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Meson Spectroscopy with S- and P-Wave–Dominant Initial-State Selection in $\bar{p}p$ Annihilation (*).

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Summary. — The possibility of selecting the initial angular-momentum state from which antiproton-proton annihilation at rest can occur can be a fundamental tool in meson spectroscopy. With the OBELIX detector different target systems have been employed, ranging from S-wave to P-wave dominance. The preliminary results both on meson spectroscopy and branching ratio measurements are discussed.

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1. – Introduction.

Antiproton-proton annihilation at rest can proceed, through the formation of the antiprotonic atom from orbital angular momentum (L) equal to 0 or 1. The initial-state quantum numbers selection restricts, by conservation rules, the possible final-state configurations.

Therefore the possibility to discriminate between $L = 0$ or 1 for the initial state can play a fundamental role in the search of new resonances which can be otherwise overwhelmed by non-resonant phase space.

Moreover the study of the branching ratios dependence on L for some selected final states has already given the signal of dynamical effects beyond the statistical approach. A systematic study of several branching ratios from a defined initial state will allow to discriminate among different models and to clarify the role played by quark-gluon degrees of freedom in the dynamics of annihilation. Despite these motivations, a comprehensive set of measurements is still missing. The ASTERIX collaboration pioneered in this field by selecting P-wave annihilation by means of X-rays detected in coincidence. Notwithstanding the interest of these results, several limitations were presented and this approach has not been carried on by other experiments.

Recently the OBELIX collaboration proposed the use of low-pressure targets to select P-wave dominant annihilation. The first results are promising and claim for large-statistics measurements in the next future.

2. – Experimental techniques.

When an antiproton stops in hydrogen it can replace the electron in a hydrogen atom to form an antiprotonic-hydrogen atom (protonium) in a highly excited state.

The de-excitation proceeds through emission of X-rays until the annihilation occurs. In vacuum protonium atoms would de-excite down to the $2P$-level where the hadronic width is much larger than the radiative width. Therefore, under these conditions annihilation takes place dominantly from P-wave.

In liquid hydrogen the atomic S-wave dominates the annihilation at rest. The percentage of S-wave is related to the target density. This effect is known as Day-Snow-Sucher mechanism [1]. It is due to the Stark mixing among levels with the same principal quantum number n but different angular momentum L in the presence of the strong electric field originated by the neighbouring H_2 molecules. This leads to absorption from low-angular-momentum states at high n values. As a result the S/P wave ratio increases with the target density in which the probability of collisions is enhanced.

The ASTERIX experiment was the first one to perform measurements selecting P-wave annihilation by means of the protonium X-rays detected in coincidence. This approach [2] is based on the following considerations.

As discussed above the electromagnetic cascade can develop down to the $2P$-level. The cascade is accompanied by X-ray emission. Therefore, by detecting the Balmer X-ray associated to the transition to the $2P$-level, it is possible to tag P-wave annihilation. In the ASTERIX apparatus the X-rays were detected by conversion in an argon-ethane drift chamber devoted to this purpose (XDC). By means of this procedure they performed branching ratios [2] and meson spectroscopy measurements [3] from atomic P-states.

The relevance of performing measurements under a defined initial L has been already discussed in the introduction. From fig. 1*a*)-*c*) we can see that a dramatic change in the invariant-mass distribution is achieved by comparing bubble chamber results with the Asterix data. In spite of the interest of the obtained results, there are some drawbacks which represent the main limitation in this technique. First of all there is the background contribution to the X-ray spectrum. This background arises mainly from the bremsstrahlung due to the sudden acceleration of the charged particles produced in the annihilation and from argon fluorescence around 3 keV. As recognized by the authors [2], this background is channel dependent and can amount up to 34% with an uncertainty of 7%. Secondly there is the problem related to a proper efficiency evaluation of the X-ray trigger. These problems prevented accurate absolute measurements. Moreover, the difficulties discouraged from performing further measurements with this method in other experiments.

An alternative procedure to select P-wave dominant annihilation has been proposed by the OBELIX collaboration.

