PERSPECTIVES IN TWO-MESON ANNIHILATION DYNAMICS

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ABSTRACT

Recent results in antiproton-proton annihilation at rest into two mesons final states are reviewed. The experimental results are interpreted both in terms of annihilation dynamics and in terms of the protonium initial state distribution. Future perspectives, based on measurements of $\bar{p}p$ annihilation cross section of two body final states in flight at very low momentum, are described.

1. Introduction

Antiproton-proton ($\bar{p}p$) annihilation at rest is a valuable tool to investigate phenomena in the low energy regime of Quantum ChromoDynamics (QCD). In this frame, among other things, it is very important the study of the $\bar{p}p$ branching ratios at rest into two mesons.

In fact branching-ratios (BR) and ratios of BR of two mesons final states can be used to understand the composition of the protonium initial states from which annihilation occurs (the so called S/P wave problem), giving useful input to other field of research like, for example, meson spectroscopy [1].

On the other hand these data can be compared to a wide range of theoretical predictions based both on QCD [2] and on hadron exchange models [3]. As an example one can check the violation of the OZI rule [4] in the antinucleon-nucleon annihilation and investigate the possible presence of strangeness in the proton [5].

Moreover, in the frame of the Quark Line Rule (QLR), it is possible to establish the relative weights of quark annihilation and rearrangement mechanisms [2] .

The layout of this paper is as follows. Section 2 discusses the features of the protonium system and the present experimental situation concerning BR of two body final states at rest in different target conditions. In section 3 the experimental results are used to extract information on the initial state distribution of the protonium.

Section 4 gives some data interpretations in terms of annihilation dynamics, with particular attention to the study of Dynamical Selection Rules (DSR). Section 5 discusses a promising method that would allow to disentangle for the first time the atomic contribution from the nuclear one in the experimental BR. This approach, based on the analysis of data taken in flight at very low momentum, opens new perspectives in the field of two mesons annihilation dynamics.

2. The protonium system and the experimental situation

In the experiments at rest the antiprotons are moderated and stopped in hydrogen targets, where they form antiprotonic atoms. The $\bar{p}p$ systems are formed with the principal quantum number $n \sim 30$, while the angular momentum is approximately statistically distributed around $l \sim 20$ [6] . Then the protonium undergoes two competing processes: a) deexcitation to lower levels by X-rays or external Auger electron emission; b) Stark mixing between the various l levels (with the same principal quantum number n) due to the interaction with the electric field of the neighboring atoms. Once the $\bar{p}p$ system reaches a state of low angular momentum (S and P orbitals) annihilation occurs. In particular only six initial states are involved in the annihilation process, two from S-wave ($^1S_0$, $^3S_1$) and four from P-wave ($^1P_1$, $^3P_0$, $^3P_1$, $^3P_2$). In liquid hydrogen (LH), due to the high density, the Stark mixing is dominant and annihilation proceeds mainly from S orbital, with high principal quantum number n. On the contrary in gaseous hydrogen at NTP, where the radiative deexcitation processes are dominant, annihilation from P orbitals becomes important. Furthermore at very low pressure (few mbar) the six initial levels are expected to be statistically distributed with the following relative weights: 1/4 and 3/4 for the two S-wave states; 3/12 , 1/12 , 3/12 and 5/12 for the four P-wave states [1]. On the contrary deviations are expected at high density [6] due to the presence of the Stark effect.

In general a given final state is produced only from a subset of the possible initial levels. In particular considering two body final states, one must apply simple selection rules based on the conservation of the total angular momentum J, of the parity P and of the charge conjugation C. The possible $\bar{p}p$ initial states from which some two body reactions of interest can proceed are listed in Tab. 1. As one can see only few of the six possible levels are allowed for each channel. For example the K_SK_L final state can proceed only from the S-wave triplet state ($^3S_1$). On the contrary the K_SK_S , $\pi^o\pi^o$, $\pi^o\eta$ and $\eta\eta$ reactions occur only from two of the triplet P-wave states. Moreover channels like $\phi\pi^o$, $\omega\pi^o$ and $\phi\eta$ proceed from the same two J^{PC}states (the triplet S-wave ($^3S_1$) and the singlet P-wave ($^1P_1$)) , while the isospin is different being I=1 for the first two channels and I=0 for the last one.

