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Measurement of the $\eta(1440) \to K^{\pm}K_L^0\pi^{\mp}$ production rates from $\bar{p}p$ annihilation at rest at three different hydrogen target densities

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Abstract

From the study of the annihilation at rest $\bar{p}p \to K^{\pm}K^0_{\rm miss}\pi^{\mp}\pi^+\pi^-$ the production rates of the $\eta(1440) \to K^{\pm}K^0_L\pi^{\mp}$ were obtained for three different hydrogen target densities: liquid, gaseous at NTP and at low pressure (5 mbar). The rate values are: $f_{\eta(1440)}$ (LH) = $(6.0 \pm 0.5) \cdot 10^{-4}$, $f_{\eta(1440)}$ (NTP) = $(2.9 \pm 0.4) \cdot 10^{-4}$ and $f_{\eta(1440)}$ (5 mbar) = $(1.0 \pm 0.2) \cdot 10^{-4}$. From these results, the density dependence of the annihilation fraction from the $^1S_0$ protonium level can be extracted directly.

An antiproton brought to rest in a hydrogen target forms a $\bar{p}p$ atom (protonium) in a highly excited state. The protonium undergoes an atomic cascade which ends with annihilation from a low n level. In particular, $\bar{p}p$ annihilations at rest occur from the two S-wave atomic states $^1S_0$ (0^{-+}) and $^3S_1$ (1^{--}) and the four P-wave states $^1P_1$ (1^{+-}), $^3P_0$ (0^{++}), $^3P_1$ (1^{++}), $^3P_2$ (2^{++}). Higher orbital angular momentum states do not enter, due to the negligible overlap of the p and $\bar{p}$ wave functions for $l > 1$. The population of a level from which annihilation may occur depends on the atomic cascade and on the distribution of initial states of protonium at its formation. Chemical, Auger and Stark induced transitions are directly related to the number of collisions of protonium atoms with the surrounding medium, then to the target density. Therefore, the populations of the levels depend on the density, and, consequently, the annihilation probabilities among the six above initial states, i.e. the annihilation fractions, are connected to the target density.

Experimental data from LEAR show indeed that variations of the target density are accompanied by variations of the frequencies of some exclusive annihilation channels, as e.g. K^+K^-, $\pi^+\pi^-$, $K^0_SK^0_L$ [1], as well as by variations of the ratio between these frequencies, as e.g. the ratio $(K^+K^-)/(\pi^+\pi^-)$ [1-3]. The determination of the annihilation fractions is important to atomic physics, to the study of the dynamics of nucleon-antinucleon annihilation and as input to spin-parity analyses in meson spectroscopy [4]. In general, from the conservation rules of J,P and C quantum numbers, a given final state is produced only from a specific subset of the six initial atomic states. The effect of these selection rules is more transparent for two body final states: for instance, the reaction $\bar{p}p \to K^0_SK^0_L$ can proceed only from the $^3S_1$ initial state and therefore the measurement of its frequency is directly related to the $^3S_1$ population (annihilation fraction). Besides the standard conservation laws, additional constraints on the allowed protonium initial states might be related to the available center of mass energy and the nature of the particles in the final state. This is the case of the production of the $\eta(1440)$ in $\bar{p}p$ annihilation at rest:

$$\bar{p}p \to \eta(1440)\pi\pi \qquad (1)$$

The resonance $\eta(1440)$ is the pseudoscalar component of the old puzzling E/ι. The Review of Particle Properties lists under the $\eta(1440)$ all the results on the 0^{-+} system in the 1380-1490 MeV/c^2 region [5].

In the $\eta(1440)$ production reaction, the dipion and the resonance are produced with relative orbital angular momentum $L = 0$ [6,7]. As far as the $\pi\pi$ system is concerned, it is expected that the $\pi^{\pm}\pi^{\mp}$ interaction should occur mainly with relative orbital angular momentum $l = 0$, since its invariant mass is less than 500 MeV/c^2 and the isoscalar pion-pion scattering at low energy is dominated by $l = 0$ [8]. The assumption $L = l = 0$ implies that the $\eta(1440)$ production is possible only from the $^1S_0$ initial state. As a consequence, the measurement of the $\eta(1440)$ production frequency is directly related to the singlet S-wave population.