It has been pointed out that, in the ideal case of the isolated atom, the absence of stark mixing makes the protonium cascade proceed down to the $2P$-level, where annihilation occurs with much higher probability (99%) with respect to the radiative transition to the S-orbital.

Therefore, by selecting an appropriate low density it is possible to approach this condition [4]. Figure 2 shows the P-wave fraction *vs.* the target pressure as calculated by the model of Reifenröther and Klempt [5].

Following these ideas, the OBELIX collaboration developed a system which allows to perform measurements at a pressure of a few mbar and below [6].

A detailed description of the OBELIX detector can be found in ref. [7]. Figure 3 shows the detector layout with the low-pressure target assembly. The target entrance region with the $\bar{\mathrm{p}}$ energy degraders is shown in detail. To reduce the beam dispersion in the target gas and to minimize the fraction of $\bar{p}$'s annihilating in the target end-wall, it is mandatory to have the largest number of $\bar{p}$'s with momentum as close as possible to the nominal value. Consequently the effectiveness of this technique depends critically on the monochromaticity and tuning of the $\bar{p}$ beam and on the ability to manage efficiently a very low-density hydrogen target.

The LEAR accelerator delivers a monochromatic 105 MeV/c $\bar{p}$ beam, which crosses some materials (the Be window closing the beam pipe, air mylar sheets and a scintillator detector) before entering the hydrogen target, which is 75 cm long. Hence, at the target inlet, the beam has lower intensity and energy, and also a spread in energy and direction. The energy spread produces a distribution of the $\bar{p}$ stopping points along the target. Concerning the spread in direction, we remark that the OBELIX magnetic field (~ 0.5 T) is oriented along the beam axis and its effect is to force the $\bar{p}$'s which, are scattered away to spiralize along the z-axis, thus avoiding annihilations on the vessel's walls. The annihilation volume is, therefore, nearly cylindrical with a radius of about 4 cm.

In fig. 4 we show the on-line experimental annihilation time distribution of the $\bar{p}$'s. The starting time t_0 is given by the $\bar{p}$ crossing the beam scintillator counter S_0. The stopping time is given by the time at which the charged particles produced in the annihilation hit the time-of-flight (TOF) scintillator barrel surrounding the target. The first peak on the left is due to the annihilations on the downstream layer of the mylar window at the entrance of the hydrogen target (2 ns FWHM), the second one