It is quite evident that, changing the hydrogen target density, the measured branching ratios must change, due to the variation of the initial state distribution. In fact we can write the branching ratio for a given two body final state xy as:

$$BR(\bar{p}p \to xy, \rho) \;=\; \sum_{J^{PC}} \sum_{n} W(J^{PC}, n, \rho)\, B_{J^{PC}}(xy, n) \tag{1}$$

where the two sums, running over the principal quantum number n and the six J^{PC}states, are extended to all the initial states available. $W(J^{PC}, n, \rho)$ is the annihilation probability, $B_{J^{PC}}$ are the so called elementary branching ratio and ρ is the target density.

This expression can be simplified by assuming the independence of the $B_{J^{PC}}$ terms from the principal quantum number n, as follows [1]:

$$BR(\bar{p}p \to xy, \rho) \;=\; \sum_{J^{PC}} W(J^{PC}, \rho)\, B_{J^{PC}}(xy) \tag{2}$$

with

$$W(J^{PC}, \rho) \;=\; \sum_{n} W(J^{PC}, n, \rho) \tag{3}$$

where the $W(J^{PC}, \rho)$ terms fulfill to the normalization relation:

$$\sum_{J^{PC}} W(J^{PC}, \rho) \;=\; 1 \tag{4}$$

The annihilation probabilities $W(J^{PC}, \rho)$ depend on the target density, being determined by the protonium deexcitation processes. On the contrary the elementary branching ratios $B_{J^{PC}}(xy)$ are fully determined by annihilation dynamics and are density independent.

The final goal for measurements on two body final states is to evaluate experimentally and separately the annihilation probabilities and the elementary BR. It is quite evident that, due to the presence of too many terms, it is impossible to obtain this result unless a very big number of measurements in a wide range of conditions becomes available.

In order to overcome this problem some authors have used a more simplified approach to write the branching ratio [7]. In fact, by factorizing the percentage of P-wave in eq.2, the BR can be easily expressed as a sum of two terms, as follows :

$$BR(\bar{p}p \to xy, \rho) \;=\; [1 - F_P(\rho)]\, R_S(\rho) \;+\; F_P(\rho)\, R_P(\rho) \tag{5}$$

with

$$R_S(\rho) = \sum_S \frac{W(J^{PC},\rho)}{1-F_P(\rho)} B_{J^{PC}}(xy) \quad , \quad R_P(\rho) = \sum_P \frac{W(J^{PC},\rho)}{F_P(\rho)} B_{J^{PC}}(xy) \quad (6)$$

and

$$F_S(\rho) = \sum_S W(J^{PC},\rho) \quad , \quad F_P(\rho) = \sum_P W(J^{PC},\rho) \quad (7)$$

where the two sums run respectively over the two S-wave and the four P-wave J^{PC}initial states. The limit of this scheme is that the two quasi elementary BR R_S and R_P can be considered constant only if the ratios between the annihilation probabilities $W(J^{PC},\rho)$ and the S/P-wave percentages do not change with the density. This assumption is not straightforward, due to the different mechanisms involved in the protonium deexcitation processes. In fact, as we have already said, the protonium initial states are statistically distributed only at very low density, while big deviations are expected at high density [8, 9].

To overcome these problems a new approach has been developed by Batty [9]. The idea is to use some enhancement factors in order to take into account deviations from the initial state statistical distribution. In this way, a branching ratio can be expressed as:

$$\begin{aligned} BR(\bar{p}p \to xy,\rho) &= \\ & [1-F_P(\rho)]\,\{\frac{1}{4}\,E(^1S_0,\rho)\,B_{0-+}(xy) + \frac{3}{4}\,E(^3S_1,\rho)\,B_{1--}(xy)\} + \\ + \quad & F_P(\rho)\{\frac{3}{12}\,E(^1P_1,\rho)\,B_{1+-}(xy) + \frac{1}{12}\,E(^3P_0,\rho)\,B_{0++}(xy) + \\ + \quad & \frac{3}{12}\,E(^3P_1,\rho)\,B_{1++}(xy) + \frac{5}{12}\,E(^3P_2,\rho)\,B_{2++}(xy)\,\} \end{aligned} \quad (8)$$

where $E(J^{PC},\rho)$ are the enhancement factors that depend both on the J^{PC}state and on the target density. The fractions correspond to the statistical weights of the states and are separately normalized to unity for S and P-waves. The terms $B_{J^{PC}}(xy)$ are the elementary branching ratios of eq. 2. In this case the number of variables to be determined is lower than in eq. 2. In fact the values of enhancement factors can be independently determined by fitting the available data of X-rays experiments with suitable cascade models.