Following the notation of Ref. [9]:

$$^{\rho}f(\bar{p}p \to \eta(1440)) = {}^{\rho}F_{^1S_0} \cdot B[\eta(1440)]_{^1S_0}, \qquad (2)$$

where $^{\rho}f$ is the $\eta(1440)$ production frequency, at a given density ρ, $^{\rho}F_{^1S_0}$ is the fraction of $\bar{p}p$ annihilations at rest from the $^1S_0$ initial state and $B[\eta(1440)]_{^1S_0}$ is the branching ratio from this state for $\eta(1440)$ production. This shows that the annihilation fraction $^{\rho}F_{^1S_0}$ changes with density proportionally to the production frequency:

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$$\frac{^{\rm NTP}F_{^1S_0}}{^{\rm LH}F_{^1S_0}} = \frac{^{\rm NTP}f(\eta(1440))}{^{\rm LH}f(\eta(1440))}, \tag{3}$$

$$\frac{^{5\ \rm mbar}F_{^1S_0}}{^{\rm LH}F_{^1S_0}} = \frac{^{5\ \rm mbar}f(\eta(1440))}{^{\rm LH}f(\eta(1440))}. \tag{4}$$

In this paper, we report on the measurement of the $\eta(1440)$ production rates, seen in $\bar{p}p$ annihilation at rest, in the channel $K^{\pm}K^0_{\rm miss}\pi^{\mp}\pi^+\pi^-$, in three different target conditions: liquid hydrogen (LH), gaseous hydrogen at normal temperature and pressure (NTP) and gaseous hydrogen at low pressure (5 mbar). This was the first time the $\eta(1440)$ was produced at three different hydrogen densities, covering more than five orders of magnitude, with the same detector setting in order to reduce drastically the effect of systematic errors in the comparison of the production rates.

The obtained results compare favorably with both old bubble chamber [10] and ASTERIX results [7].

The annihilation frequencies at rest in five pions final state: $\bar{p}p \to \pi^+\pi^-\pi^+\pi^-\pi^0$ were also measured in LH and in gaseous hydrogen at NTP, for normalization purposes.

The measurement was performed at the Low Energy Antiproton Ring (LEAR) at CERN, using the OBELIX spectrometer (a detailed description of the detector can be found in Ref. [12]). The whole apparatus is immersed in a magnetic field, whose intensity reaches its maximum of 0.5 T along its axis. In order to optimize the number of stopped antiprotons, different geometries for the target were used at the three densities. The target is surrounded by a first layer of 30 thin (1cm) plastic scintillators, arranged in a barrel and providing the start to the time-of-flight system (TOF). An outer jet drift (JDC) is devoted to the tracking of charged particles. It allows the measurement of the particle momenta and of their dE/dx and contributes to the determination of the annihilation vertex and of the topology of the event.

For each density, a 4-prong and a minimum bias trigger sample were collected. The 4-prong trigger allowed to select a final state with at least one charged kaon, by requiring 4 hits in the inner TOF barrel, 3-4 hits in the outer TOF barrel and at least one track with the time of flight $\geq$8.5 ns between the internal and the external barrel. The enrichment factor provided by this trigger on the channel $K^{\pm}K^0_{\rm miss}\pi^{\mp}\pi^+\pi^-$, with respect to the minimum bias, was five.

About 18 million events were collected with the liquid hydrogen target; 24 million events with the hydrogen target at NTP and 6 million events with the hydrogen target at 5 mbar pressure. The three data samples consisted of 4-prong events with zero total charge, all pointing to the annihilation vertex. A data selection procedure identical for the three data sets was applied. The K^0 was not detected but reconstructed by 1C kinematic fit. The selection criteria were based mainly on the identification of the charged particles by dE/dx. This selection algorithm was tuned (efficiency and background reduction) with the help of the TOF information on the channel $K^+K^-\pi^+\pi^-$. An agreement between TOF and dE/dx for kaon identification greater than 90%, a pion rejection greater than 99% and a flat momentum efficiency of about 80% were achieved. As an example, Fig. 1 shows the dE/dx as a function of momentum with superimposed the selection functions for pions and kaons (Fig. 1a) and the efficiency curve for kaons (Fig. 1b).The data are from the NTP gaseous hydrogen data sample.

