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Protonium annihilation into $K_S K_L$ at three different target densities

OBELIX Collaboration

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Abstract

The frequency of the protonium annihilation channel $\bar{p}p \rightarrow K_S K_L$ has been measured at three different target densities: liquid hydrogen (LH), gaseous hydrogen at NTP conditions and gaseous hydrogen at low pressure (5 mbar). The obtained results are: $f(\bar{p}p \rightarrow K_S K_L, LH) = (7.8 \pm 0.7_{stat} \pm 0.3_{sys}) \times 10^{-4}$, $f(\bar{p}p \rightarrow K_S K_L, NTP) = (3.5 \pm 0.5_{stat} \pm 0.2_{sys}) \times 10^{-4}$ and $f(\bar{p}p \rightarrow K_S K_L, 5\text{ mbar}) = (1.0 \pm 0.3_{stat} \pm 0.1_{sys}) \times 10^{-4}$. Since the $K_S K_L$ final state can be originated only from the $^3S_1$ initial state, these values give direct information on the scaling of the protonium spin-triplet S-wave annihilation probability with the density.

1. Introduction

One of the most intriguing problem of antiproton-proton annihilation at rest concerns the distribution of the initial state from which annihilation occurs. The knowledge of this distribution is important for the atomic physics and annihilation dynamics models and it can turn out a powerful input in the spin-parity analyses (for recent reviews see [?,?,?,?]). An important investigation tool in this field is the determination of two body annihilation frequencies at rest in different target conditions since they are selectively sensitive only to some of the initial states. Under the hypothesis that protonium annihilations occur only from S and P waves [?], the possible initial states are (in $^{2S+1}L_J(J^{PC})$ notation): $^1S_0$ (0^{-+}), $^3S_1$ (1^{--}), $^1P_1$ (1^{+-}), $^3P_0$ (0^{++}), $^3P_1$ (1^{++}) and $^3P_2$ (2^{++}).

The distribution of annihilation probability among these states is a function of the density of the target within which the protonium de-excitates; in a liquid target, due to the Day-Snow-Sucher effect [?], annihilations occur mainly from the two S-wave states, in a gaseous one at *NTP* the contributions of the S and P waves are quite similar and in a low pressure target, due to the dominance of radiative de-excitation, annihilations happen mainly from P-wave states. In general, for the conservation rules of J, P and C quantum numbers, a given reaction is produced only from a subset of the six initial states. These rules are particularly strong for two body final states and allow an easier comprehension of the protonium de-excitation and annihilation processes. In this context, the study of the reaction $\bar{p}p \rightarrow K_S K_L$ is very important since it can proceed only from $^3S_1$ initial state. As a consequence, the measurement of its annihilation frequency as a function of the density is directly related to the variation of the triplet S-wave population. Using the notation of Refs. [?,?], the $K_S K_L$ annihilation frequency can be written as:

$$f(\bar{p}p \rightarrow K_S K_L, \rho) = W(^3S_1, \rho) BR(\bar{p}p \rightarrow K_S K_L, ^3S_1) \quad (1)$$

where $W(^3S_1, \rho)$ is the $\bar{p}p$ annihilation probability from $^3S_1$ initial state that is a function of the target density ρ; $BR(K_S K_L, ^3S_1)$ is the $K_S K_L$ elementary branching ratio from the $^3S_1$ state and depends on the annihilation dynamics only. In this paper, we report on the measurement of the $K_S K_L$ annihilation frequency in three different target conditions: liquid hydrogen (LH), gaseous hydrogen at standard temperature and pressure conditions (NTP) and gaseous hydrogen at 5 mbar pressure (LP, low pressure). This is the first time that the same apparatus is used with hydrogen targets of three different densities spanning five orders of magnitude and reducing in this way the effect of systematic errors in the data interpretation. The present experimental situation is reported in Table ??. As one can see, three previous results in LH conditions are available, two of them from bubble chamber experiments [?,?], the last one from the Crystal Bar-

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Table 1
Previous experimental results on $\bar{p}p$ annihilation frequency to the K_SK_L final state. The caption $NTP - X$ refers to data taken in coincidence with protonium deexcitation X-rays, at NTP conditions.