Considering these approaches, it is evident the advantage to perform measurements at different target densities in order to try to determine experimentally the terms present in eqs. 2 and 8. With this in mind, the last generation of experiments at LEAR has studied two mesons reactions from different initial states: S-wave dominance with liquid hydrogen (LH) ; S/P wave equilibrium with gaseous hydrogen NTP conditions (GH); P-wave dominance with gaseous hydrogen in Low Pressure (LP) and with a protonium deexcitation X-rays (2P) selection.

The present experimental situation is summarized in Tab. 2 for some reactions of interest. As one can see, the situation is quite complete in LH and GH conditions, while some lacks are present for the LP condition. Moreover discrepancies in the data are evident for some final states like $\pi^o\pi^o$, while other channels like K_SK_S are measured with poor precision.

3. Atomic Physics

As a first step one can obtain information on the S- and P-state annihilation in $\bar{p}p$ interaction at rest by studying the BR variations with the density. As an example let us consider the process $\bar{p}p \rightarrow K_SK_L$ that proceeds only from the $^3S_1$ initial state (see Tab. 1). Some conclusions can be drawn by studying the available experimental results as shown in Fig.1.

First of all, the observation of this reaction at low pressure (5 mbar) is a clear indication that there must be some S-wave annihilation in low density targets. This is a very important result in contrast with the previsions of some models [9]. Furthermore, following eq.2, the branching ratio for the K_SK_L final state can be written as:

$$BR(\bar{p}p \rightarrow K_SK_L, \rho) \;=\; W(^3S_1, \rho)\, B_{1^{--}}(K_SK_L) \;=\; W(^3S_1, \rho)\, D_{01} \qquad (9)$$

where for simplicity we have written the elementary branching ratio $B_{1^{--}}(K_SK_L)$ as D_{01}. It is quite evident that the ratio of this BR at different densities is directly related to the variation of the triplet S-wave annihilation probability. In this way one gets

$$W(^3S_1, LH) : W(^3S_1, GH) : W(^3S_1, LP) \;\simeq\; 7.8 : 3.6 : 1.0 \qquad (10)$$

As one can see this quantity varies of about a factor ten passing from liquid to low pressure conditions, then changing the density in a range of five orders of magnitude. Besides, it must be noted that by studying this reaction together with the channel $\bar{p}p \rightarrow E/\iota\ \pi^+\pi^-$, that proceeds only from the singlet S-wave state ($^1S_0$), it would be possible to determine, for the first time, the behavior of the two S-wave annihilation probability as a function of the density [29].

A more general approach to get information on the $\bar{p}p$ initial state distribution is to fit together all the existing experimental results. In fact, following eq.8 one can express some of the final states reported in Tab.2 as:

$$BR(\pi^o\pi^o,\rho) = \tfrac{1}{2}\ F_P(\rho)\{\tfrac{1}{12}\ E_{10}\ B_{10}\ +\ \tfrac{5}{12}\ E_{12}\ B_{12}\} \tag{11}$$

$$BR(\pi^+\pi^-,\rho) = [1 - F_P(\rho)]\ \tfrac{3}{4}\ E_{01}\ B_{01}\ +\ F_P(\rho)\{\tfrac{1}{12}\ E_{10}\ B_{10}\ +\ \tfrac{5}{12}\ E_{12}\ B_{12}\} \tag{12}$$

$$BR(\pi^+\pi^-,\rho)_{2P} = \tfrac{1}{12}\ B_{10}\ +\ \tfrac{5}{12}\ B_{12} \tag{13}$$

$$BR(K^+K^-,\rho) = [1 - F_P(\rho)]\ \tfrac{3}{4}\ E_{01}\ C_{01}\ +\ F_P(\rho)\{\tfrac{1}{12}\ E_{10}\ C_{10}\ +\ \tfrac{5}{12}\ E_{12}\ C_{12}\} \tag{14}$$

$$BR(K^+K^-,\rho)_{2P} = \tfrac{1}{12}\ C_{10}\ +\ \tfrac{5}{12}\ C_{12} \tag{15}$$

$$BR(K_SK_S,\rho) = \tfrac{1}{2}\ F_P(\rho)\{\tfrac{1}{12}\ E_{10}\ D_{10}\ +\ \tfrac{5}{12}\ E_{12}\ D_{12}\} \tag{16}$$

$$BR(K_SK_S,\rho)_{2P} = \tfrac{1}{2}\ \{\tfrac{1}{12}\ D_{10}\ +\ \tfrac{5}{12}\ D_{12}\} \tag{17}$$