Particle identification was applied to all particles detected in the final state, looking for one kaon and two pions of opposite charge with respect to the kaon. A careful calibration procedure was applied in order to ensure that particle identification worked in the same way for all the three data samples and was well reproduced by Monte Carlo. Channels like $\pi^+\pi^-\pi^+\pi^-n\pi^0$ (n = 0,1) and $K^{\pm}K^0_S\pi^{\mp}n\pi^0$ (n = 0,1) were rejected by kinematic fit and did not contribute to the K^0 missing mass region. A cut on the $\pi^+\pi^-$ invariant mass was applied to all three samples, in order to reject the $K^{\pm}K^0_S\pi^{\mp}n\pi^0$ ($n \geq 1$) channels. All these cuts featured a high (> 90%) and smooth efficiency for the selected channel and allowed to obtain a consistent background reduction.

The square missing mass to the $K^{\pm}\pi^{\mp}\pi^+\pi^-$ system for the three data samples is shown in Fig. 2 a, b, c. A clear K^0 signal is visible. The hatched area in Fig. 2 a, b, c shows the events selected by the 1C kinematic fit (CL > 90%) in the square mass interval $0.21 \div 0.31$ GeV$^2/c^4$.

After applying all the selection criteria, 3648 events from the LH sample, 5286 events from the NTP sample and 485 events from the 5 mbar sample were left. The background contributions were, respectively: 20% for LH sample, 15% for the NTP sample and 35% for the 5 mbar sample. This residual contamina-

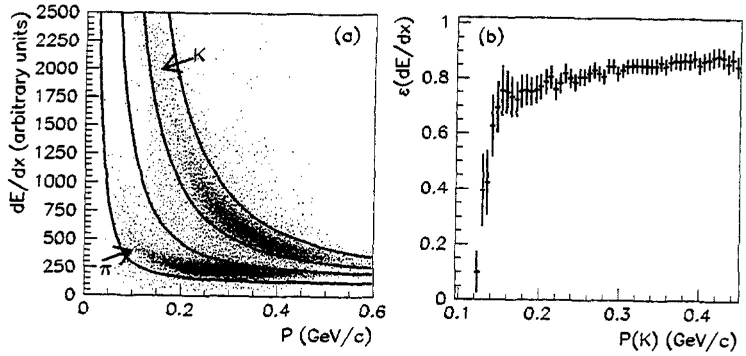

Fig. 1. NTP data: **a)** dE/dx as a function of momentum with superimposed the selection functions for kaons and pions; **b)** dE/dx efficiency curve for kaons as a function of momentum.