$f(\bar{p}p \to K_SK_L, \rho)$	target density	reference
$(6.1 \pm 0.9) \times 10^{-4}$	LH	[8]
$(8.0 \pm 0.5) \times 10^{-4}$	LH	[9]
$(9.0 \pm 0.6) \times 10^{-4}$	LH	[10]
$(3.6 \pm 0.6) \times 10^{-4}$	NTP	[11]
$(0.73 \pm 0.56) \times 10^{-4}$	$NTP - X$	[11]

rel collaboration [10]. At the NTP conditions, there is only the Asterix result [11], while at LP there are no data at all. Asterix has also measured at NTP the frequency of the K_SK_L final state in coincidence with X-rays emitted by protonium.

2. Experimental layout and data samples

Measurements were performed with the Obelix detector by exploiting the LEAR $\bar{p}$ beam at CERN. The apparatus, described elsewhere [12], consists of the target, the vertex detector (SPC), used only at NTP conditions, the time of flight system (TOF), the drift chambers (JDC), the electromagnetic calorimeter (HARGD) and the magnet that provides an axial field. In order to optimize the beam stopping, we used different targets for the three measurements. The beam and target set-up used were the following:

- for the LH data sample, we used a 200 MeV/c momentum $\bar{p}$ beam entering a 25 cm long and 7.5 cm radius liquid hydrogen cylindrical target;
- for the NTP sample, we used a 105.5 MeV/c momentum beam; the hydrogen target gas was contained by a 3 cm radius, 60 cm length, 20 μm thick aluminized mylar tube which was also the internal cathode of the SPC vertex detector;
- for the LP sample, the 105.5 MeV/c beam was slowed down with suitable thickness mylar foils before entering a 5.0 ± 0.1 mbar pressure hydrogen target of 15 cm radius and 75 cm length.

At each density two different triggers were used: *minimum bias* (MB: by requiring an incident antiproton and at least one hit in the internal barrel of the time of flight) and *two prongs* (2P: by requiring the entering antiproton, 2 hits in the internal scintillators of the time of flight system and 2 in the external one). In order to select annihilations at rest and to avoid annihilations outside the target we used time gates to count scintillator hits [13]. Gates were optimized to take into account the dependence of the time delay between the $\bar{p}$ beam monitor signal and the scintillator hits on beam momentum, slowing thickness, target density and dimensions [14]. Moreover the time distribution of the wall annihilation are strongly different from at rest ones. With this method, the fraction of annihilations within the time gate that are not due to $\bar{p}p$ at rest is negligible for the LH sample, is of the order of 4 % for the NTP sample and is much higher for the LP one since about 95 % of the beam is lost in the slowing materials, in the target window entrance and in the end wall. Piled-up antiprotons were rejected on-line. We collected about 2×10^6 2P events in LH and at NTP conditions and 4×10^6 2P events at LP. The corresponding number of annihilations at rest has been evaluated for the LH and NTP samples directly from the run counters. Cross checks have been made both on the MB samples and by normalizing on the $\pi^+\pi^-$ reaction. The number of annihilations in hydrogen at rest for the LH sample is $N_{\bar{p}}^{LH} = (25.36 \pm 0.05_{sys}) \times 10^6$ and for the NTP one is $N_{\bar{p}}^{NTP} = (17.2 \pm 0.2_{sys}) \times 10^6$. For the LP sample, the number of annihilations at rest has been evaluated only using the annihilation frequency of the $\pi^+\pi^-$ reaction (see end of Section 3) for which there was a previous measurement [15] performed on a different data set.

3. Data analysis and results

We evaluate the annihilation frequency of the K_SK_L final state using the following formula:

$$f(\bar{p}p \to K_SK_L, \rho) = \frac{N^{\rho}_{K_SK_L} - N^{\rho}_{BG}}{\epsilon^{\rho}_{K_SK_L} N^{\rho}_{\bar{p}}} \tag{2}$$

where ρ is the target density, $N^{\rho}_{K_SK_L}$ is the number of events corresponding to the K_SK_L final state (plus background), N^{ρ}_{BG} is the estimated number of background events, $\epsilon^{\rho}_{K_SK_L}$ is the reconstruction efficiency and $N^{\rho}_{\bar{p}}$ is the number of annihilations at rest.