$$BR(K_SK_L,\rho) = [1 - F_P(\rho)]\ \tfrac{3}{4}\ E_{01}\ D_{01} \tag{18}$$

where for sake of simplicity the enhancement factors $E(^SL_J,\rho)$ are written in the form E_{LJ} and the elementary BR $B_{J^{PC}}(xy)$ in the form B_{LJ}, C_{LJ} or D_{LJ}, depending on the particular channel. The notation $2P$ indicates those cases when the BR was measured in coincidence with the protonium deexcitation L X-rays, so that annihilation only occurs from 2P states. In these relations the terms F_P and E_{LJ} depend on the target density, while the elementary BR are density independent. Using these relations one can fit the experimental data leaving as free parameters the P-wave percentage $F_P(\rho)$ and all the elementary branching ratios. The enhancement factors are evaluated independently [9] by using the data from X-rays experiments.

The obtained results for the P-wave percentage are reported in Fig.2, where the predictions of two protonium cascade models [31, 32] are also shown. Some discrepancies are evident both in the low density region and in the liquid one. Moreover the analysis of the partial χ^2 shows the presence of some discrepancies in the data (mainly in the field of pionic BR), even if the normalized χ^2 obtained is not too high $\chi^2 \sim 2$. The annihilation probabilities obtained from the fit are shown in Tab. 3. The total S-wave fraction F_S decreases from about 90% at LH to 15% at LP, while the distribution of the two corresponding states is statistical at each density. On the contrary the distribution of the triplet P-wave states is statistical only at low density, being the $^3P_0$ state enhanced in liquid condition. From the fit it is also possible to obtain the elementary BR for each reaction. As an example, for the K_SK_L final state, one gets:

$$D_{01}\ =\ B_{1^{--}}\ (K_SK_L)\ =\ (\ 1.34 \pm 0.15\ )\ 10^{-3} \tag{19}$$

As a conclusion, the existing results on two body BR can be used, under suitable assumptions, to obtain information both on the $\bar{p}p$ initial state distributions and on the elementary branching ratios. Anyway it is necessary to complete (and in some cases verify) the measurements of branching ratios to check the consistency and the validity of the present analysis.

4. Annihilation Dynamics

Some tests on the annihilation dynamics can be performed by measuring ratios of two mesons BR and by studying the scaling with the density of the yield of some final states. In this section we consider dynamical selection rules and the quark dynamics in the annihilation. In this paper the OZI rule is not considered being specifically discussed in another talk [33].

4.1. Study of Branching-Ratios

Dynamical selection rules (DSR) are present when some channels are suppressed even if they are not forbidden by conservation laws. Up to now a lot of DSR have been discovered [1], among them we want to point our attention on the $\phi\pi^o$ one. As it is shown in Tab. 1, this channel, as the $\omega\pi^o$ one, can proceed only from the triplet S-wave ($^3S_1$) and singlet P-wave ($^1P_1$) states, and, following eq.2, the BR can be expressed as:

$$BR(\bar{p}p \rightarrow \phi\pi^o, \rho) \;=\; W(^3S_1, \rho)\, B_{1--}\;(\phi\pi^o) \;+\; W(^1P_1, \rho)\, B_{1+-}\;(\phi\pi^o) \qquad (20)$$

For this final state measurements have been performed at three different target densities and are shown in Fig.3a. The BR decreases with the density as the $K_S K_L$ final state, that is produced only from S-wave. In fact, as it is shown in Fig.3b, the ratio of these two BR is constant.

Moreover a measurement performed by Asterix [26] in coincidence with the protonium deexcitation X-rays, gives a result compatible with zero. This means that the $\phi\pi^o$ final state is almost completely produced from S-wave, with an unexplained strong suppression from P-wave.

The presence of this DSR has been recently confirmed [27]. In fact the Obelix experiment, by analyzing the decay angular distribution of the ϕ particle, has found the $\phi\pi^o$ final state compatible with a total production from S-wave.

Very recently a similar measurement has been performed in NTP conditions [23] on the $\omega\pi^o$ channel, that can proceed from the same two initial states. Previously only two results in LH conditions were available [13, 15].

The scaling of this BR as a function of the density is shown in Fig.3a. It is quite evident that the yield of the $\omega\pi^o$ and $\phi\pi^o$ reactions is almost equal and it scales as the

$K_S K_L$ final state. This fact suggests that, also for the $\omega\pi^o$ channel, the production from the ${}^1P_1$ state is suppressed. This effect has been confirmed, even if with a poor statistic, by the analysis of the ω decay angular distribution, that has been found to be compatible with a total production from S-wave.