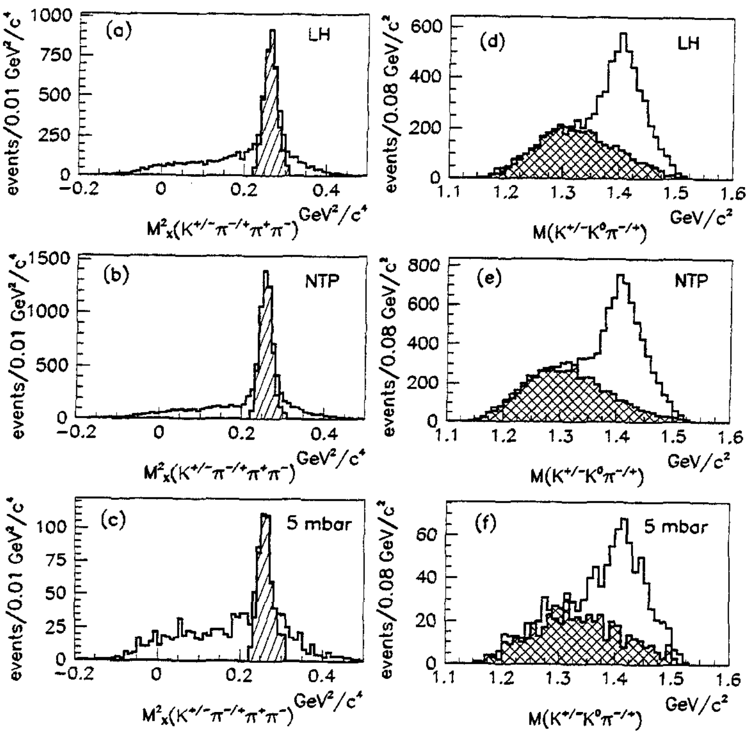

Fig. 2. **a), b), c)** square missing mass of the $K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$ selected events for the three data samples (the shaded areas show the events selected by the 1C kinematic fit to the $K^{\pm}K^{0}_{\rm miss}\pi^{\mp}\pi^{+}\pi^{-}$ hypothesis with C.L. > 90%). **d), e), f)** $K^{\pm}K^{0}_{\rm miss}\pi^{\mp}$ invariant mass distributions of the selected events for the three density samples (the shaded distributions correspond to the double charge combination $K^{\pm}K^{0}_{\rm miss}\pi^{\pm}$).

tion comes mainly from the channels $\pi^{+}\pi^{-}\pi^{+}\pi^{-}n\pi^{0}$ ($n > 1$) with one pion misidentified as a kaon, or $K^{+}K^{-}\pi^{+}\pi^{-}\pi^{0}$ with one kaon misidentified as a pion or decaying close to the vertex region. The channel with all pions gives a smooth contribution decreasing with mass in the region of interest. The shape of the background from $K^{+}K^{-}\pi^{+}\pi^{-}\pi^{0}$ events in the $K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$ missing mass spectrum was obtained by Monte Carlo simulation, applying the same analysis criteria as for real data. It is in good agreement with the shape of the background obtained by a fit on real data.

Table 1
Annihilation frequency of the reaction $\bar{p}p \to \pi^+\pi^-\pi^+\pi^-\pi^0$ at rest at two target densities from a set of minimum bias data samples in liquid hydrogen (LH) and gaseous hydrogen at NTP. N_{ev}: number of annihilations, $N_{5\pi}$,$\epsilon_{5\pi}$,$b_{5\pi}$,$f_{5\pi}$: number of events, acceptance,fraction of background and frequency of the five pion final state annihilation reaction

	N_{ev}	$N_{5\pi}$	$\epsilon_{5\pi} \cdot 10^{-2}$	$b_{5\pi}$	$f_{5\pi} \cdot 10^{-2}$
LH	330170	9763	14.3±0.4	0.09±0.02	18.0±0.7
NTP	155042	5346	16.9±0.5	0.09±0.02	17.8±0.7

The $K^\pm K^0_{miss}\pi^\mp$ invariant mass distributions for the selected events from the three different target density samples are shown in Fig. 2 d, e, f. A prominent signal in the mass region around 1400 MeV/c^2 is evident. The distributions have two entries per event, due to the presence of two identical pions in the final state. The hatched areas in the distributions of Fig. 2 d, e, f correspond to the double charge combination $K^\pm K^0_{miss}\pi^\pm$.

In order to remove all systematic errors related to trigger, beam variations and selection criteria, the $\bar{p}p \to \pi^+\pi^-\pi^+\pi^-\pi^0$ annihilation channel was used as a normalization channel. The absolute rates were evaluated both from a minimum bias and the 4 prong trigger data sample. They could be evaluated only for LH and NTP, not for the low pressure data sample, due to technical problems related to the beam counting. The resulting frequencies are reported in Table 1. The results are in agreement, within the errors, with the results of previous experiments [11]. The statistical error is negligible and the systematic error was evaluated by taking into account the maximum variation of the frequencies changing trigger conditions and selection criteria. The $\pi^+\pi^-\pi^+\pi^-\pi^0$ frequency shows no dependence on the target density, going from liquid to gaseous hydrogen. A weighted average among the present results and those from previous experiments [11] is:

$$\langle f_{5\pi} \rangle = (17.84 \pm 0.35) \cdot 10^{-2}. \quad (5)$$

The same value was also taken for the 5 mbar data sample, under the assumption that the $\pi^+\pi^-\pi^+\pi^-\pi^0$ frequency is independent from the target density.