The reaction reconstruction technique used to evaluate $N^{\rho}_{K_SK_L}$ is the same for all the data sets: the K_S is observed through its decay into $\pi^+\pi^-$ while the K_L is

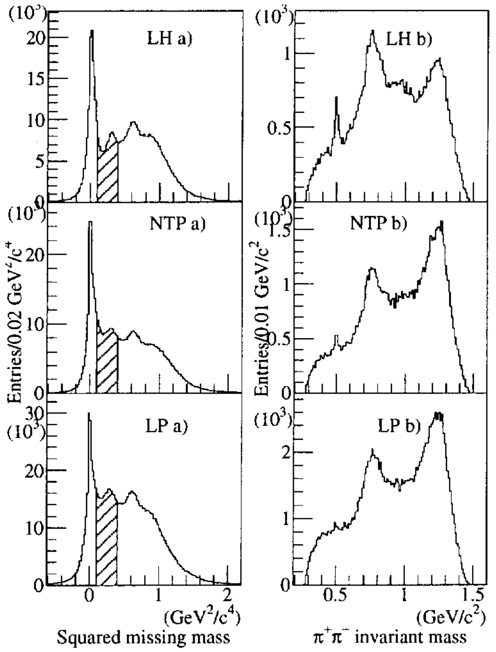

Fig. 1. *LH*, *NTP* and *LP* samples: (a) Squared missing mass for all events with 2 charged tracks and (b) $\pi^+\pi^-$ invariant mass for events with a missing mass in the shaded area of (a) (K_L selection window).

required selecting a window in the missing mass. For the analysis, we start selecting events of the 2P samples with two long tracks in the SPC (only present at NTP) and in the JDC detectors, of opposite charge, with a vertex inside a fiducial volume. The squared missing mass for the selected events of the three samples is shown in Fig. 1a. The peaks due to the π^o together with the back-to-back events, η and ω missing particles are fairly evident. In order to observe the K_SK_L final state we select those events with a squared missing mass in the window $[0.1-0.4]$ GeV$^2/c^4$ that is centered around the K_L missing mass (shaded areas in Figs. 1a). For these events we search for the K_S looking at the $\pi^+\pi^-$ invariant mass (see Figs. 1b). Clear peaks due to the K_S particle, the $\rho^o(770)$ and $f_2(1270)$ resonances appear in all samples. The K_S peak is mainly due to K_SK_L events and background events with a K_S and a missing mass in the K_L selection window (K_SM_{miss}). This peak is above a continuous background mainly given by reactions with neutral particles. In Fig. 2a, it is shown an expansion of the previous histogram (Fig. 1b) in our region of interest for the *LH* sample. In order to evaluate the number of events under the peak we fit the $0.3-0.7$ GeV$/c^2$ invariant mass region with a smooth cubic polynomial background function plus a gaussian for the peak. In this way we can evaluate the number of events in the peak ($N^{\rho}_{K_SK_L}$) and the continuous background.

The reconstruction efficiencies are evaluated by means of extensive Monte Carlo simulations based on the GEANT 3 package [16]. Detection and response efficiencies of the different parts of the detector are evaluated experimentally on the MB samples and are included in the simulation program.