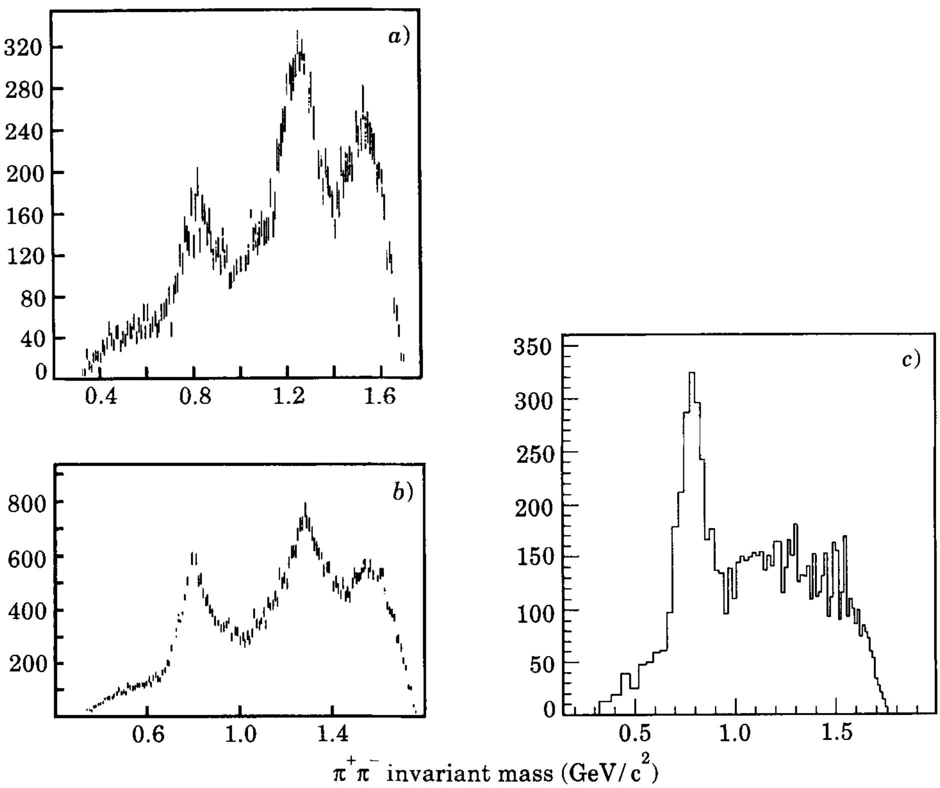

Fig. 1. – a) $\pi^+\pi^-$ invariant-mass distribution for data in gaseous H_2 at NTP with X-ray trigger [3]; b) same data without X-ray trigger [3]; c) same distribution in liquid H_2 [8].

(starting ~ 50 ns later) corresponds to the annihilations on the target end-wall. The plateau following the second peak is due to the annihilations within the hydrogen target delayed due to the protonium formation and decay.

An appropriate time gate can, therefore, discriminate the annihilations in H_2 from the other contributions.

Figure 5*a*) shows the distribution of the annihilation times, for annihilations within the H_2 target, as a function of the z-coordinate of the vertices. The two bands correspond to annihilations at rest and in flight at very low energy. Figures 5*b*) and *c*) show the associated $\pi^+\pi^-$ invariant-mass distributions for $\pi^+\pi^-\pi^0$ events.

Annihilation in flight at very low energy ($P_{\bar{p}} \leq 50\,\mathrm{MeV}/c$) occurs mainly from S-wave, as confirmed by the comparison of fig. 5*c*) and 1*c*).

For annihilation at rest, the relative S- and P-wave fraction depends on the target