Table 2 reports for the three different target densities: the number of collected events (N_{ev}), the number of $K\bar{K}\pi$ events ($N_{K\bar{K}\pi}$) identified in the channel $K^\pm K^0_{miss}\pi^\mp\pi^+\pi^-$, the residual background fraction ($b_{K\bar{K}\pi}$), the acceptance correction ($\epsilon_{K\bar{K}\pi}$) and the pseudoscalar resonant fraction in the channel ($N_{\eta(1440)}/N_{K\bar{K}\pi}$). This component was obtained as a result of the spin-parity analyses of the liquid and gaseous hydrogen at NTP data samples. For the liquid hydrogen data, the recent OBELIX results [6] were taken. For the NTP sample, a more advanced analysis with respect to the preliminary one of ref [13] was performed, with the main aim to identify the S-wave resonant contribution to the $K^\pm K^0\pi^\mp\pi^+\pi^-$ channel. For the 5 mbar data sample, the statistics was not enough to perform a spin-parity analysis and therefore the $\eta(1440)$ pseudoscalar fraction was inferred from the shape of the experimental distribution. The procedure consisted in evaluating the resonant fraction from a fit of the double entry $K\bar{K}\pi$ invariant mass spectrum. The crucial assumption which was done was to assume that the resonant signal present in the 5 mbar data was dominantly pseudoscalar in nature and, therefore, associated uniquely to the singlet protonium S-wave. Such assumption was justified from both the observed low absolute yield of $K^\pm K^0\pi^\mp\pi^+\pi^-$ events in the 5 mbar data sample and from the small contribution of an axial vector resonance contribution (1^{++}) coming from the protonium P-waves in the NTP data analysis. The relative pseudoscalar resonant fraction turned out to be about 65% of the overall low pressure $K\bar{K}\pi$ mass spectrum with a conservative 15% error to take into account all the approximations. As a check of this procedure the relative resonant fractions for the liquid and gaseous data samples were evaluated. A good agreement (better than 5%) with the results derived from the spin parity analysis was found.

From the present analysis the non-resonant pseudoscalar contribution was below 5% for all the data sets.

The $K\bar{K}\pi$ and $\eta(1440)$ yelds normalized to the five pion channel were evaluated. After background subtraction and acceptance correction, they are:

$$R_{K\bar{K}\pi} = \frac{N_{K\bar{K}\pi}(1 - b_{K\bar{K}\pi})}{N_{5\pi}(1 - b_{5\pi})} \cdot \frac{\epsilon_{5\pi}}{\epsilon_{K\bar{K}\pi}}, \quad (6)$$

$$R_{\eta(1440)} = R_{K\bar{K}\pi} \cdot \frac{N_{\eta(1440)}}{N_{K\bar{K}\pi}}. \quad (7)$$

The corresponding results are reported in Table 2. Using the average frequency of the five pions channel

Table 2
Annihilation frequency for the $\bar{p}p \to K^{\pm}K^0_{\text{miss}}\pi^{\mp}\pi^+\pi^-$ and $\bar{p}p \to \eta(1440)\pi^+\pi^-$ ($\eta(1440) \to K^{\pm}K^0_{\text{miss}}\pi^{\mp}$) reactions, at rest for three target densities. N_{ev}: number of annihilations; $N_{K\bar{K}\pi}$: number of $(K\bar{K}\pi)$ events; $N_{\eta(1440)}/N_{K\bar{K}\pi}$: fraction of resonant pseudoscalar in $(K\bar{K}\pi)$ events; $b_{K\bar{K}\pi}$: fraction of residual background contamination to the $K^{\pm}K^0_{\text{miss}}\pi^{\mp}\pi^+\pi^-$ selected final state; $N_{5\pi}, b_{5\pi}, \epsilon_{K\bar{K}\pi}/\epsilon_{5\pi}$: number of events, fraction of background in the five pion final state, relative acceptance of the $(K\bar{K}\pi)$ channel with respect to the five pion final state; $f_{K\bar{K}\pi}$: frequency of the reaction $\bar{p}p \to K^{\pm}K^0_{\text{miss}}\pi^{\mp}\pi^+\pi^-$ at rest; $f_{\eta(1440)}$: frequency of the reaction $\bar{p}p \to \eta(1440)\pi^+\pi^-$ ($\eta(1440) \to K^{\pm}K^0_{\text{miss}}\pi^{\mp}$) at rest