This two facts suggest the presence of a DSR also for the $\omega\pi^o$ final state, due to its production suppression from the ${}^1P_1$ level.

Is this a general rule valid for all the $(0^{-+}, 1^{--})$ two body final states, or is it restricted only to these two channels? Considering Tab. 2 one can note that the BR of the $\phi\eta$ final state measured in coincidence with X-rays is non negligible. This means that its yield from the ${}^1P_1$ level it is not suppressed. Furthermore this channel proceed from states with $I = 0$. Then this DSR could be valid only for the $(0^{-+}, 1^{--})$ two body final states occurring from $I = 1$ initial states.

4.2. Ratios of Branching-ratios

In this section we will make simple considerations studying the ratios of BR $R_1 = \pi^o\eta/\pi^o\pi^o$ and $R_2 = \eta\eta/\pi^o\pi^o$. In these cases all the reactions proceed from the same initial states: the two P-wave triplet levels ${}^3P_0$ and ${}^3P_2$, that have the same parity and charge conjugation. There are many theoretical predictions on these ratios based on different models. For example the quark-line-rule [2] describes the annihilation process in terms of quark annihilation and rearrangement diagrams. The comparison between the experimental results and this model can give the relative weight in the annihilation of these graphs.

In Fig. 4 we report the ratios R_1 and R_2 as a function of the target density. The two ratios seem to be density independent. This surprising result can be better understood considering the expression of these ratios in terms of eq.2. In fact we can write:

$$R_1(\rho) = \frac{BR(\pi^o\eta)}{BR(\pi^o\pi^o)} = \frac{W({}^3P_0,\rho)\, B_{0^{++}}(\pi^o\eta) + W({}^3P_2,\rho)\, B_{2^{++}}(\pi^o\eta)}{W({}^3P_0,\rho)\, B_{0^{++}}(\pi^o\pi^o) + W({}^3P_2,\rho)\, B_{2^{++}}(\pi^o\pi^o)} \tag{21}$$

The independence of the ratios from the density can be due to one of the following effects:

- one of the two $W(J^{PC},\rho)$ terms is zero;
- for each annihilation channel xy, one of the two elementary branching ratios $B_{J^{PC}}(xy)$ is zero;
- for each density the two $W(J^{PC},\rho)$ terms are proportional or equal to each other;
- for each final state xy , $B_{0^{++}}(xy)$ is proportional or equal to $B_{2^{++}}(xy)$.

The second point implies the existence of a dynamical selection rule for each of the three channels, which would be a very unexpected effect. The third statement is compatible with the hypothesis of the statistical population of the S/P wave levels. But it is in contrast with the results obtained in section 3. Finally the fourth point is in agreement with the annihilation model of Klempt and collaborators [34], which predicts the elementary BR $B_{J^{PC}}(xy)$ depending only on the charge conjugation states (i.e. $B_{0^{++}}(xy) = B_{2^{++}}(xy)$).

Moreover these two ratios allow an estimate of the relative weights of annihilation/rearrangement graphs, by comparing the experimental results with the theory previsions. Due to their independence on the density, one can average all the existing data obtaining:

$$R_1 \;=\; 0.28 \;\pm\; 0.05 \quad , \quad R_2 \;=\; 0.22 \;\pm\; 0.03 \tag{22}$$

We can compare these values with the previsions of some models. When the rearrangement mechanisms are dominant models foresee $R_1 \sim 0.03$ [35], on the contrary when the annihilation/creation graphs hold, one gets $R_1 \sim 0.30 \div 0.48$ [36] and $R_2 \sim 0.23$ [35] .

Comparing these previsions with the experimental results of eq. 22 a clear dominance of annihilation graphs is apparent, even if a significant contribution of the rearrangement ones cannot be excluded. The test is, therefore, inconclusive and more accurate data are needed.

5. Annihilation in flight at very low momentum

A new important tool of investigation in the field of annihilation dynamics is the study of the $\bar{p}p$ annihilation in flight at very low momentum. In this section we will discuss the importance to measure the cross sections of two body reactions at very low momentum, when annihilation proceeds almost completely from S-wave. In fact this method represents a powerful alternative to measure separately the atomic and the nuclear part in the experimental BR (see eq. 2).

