mp}K^0_{miss}\pi^+\pi^-$$
$$\bar{p}p \rightarrow K^{\pm}K^{\mp}\pi^0\pi^+\pi^-$$

All the above final states have to be analyzed at least at two target densities, to disentangle the contribution of initial angular momentum states to the production of exotics.

To achieve this goal a 18 week data taking at 100 MeV/c in gaseous Hydrogen target and a 6 week data taking in liquid Hydrogen target at 200 MeV/c are necessary.

- *Meson Spectroscopy studies in flight.*
  To explore the existence of a third resonance in the E/ι region, with the quantum numbers of an axial vector, one way is to increase the annihilation yield of the initial $\bar{p}p$ in P-wave state. However, from the analysis of a data sample taken in gaseous hydrogen at 5 mbar pressure, the rate of the $(K\bar{K}\pi)$ events was found to be much lower than in liquid hydrogen. A possibility is that at rest this state is less produced for some dynamical reasons.
  Another approach is to go to in flight annihilations. Indeed, in this case one simultaneously enriches the P-wave initial states, while overcoming the centrifugal barrier present in the S-wave initial state between an axial vector E/ι and the recoiling dipion with relative orbital angular momentum $L = 1$. This argument is confirmed by the old bubble chamber data in flight. We plan to extend our E/ι studies in annihilations in flight (momentum of 700 MeV/c) in liquid Hydrogen target, with both 4-prong and 6-prong multiplicity trigger, in order to explore centrifugal or dynamical effects in the production of axial vectors.

  Furthermore, a sample of in flight antineutron data is necessary to complete our statistics on the $\bar{n}p$ annihilations.

  We foresee a 3 week data taking with a 400 Mev/c momentum beam and a 5 week data taking with a 700 MeV/c momentum beam to fulfill this program.

- *Branching ratios at rest*
  In principle, to extract hadronic branching ratios starting from the measured rates, extensive measurements are necessary at four different densities. This is a unique opportunity, and it depends in first instance on the

quality of the work of measuring density dependent frequencies and angular distributions of simple annihilation channels at different target conditions. To complete this task, for the channels accessible to OBELIX, we require 10^7 events at four densities taken with the minimum bias trigger (incident $\bar{p}$). We plan also to collect statistics with dedicated trigger to select charged and neutrals final particles. The time request is of 4 weeks at 100 MeV/c and of 2 weeks at 200 MeV/c.

- *Pontecorvo reactions*

  The study of the Pontecorvo reaction

  $$\bar{p}\,^3He \rightarrow pn \ ,$$

  which, in the conventional framework, implies a double meson absorption, allows in principle to discriminate between rescattering and direct annihilation on 6-quarks bag models (predictions are different by two order of magnitude).

  To achieve for this reaction an upper limit of 10^{-9}, one week of data taking at 100 MeV/c is necessary.

- *Low energy $\bar{N}N$ cross sections*

  We have the intention to perform a detailed scanning of the $\bar{p}p$ cross section below 180 MeV/c. The OBELIX experiment is the only capable to reach such low values of incident momentum and no measurement but the OBELIX ones are available at present.

  These results are extremely useful for the investigation of the possible presence of resonant states near threshold and to fix the scattering lengths of the interaction.

  The time request is of one week at 100 MeV/c and of one week at 200 MeV/c.

- *Atomic physics*

  To complete our studies on the $\bar{p}$ stopping power and on antiprotonic stom metastable states, one week at 100 Mev/c is necessary.

In conclusion, our total beam request for 1996 and beyond is the following:

- 25 weeks with antiproton momentum of 100 MeV/c;
- 9 weeks with antiproton momentum of 200 MeV/c;
- 3 weeks with antiproton momentum of 400 MeV/c;
- 5 weeks with antiproton momentum of 700 MeV/c;

This beam request (42 weeks) requires that the LEAR activity continues beyond 1996. We think that this effort will be compensated by new results on exotic mesons and annihilation dynamics, which will be a benchmark for our knowledge of non-perturbative QCD.

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