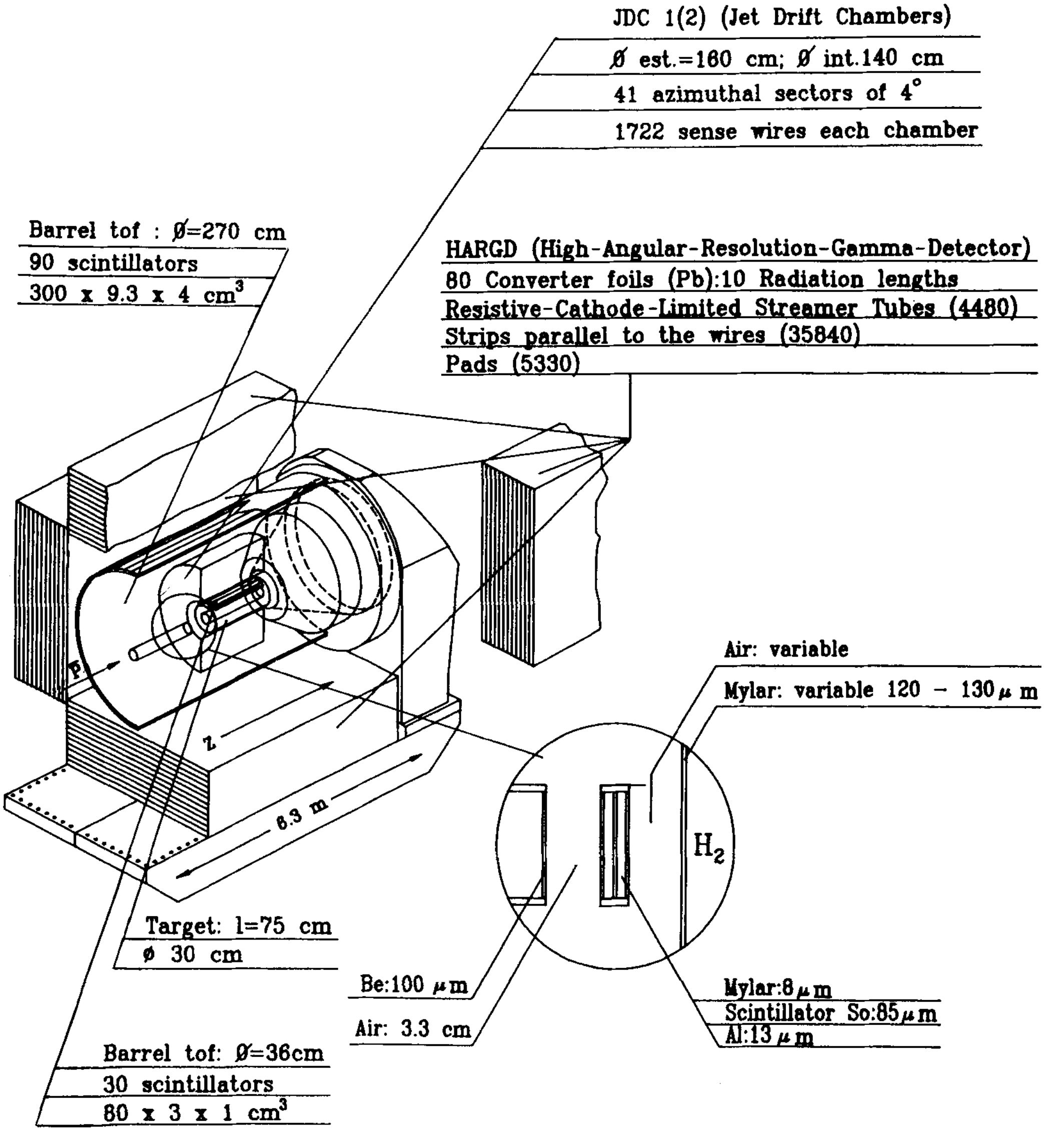

Fig. 2. – Layout of the OBELIX detector for low-pressure measurements.

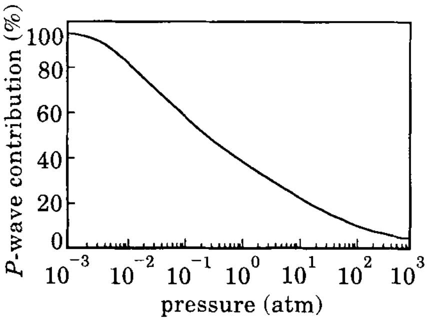

Fig. 3. – P-wave fraction *vs.* pressure [5].

pressure. Figures 6*a*), *b*) show our data at NTP and at the lowest pressure reached up to now (2 mbar). We can note enhancement of the AX peak as for the ASTERIX data with X-rays (fig. 1).

At 5 mbar we measured also the $\pi^+\pi^-$ and K^+K^- branching ratios using a dedicated back-to-back trigger [9].

We found: $BR_{\pi\pi} = (4.27 \pm 0.09) \cdot 10^{-3}$, $BR_{KK} = (0.46 \pm 0.03) \cdot 10^{-3}$. The ratio $R = BR_{KK}/BR_{\pi\pi}$ has been measured also at a pressure of 2 mbar. The results are: $R_{5\,\mathrm{mbar}} = 0.107 \pm 0.007$, $R_{2\,\mathrm{mbar}} = 0.102 \pm 0.015$.

The results obtained show that the systematic errors are well under control and that good accuracy, by profiting with the OBELIX trigger capabilities, can be achieved even with limited total statistics. With this trigger an enhancement of the intriguing region of the AX structure (1.56 GeV) was also obtained.