The K_S peak, mainly given by the K_SK_L events, has a background contribution (N^{ρ}_{BG}), that has to be evaluated separately, due to other final states containing at least one K_S. The main sources of this background are the K_SK_S reaction with an undetected K_S and the $K_SK^o\pi^o$ ones with both K^o and π^o missing. This contribution to the K_S peak is calculated with the help of the Monte Carlo simulations for the evaluation of the reconstruction efficiency of these background reactions as fake K_SK_L events. The number of background events N^{ρ}_{BG} is given by the relation:

$$N^{\rho}_{BG} = N^{\rho}_{\bar{p}} \sum_X \epsilon^{\rho}_X f(X,\rho) \tag{3}$$

with $X \in \{K_SK_S,\ K_SK_S\pi^o,\ K_SK_L\pi^o\}$, where $f(X,\ \rho)$ represents the experimental annihilation frequency measured for the X final states, ϵ^{ρ}_X is the feed-through probability to the K_SK_L hypothesis and $N^{\rho}_{\bar{p}}$ is the number of $\bar{p}$ annihilations at rest in the hydrogen target. With this method we get that the most important feed-through probability is due to the K_SK_S two body final state (with the subsequent decays $K_S \to \pi^+\pi^-$ and $K_S \to \pi^o\pi^o$) that has the same kinematic of the K_SK_L reaction. On the contrary the $K_SK_L\pi^o$ and $K_SK_S\pi^o$ three body final states are strongly suppressed (by near two orders of magnitude with respect the K_SK_S one) because of the missing mass cut. In fact for these reactions the nominal value of the missing mass recoiling against a K_S is greater than the upper cut applied.

We check the results obtained with this classical analysis [11] by applying additional cuts exploiting the information of the electromagnetic calorimeter. In fact, the observed K_SK_L events give a maximum of one neutral cluster detected in the calorimeter due to the K_L interaction. On the contrary the reactions con-

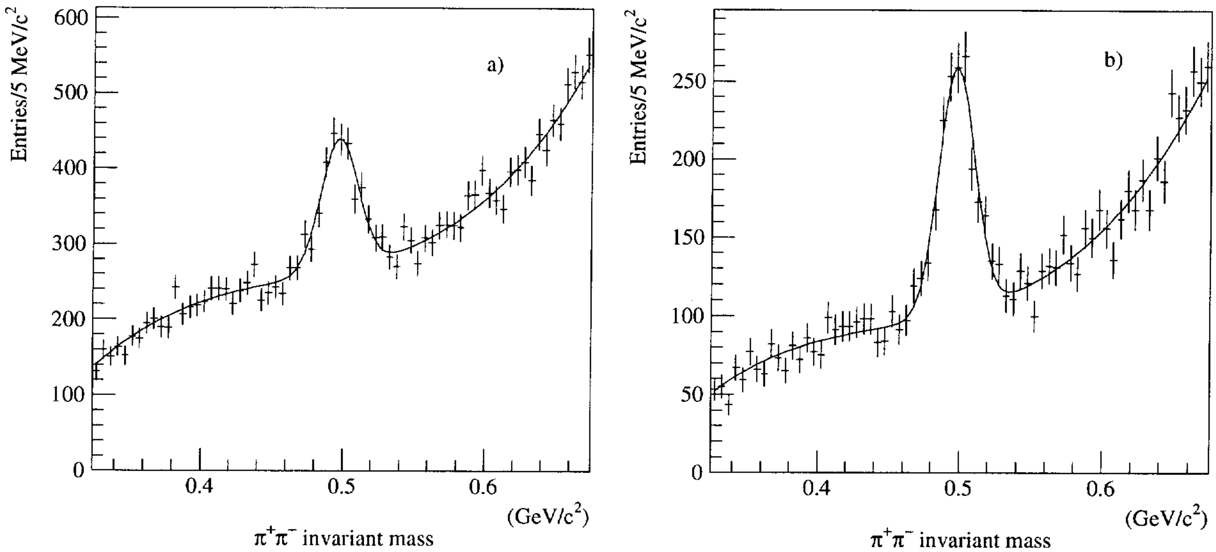

Fig. 2. *LH* sample: (a) $\pi^+\pi^-$ invariant mass (GeV/c^2) around the K_S peak for events in the K_L selection window without any request on the calorimeter and (b) with the request of no more than 1 neutral cluster. The background below the K_S peak is reduced in this case by a factor 2.6.