	N_{ev}	$N_{K\bar{K}\pi}$	$N_{\eta(1440)}/N_{K\bar{K}\pi}$	$b_{K\bar{K}\pi}$	$N_{5\pi}$	$b_{5\pi}$	$\epsilon_{K\bar{K}\pi}/\epsilon_{5\pi}$	$f_{K\bar{K}\pi}\cdot 10^{-4}$	$f_{\eta(1440)}\cdot 10^{-4}$
LH	$17\cdot 10^6$	3648	0.90±0.05	0.20±0.04	891400	0.09±0.02	0.76±0.01	8.5±0.5	7.6±0.6
NTP	$24\cdot 10^6$	5286	0.75±0.10	0.15±0.03	1571000	0.09±0.02	1.16±0.02	4.8±0.2	3.6±0.5
5 mbar	$6\cdot 10^6$	485	0.65±0.10	0.35±0.07	302000	0.09±0.02	1.03±0.02	2.0±0.2	1.3±0.3

$\langle f_{5\pi}\rangle = (17.84 \pm 0.35)\cdot 10^{-2}$, the annihilation frequency of the channel $\bar{p}p \to K^{\pm}K^0_{\text{miss}}\pi^{\mp}\pi^+\pi^-$ is given by

$$f_{K\bar{K}\pi} = R_{K\bar{K}\pi}\cdot\langle f_{5\pi}\rangle. \quad (8)$$

The rate for η production is:

$$f_{\eta(1440)} = f_{K\bar{K}\pi}\cdot\frac{N_{\eta(1440)}}{N_{K\bar{K}\pi}}. \quad (9)$$

The results are reported in Table 2. From Table 2, after normalization to the liquid hydrogen sample, one finally gets the variation with density of the population of the $^1S_0$ protonium level:

$$\frac{^{\text{NTP}}F_{^1S_0}}{^{\text{LH}}F_{^1S_0}} = \frac{^{\text{NTP}}f(\eta(1440))}{^{\text{LH}}f(\eta(1440))} = 0.49 \pm 0.07, \quad (10)$$

$$\frac{^{5\text{ mbar}}F_{^1S_0}}{^{\text{LH}}F_{^1S_0}} = \frac{^{5\text{ mbar}}f(\eta(1440))}{^{\text{LH}}f(\eta(1440))} = 0.17 \pm 0.03. \quad (11)$$

In the above ratios, systematic effects in measurements are further reduced. This was carefully checked by Monte Carlo simulation, where it was seen that even changing significantly the detector efficiencies the results remained stable.

The behaviour with density of the population of the $^1S_0$ protonium level was then compared with the behaviour with density of the population of the $^3S_1$ protonium level. This was possible by considering the measured frequency of the channel $\bar{p}p \to K^0_S K^0_L$ which can proceed only from $^3S_1$ state, at the three different target densities [14,15]. It was found:

$$\frac{^{\text{NTP}}F_{^3S_1}}{^{\text{LH}}F_{^3S_1}} = \frac{^{\text{NTP}}f(K^0_S K^0_L)}{^{\text{LH}}f(K^0_S K^0_L)} = 0.44 \pm 0.06, \quad (12)$$

$$\frac{^{5\text{ mbar}}F_{^3S_1}}{^{\text{LH}}F_{^3S_1}} = \frac{^{5\text{ mbar}}f(K^0_S K^0_L)}{^{\text{LH}}f(K^0_S K^0_L)} = 0.13 \pm 0.04. \quad (13)$$

These results indicate that the trend with density of the populations of the two S-wave levels of protonium is, within the experimental errors, the same and therefore it can be considered as the variation with density of the total S-wave level population of protonium.

In order to obtain the rate for $\eta(1440)$ decaying to $K^{\pm}K^0_L\pi^{\mp}$ it was necessary to correct the frequencies given in Table 2 by the factor

$$F_{\text{miss}} = \frac{f(K^0_L)}{f(K^0_{\text{miss}})} = \frac{f(K^0_L)}{f(K^0_L) + f(K^0_S \to \pi^0\pi^0) + f(K^0_S \to \pi^+\pi^-)}, \quad (14)$$

where $f(K^0_L)$ is the probability that $K^0 = K^0_L$ is missing; $f(K^0_S \to \pi^0\pi^0)$ ($f(K^0_S \to \pi^+\pi^-)$) is the corresponding probability when $K^0 = K^0_S$, multiplied by the branching ratio for the $\pi^0\pi^0$ ($\pi^+\pi^-$) K^0_S decay mode. From a Monte Carlo simulation, the correction factor turned out to be

$$F_{\text{miss}} = \frac{f(K^0_L)}{f(K^0_{\text{miss}})} = 0.791 \pm 0.005. \quad (15)$$

In the ideal case (all the K^0_L decay outside the detector, the neutral decay mode of K^0_S is not detected, the probability that the channel $K^0_S \to \pi^+\pi^-$ is misidentified as K^0_{miss} due to the undetection of both decaying pions is below 1%), the F_{miss} value is 0.762. Thus, the real situation was not far from the ideal one.