The analysis of the Dalitz plot for the $\pi^+\pi^-\pi^0$ channel has been performed using Zemach method with $(\pi\pi)$ amplitudes for $l = 0, 1, 2$ parametrized in K-matrix formalism, as well as by using Breit-Wigner fits for ρ_0, f_2 and AX. The parameters

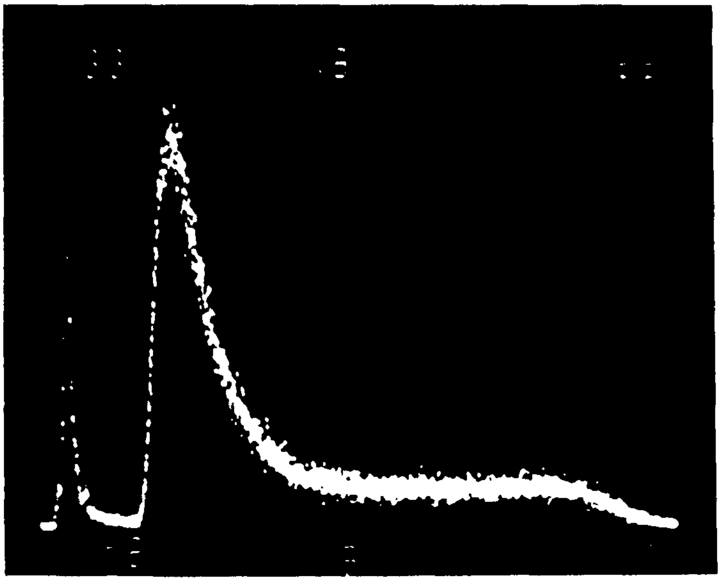

Fig. 4. – On-line distribution of annihilation times as given by the internal scintillator barrel.

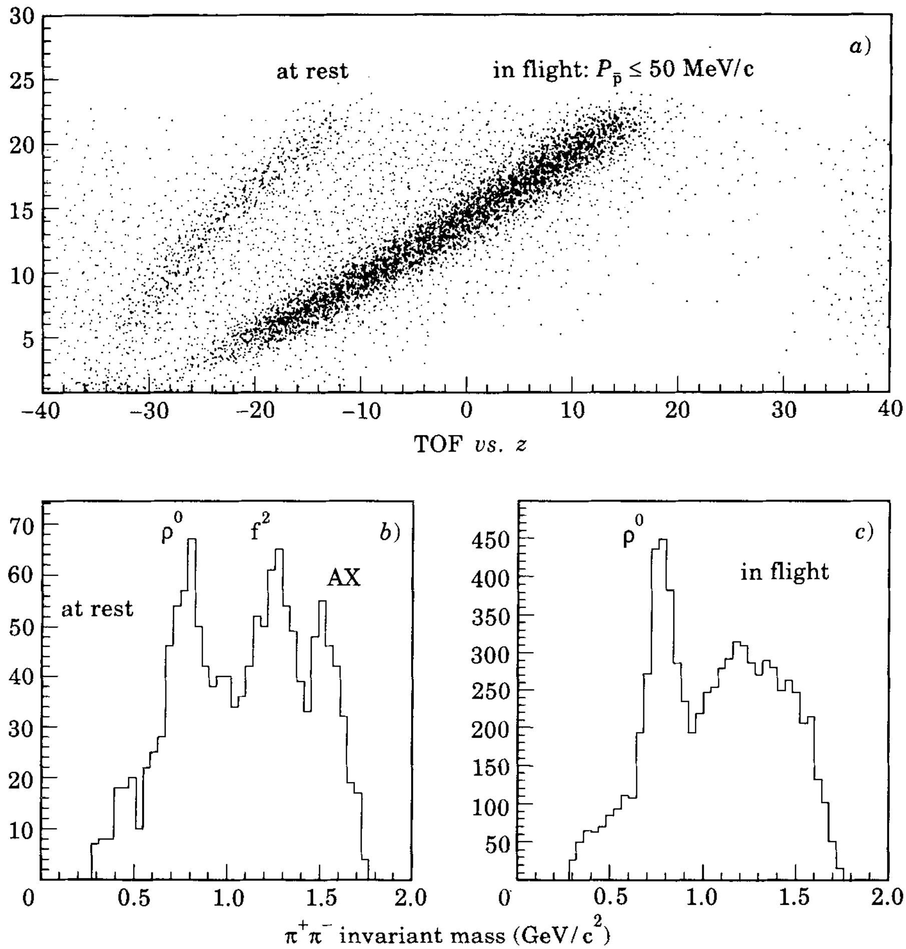

Fig. 5. – *a*) Annihilation times *vs.* z-coordinate of the annihilation vertices; *b*) $\pi^+\pi^-$ invariant-mass distribution for the data at rest; *c*) same distribution for in-flight annihilations.