tributing to the background inside the K_S peak (K_SK_S, $K_SK_L\pi^o$ and $K_SK_S\pi^o$) and to the continuous background (e.g. $\pi^+\pi^-n\pi^o$ with $n \geq 1$ or $\pi^+\pi^-\eta$) contain at least two gammas in the final state. For this reason we select a sub-sample of events with at most one neutral cluster. In this way, we cut down channels containing π^os and η and we perform a direct background rejection without loosing K_SK_L events. The $\pi^+\pi^-$ invariant mass distribution of the selected events for the *LH* sample is shown in Fig. 2b. With this method the K_SK_S feed-through probability is reduced by about a factor four. Furthermore, as one can see, the continuous background is lowered by a factor about 2 below the K_S peak and, as a consequence, the signal-to-noise ratio is improved by roughly the same factor.

The systematic error has been estimated by considering the result stability as a function of the applied cuts and of the procedure applied for the evaluation of the signal, the efficiency, the background and the beam. As an example we have changed the selection window in the missing mass and we have introduced additional cuts (e.g. on the K_S momentum). Moreover tests have been made using a one constraint kinematic fit to the reaction $\pi^+\pi^-K_L(missing)$ without any significant improvement with respect to the K_L window selection.

In the *LH* sample, we find, with the classical analysis a clear K_S signal containing 1140 ± 90 events (see Fig. 2a). In this condition, due to the smallness of $f(K_SK_S, LH) = (4 \pm 3) \times 10^{-6}$ [8,9], the background is mainly given by $K_SK_{S,L}\pi^o$. Knowing that $f(K_SK_L\pi^o, LH) = (5.7 \pm 0.8) \times 10^{-4}$ [10,17] and $f(K_SK_S\pi^o, LH) = (7.7 \pm 0.5) \times 10^{-4}$ [18,19], we get using Eq. (3) a background contribution of about 2% . Using Eq. (2) and applying various selection criteria, we find on average:

$$f(\bar{p}p \to K_SK_L, LH) = (7.8 \pm 0.7_{stat} \pm 0.3_{sys}) \times 10^{-4} \quad (4)$$

The first error is statistical and the second is the systematic one. The obtained result is in good agreement with the existing data in *LH* (see Table 1).

Applying the same analysis chain to the *NTP* data sample, we find $N^{NTP}_{K_SK_L} = 600 \pm 80$ events (see Fig. 3a) with our loosest cuts. Knowing that $f(K_SK_S, NTP) = (0.3 \pm 0.1) \times 10^{-4}$ [11] and assuming that $f(K_SK_L\pi^o, NTP) + f(K_SK_S\pi^o, NTP)$ is of the same order of that in *LH*, we find that the main contribution to the background (at a level of 5 %) is given by the K_SK_S reaction whereas other