In Table 3, the production rates at three densities of the $\eta(1440)$ decaying to $K^{\pm}K^0_L\pi^{\mp}$ are reported and

Table 3
Frequency of the annihilation reaction at rest $\bar{p}p \to \eta(1440)\pi^+\pi^-$ ($\eta(1440) \to K^\pm K^0_L \pi^\mp$)

	This experiment	Bubble chamber [10]	ASTERIX [7]
LH	$(6.0\pm0.5)\cdot10^{-4}$	$(7.1\pm0.7)\cdot10^{-4}$	
NTP	$(2.9\pm0.4)\cdot10^{-4}$		$(3.0\pm0.9)\cdot10^{-4}$
5 mbar	$(1.0\pm0.2)\cdot10^{-4}$		

compared with bubble chamber [10] and ASTERIX [7] results. The results for NTP are in fair agreement, within the errors. The results for LH are also in good agreement, if one considers that the resonant fraction in bubble chamber data was assumed to be 100% of the $K^\pm K^0\pi^\mp\pi^+\pi^-$ channel, against the 90% found in the recent spin-parity analysis [6].

In conclusion, from the analysis of 3648 $\bar{p}p$ annihilations in liquid hydrogen, 5286 annihilations in gaseous hydrogen at NTP and 485 in gaseous hydrogen at 5 mbar pressure into the $K^\pm K^0\pi^\mp\pi^+\pi^-$ final state, the variation with density of the population of the $^1S_0$ protonium level was obtained from the production rates of the pseudoscalar resonance $\eta(1440)$ decaying to $K^\pm K^0_{miss}\pi^\mp$. This was the first time that the same apparatus was used to detect the reaction $\bar{p}p \to \eta(1440)\pi\pi$ with $\eta(1440) \to K^\pm K^0_{miss}\pi^\mp$, at three different target densities. From a comparison with the density dependence of the population of the $^3S_1$ level, obtained by the measurement of the frequencies of the annihilation channel $\bar{p}p \to K^0_S K^0_L$, an evaluation of the dependence with density of the total S-wave level population was deduced.

The production rates of $\eta(1440)$ decaying to $K^\pm K^0_L\pi^\mp$ were obtained at the three considered densities and the results were found in agreement with bubble chamber and ASTERIX data.

The annihilation frequencies at rest in five pions $\bar{p}p \to \pi^+\pi^-\pi^+\pi^-\pi^0$ were also measured for normalization purposes in liquid hydrogen and in hydrogen gas at NTP. No density dependence was found, in agreement with existing results in literature.

References

[1] M. Doser et al., (ASTERIX Collaboration), Nucl. Phys. A 486 (1988) 493; Phys. Lett. B 215 (1988) 792.
[2] A. Adamo et al., (OBELIX Collaboration), Phys. Lett. B 284 (1992) 409.
[3] R. Adler et al., (CPLEAR Collaboration), Phys. Lett. B 267 (1991) 154.
[4] C. Amsler and F. Myhrer, Ann. Rev. Nucl. Part. Sci. 41 (1991) 219;
U. Gastaldi, Nucl. Phys. Proc. Suppl. B 23 (1991) 224;
E. Lodi Rizzini, Rivista del Nuovo Cimento 15 (1992) 1;
A. Rotondi, Nucl. Phys. A 558 (1993) 235c.
[5] Particle Data Book , Phys. Rev. D 50 (1994) 1487.
[6] A. Bertin et al., (OBELIX Collaboration), Phys. Lett. B 361 (1995) 187.
[7] K.D. Duch et al., (ASTERIX Collaboration), Z. Phys. C 45 (1989) 223.