used to describe the amplitude and therefore the Dalitz plot were fixed from our preliminary analysis of high statistics $\pi^+\pi^-\pi^0$ data in gas at the normal pressure (NTP data) [10], leaving free only the total annihilation branching ratios for different initial states (only 5 parameters are left free: ${}^3S_1$, ${}^1S_0$, ${}^1P_1$, ${}^3P_1$ and ${}^3P_2$ branching ratios).

The Dalitz plot density function has been evaluated by simulating a proper Monte Carlo data sample satisfying the experimental trigger conditions. The NTP data are in agreement with the expected total annihilation branching ratio of the S-wave ($\sim 50\%$) as well as with the so-called «ρ-π» puzzle, which means a dominance of the triplet S state over the singlet one ($\sim 80\%$). The result of our preliminary fits to the *LP* data is the small contribution of the total S-wave annihilation as was expected, but with a possible dominance of the ${}^1S_0$ state over the ${}^3S_1$. A trend of lowering the relative ${}^1P_1$ contribution in comparison with other P-waves is also observed. The sensitivity of the low-pressure data to the AX structure (also due to the trigger) was tested by repeated similar fits with and without AX contribution. A clear agreement

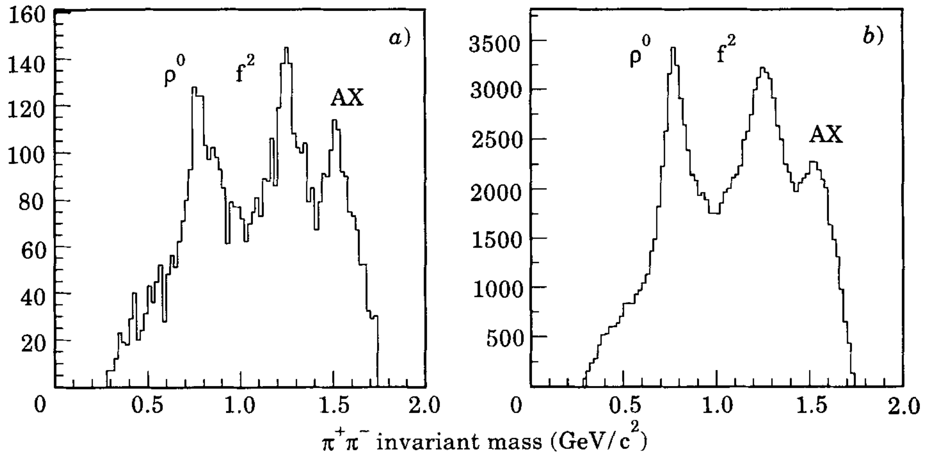

Fig. 6. – *a*) $\pi^+\pi^-$ invariant-mass distribution for annihilation at rest at the pressure of 2 mbar; *b*) same distribution for data at NTP.

between two data sample fits is obtained only when a structure is present at 1.560 GeV. A detailed discussion of these results can be found in ref. [9].

3. – Conclusions.

The results obtained show that a change of the relative *S*- and *P*-wave fraction in a particular final state can be a discriminating tool in identifying new resonances which otherwise could be overwhelmed by the backround. The ASTERIX experiment pioneered in this field selecting *P*-wave annihilation by mesons of X-ray tagging. This procedure leads to the discovery of the AX(1565) resonance.

The OBELIX collaboration developed a new technique which manages to overcome some limitations of the X-ray approach.

The method is based on the use of low-pressure H_2 targets. The data taken in some preliminary runs show that accurate measurements are possible. The results obtained make us confident of the reliability of this approach and new, large-statistics measurements are foreseen in the near future.

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