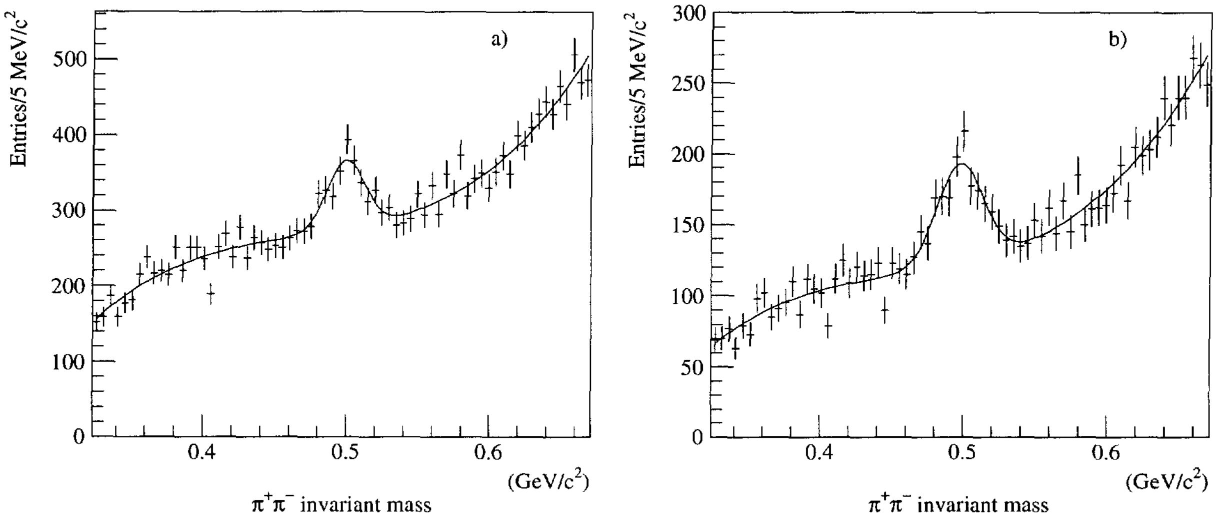

Fig. 3. *NTP* sample: (a) $\pi^+\pi^-$ invariant mass (GeV/c^2) around the K_S peak for events in the K_L selection window without any request on the calorimeter and (b) with the request of no more than 1 neutral cluster. The background below the K_S peak is reduced by a factor 2.3.

sources can be neglected at the present level of sensitivity. Averaging over different selection criteria as before, we find the following K_SK_L annihilation frequency:

$$f(\bar{p}p \to K_SK_L, NTP) = (3.5 \pm 0.5_{\text{stat}} \pm 0.2_{\text{sys}}) \times 10^{-4} \quad (5)$$

The obtained result is in good agreement with the Asterix one [11] (see Table 1).

For the *LP* sample, we face the problem of evaluating the number of $\bar{p}p$ annihilations by comparing the number $\pi^+\pi^-$ events of the present data sample to the $\pi^+\pi^-$ frequency at 5 mbar, determined by our experiment in a previous measurement [15]. We evaluate the number of events of the reaction $\bar{p}p \to \pi^+\pi^-$ by submitting the 2 well reconstructed charged events to a three constraint kinematic fit to the hypothesis of 2 particles escaping back-to-back from the target with the same momentum. The spectrum of the common momentum for those events satisfying the hypothesis with a probability greater than 10 % is shown in Fig. 4. Clear peaks due to the $\bar{p}p \to \pi^+\pi^-$ and $\bar{p}p \to K^+K^-$ reactions appear. The number of $\pi^+\pi^-$ events observed in this way in the *LP* sample is $N^{LP}_{\pi^+\pi^-} = 21550 \pm 150$ and the corresponding reconstruction efficiency, evaluated by means of Monte Carlo simulation,

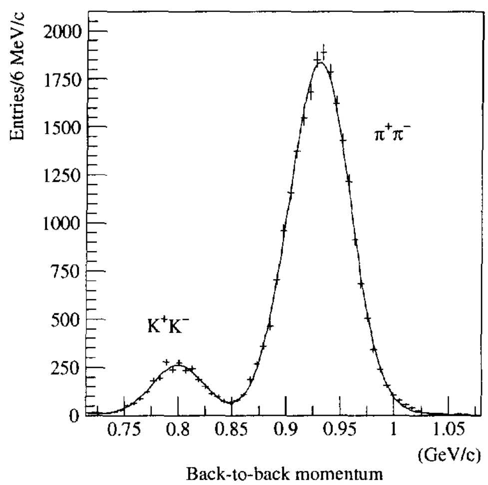

Fig. 4. *LP* sample: common momentum for back-to-back events.

is $\epsilon^{LP}_{\pi^+\pi^-} = (9.8 \pm 0.1)\%$. Of these events, an upper limit of 2% at 95% confidence level can be associated to annihilations outside the gas target. Knowing that the $\pi^+\pi^-$ annihilation frequency is $f(\pi^+\pi^-, LP) = (42.6 \pm 1.1) \times 10^{-4}$ [15], we obtain a number of $\bar{p}p$ annihilations at rest in the *LP* sample as:

$$N^{LP}_{\bar{p}} = \frac{N^{LP}_{\pi^+\pi^-}}{\epsilon^{LP}_{\pi^+\pi^-}\ f(\pi^+\pi^-,\ LP)}$$

$$= (51.6 \pm 1.4) \times 10^6 \quad (6)$$

With the analysis described above, we find a K_SK_L yield for the LP sample of $N^{LP}_{K_SK_L} = 280 \pm 70$ (see Fig. 5a). This is a 4 σ signal above the background and it reaches an higher significance ($> 4\sigma$) for those histograms with a better signal/noise ratio as in Fig. 5b, containing events with no more than one neutral cluster. We pay particular attention to the background evaluation, since none of the background channels has been measured. In order to check the stability of our signal, we apply very restrictive additional quality cuts, mainly using the electromagnetic calorimeter. In particular, requiring no neutral clusters in the calorimeter, one can see from Monte Carlo simulations that the reconstruction efficiency for the background channels (K_SM_{miss}) is reduced by about a factor 10. With this quality cut, we get $N^{LP}_{K_SK_L,0\gamma} = 240 \pm 50$ K_SK_L events and a continuous background seven times smaller than that in Fig. 5a. This procedure allows us to estimate the level of the background around 20% or less. This result has been checked with an evaluation similar to the ones performed on the LH and NTP samples. Knowing that the K_SK_S reaction occurs only in protonium P-wave, we assume for the corresponding annihilation frequency the result at NTP conditions obtained by the Asterix experiment in coincidence with the protonium de-excitation X-rays: $f(K_SK_S,\ 5\ \text{mbar}) = f(K_SK_S, NTP - X) = (0.37 \pm 0.14) \times 10^{-4}$. Moreover for $f(K_SK^o\pi^o,\ 5\ \text{mbar})$, we assume the same values as for LH and NTP. In these conditions, using Eq. (3), we obtain a background contribution in agreement with the previous result. In any case, the statistical error is dominant with respect to the background. We find, averaging over different selection criteria, the following K_SK_L annihilation frequency:

$$f(\bar{p}p \to K_SK_L, LP)$$
$$= (1.0 \pm 0.3_{\text{stat}} \pm 0.1_{\text{sys}}) \times 10^{-4} \quad (7)$$

4. Conclusions

The following conclusions can be drawn with the obtained results (see Table 2) on the K_SK_L annihilation frequency:

Table 2
Annihilation frequencies for $f(\bar{p}p \to K_SK_L, \rho)$ in 10^{-4} units.

Target density (ρ)	5 mbar	NTP	LH
Beam (10^6)	51.6 ± 1.4	17.2 ± 0.2	25.36 ± 0.05
$N^{\rho}_{K_SK_L}$	280 ± 70	600 ± 80	1140 ± 90
$f(\bar{p}p \to K_SK_L, \rho)$	1.0 ± 0.3	3.5 ± 0.5	7.8 ± 0.7

i) these frequencies have been studied for the first time as a function of the target density in a range of 5 orders of magnitude. Following Eq. (1), one can see that this dependence is entirely due to the variation of the annihilation probability $W(^3S_1,\ \rho)$ from the triplet S-wave [20]. Going from LP to LH conditions, we find experimentally an increase of this probability. This change can be quantified as follows: $W(^3S_1,\ 5\ \text{mbar}) : W(^3S_1,\ NTP) : W(^3S_1,\ LH) = 1.0 : 3.5 : 7.8$.

ii) The non-negligible LP value indicates the presence of a sizeable contribution of annihilation from the triplet S-wave at 5 mbar.

iii) Comparing these results with protonium cascade models [21–23], one can note that recent ones fit data in the medium and high density region, while all the models expect higher P wave contributions at low density.

iv) This experimental information represents a new input imposing constraints to the spin-parity analyses of complex final states at these densities.

v) These results can be compared with the measurement of the $\bar{p}p \to \eta(1440)\pi^+\pi^-$ annihilation frequency [24]. In fact, it has been shown that this reaction [25] is produced only from the singlet S-wave initial state $^1S_0$. The present experimental situation for the two reactions is summarized in Table 3. As one can see, the scaling of the $\eta(1440)\pi^+\pi^-$ frequency and that one of the K_SK_L with the density is very similar. This means that, on the basis of the K_SK_L and $\eta(1440)\pi^+\pi^-$ data alone, the ratio of the two S-wave annihilation probabilities remains constant with the density as foreseen in the model of Ref. [26].

vi) These results can be combined with the available two-body annihilation frequencies to get new insight in the evaluation of the protonium initial state distribution [26,27]. The density dependence of the annihilations in triplet S-wave obtained in

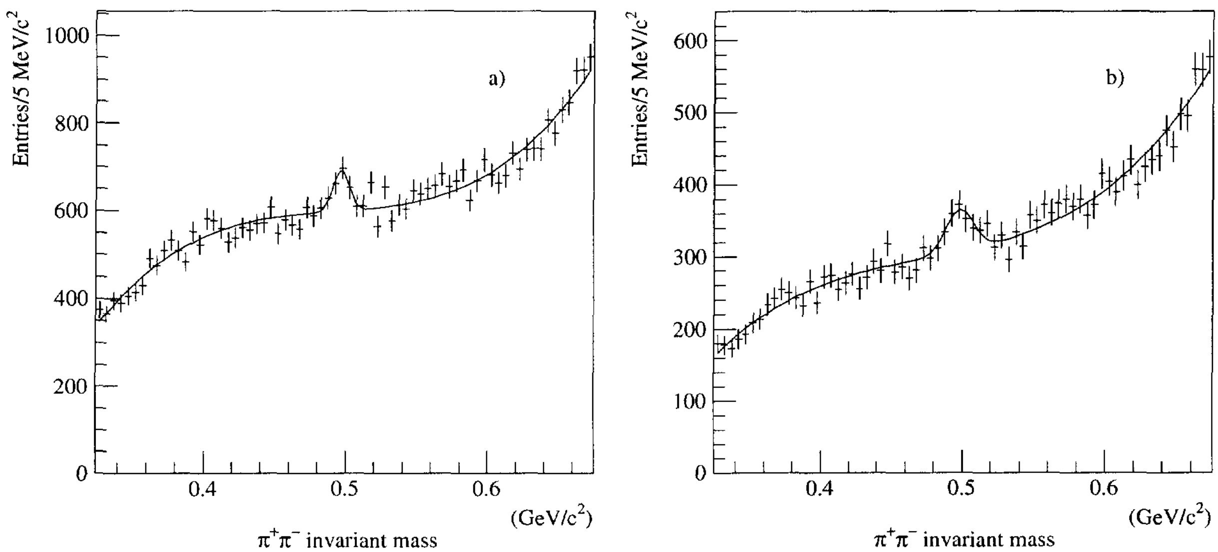

Fig. 5. *LP* sample: (a) $\pi^+\pi^-$ invariant mass (GeV/c^2) around the K_S peak for events in the K_L selection window without any request on the calorimeter and (b) with the request of no more than 1 neutral cluster. The background below the K_S peak is reduced by a factor 1.9.

Table 3
Average annihilation frequencies for $f(\bar{p}p \to K_SK_L, \rho)$ and $f(\bar{p}p \to \eta(1440)\,\pi^+\pi^-, \rho)$ in *LH*, *NTP* and 5 mbar hydrogen targets.

Target density	$f(\bar{p}p \to K_SK_L, \rho)$	ref.	$f(\bar{p}p \to \eta(1440)\,\pi^+\pi^-, \rho)$	ref.
5 mbar	$(1.0 \pm 0.3) \times 10^{-4}$	This Work (TW)	$(1.0 \pm 0.2) \times 10^{-4}$	[24]
NTP	$(3.5 \pm 0.4) \times 10^{-4}$	[11]+TW	$(2.9 \pm 0.4) \times 10^{-4}$	[24]
LH	$(8.0 \pm 0.5) \times 10^{-4}$	[8–10]+TW	$(6.7 \pm 0.3) \times 10^{-4}$	[24]

a straightforward way from the K_SK_L channel is different from that which can be calculated from $\pi^+\pi^-$ and $\pi^o\pi^o$ data [28,29]. Therefore further measurements would be needed to clarify the situation.

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