Up to now only measurement of the $\bar{p}p$ total annihilation cross section have been performed in flight in a momentum range below 70 MeV/c [38, 39]. In these conditions annihilations proceed almost completely from a pure S-wave state, as it has been recently shown [39]. On the contrary measurements of two body reaction cross sections have been performed only at high momentum, in order to study the resonance formation mechanism [37].

The idea is to follow the approach of eq. 2 (used for annihilation at rest) to write also the two body annihilation cross sections in flight at low momentum.

Let us consider, for sake of simplicity, the $K_S K_L$ final state. In this case we can write for an annihilation in flight:

$$\beta\ \sigma(\ K_S K_L, q)\ =\ \frac{3}{4}\ \beta\ \sigma^T(q)\ B_{1^{--}}(K_S K_L) \tag{23}$$

where $B_{1^{--}}(K_S K_L)$ is the elementary BR of eq. 9, β and q are respectively the velocity and the momentum of the antiproton, $\sigma^T(q)$ is the total annihilation cross section from the triplet S-wave state and $\frac{3}{4}$ is its statistical weight. The term $\sigma^T(q)$ is related to the total $\bar{p}p$ cross section by the equation:

$$\sigma^{TOT}(q)\ =\ \frac{1}{4}\ \sigma^S(q)\ +\ \frac{3}{4}\ \sigma^T(q) \tag{24}$$

The relation 23 must be compared with the corresponding equation 9 for annihilations at rest, that we report here:

$$BR(\bar{p}p \to K_S K_L, \rho)\ =\ W(^3S_1, \rho)\ B_{1^{--}}(K_S K_L) \tag{25}$$

As one can see, the elementary BR has been assumed to be the same. This is a reasonable assumption. In fact, given that in these conditions annihilation occurs mainly from S-wave, the protonium wave function is localized in a very small region. Therefore $B_{1^{--}}$ should not depend on the wave function shape and then on the kind of annihilation process.

The strategy of this approach is to measure separately the quantities $BR(\bar{p}p \to K_S K_L, \rho)$, $\sigma(\ K_S K_L, q)$ and $\sigma^T(q)$. Then from eq. 25 it is possible to extract the elementary BR and the triplet S-wave annihilation probability.

Many experimental results are available for the $K_S K_L$ BR at rest (see Tab. 1). On the contrary, only one measurement of the $K_S K_L$ cross section has been performed up to now [39], giving the very preliminary result:

$$\beta\ \sigma(\ K_S K_L, q)\ =\ (5.0\ \pm\ 1.0)\,10^{-2}\ mbarn \tag{26}$$

where $q\ =\ 50.5 \pm 6.5\ MeV/c$. At the moment, measurements on the total cross section $\sigma^T(q)$ are not available. However it is possible to evaluate this quantity from the antiprotonic atom triplet width $\Gamma(^3S_1)$. In fact following the same formalism used in ref.[40], the imaginary part of the triplet scattering length $Im(a^T)$ can be obtained from the relation:

$$Im(\ a^T\ )\ \approx\ \Gamma\ (^3S_1)\ \frac{hc}{m_p\ \alpha^3} \tag{27}$$

which is valid to the first order in a^T/a_B with $a_B = 57.6\ fm$ [6]. Then the triplet S-wave cross section can be written as:

$$\beta\sigma^T(q) = \frac{8\pi C^2(q)}{m_p} \cdot \frac{Im(a^T)}{1 + q\ Im(a^T)} \tag{28}$$

here $C^2(q)$ is the Coulomb Gamow factor, q is the antiproton momentum and m_p is the proton mass.

Actually only one measurement and some theoretical evaluations are available for the antiprotonic triplet width $\Gamma(^3S_1)$. In the first part of Tab. 4 the situation is summarized. The values of the total triplet S-wave annihilation cross section obtained from eqs.27,28 are also reported. As one can see, the results are in some cases slightly different. In the second part of Tab. 4 the K_SK_L elementary BR and the triplet S-wave annihilation probabilities obtained from eq.25 are reported. The first row corresponds to the experimental data, the last one to the results obtained from the analysis described in Section 3. Some discrepancies between the results from the two methods are evident, even if the values are in some cases quite reasonable.

Anyway to check the validity of this method more accurate and reliable measurements are needed mostly on the antiprotonic triplet width and on the K_SK_L cross section at low momentum.

6. Conclusions

In this paper the present situation on $\bar{p}p$ annihilation in two body final states has been analysed. Indications for a new important dynamical selection rule have been put to evidence for the $\omega\pi^o$ channel, whose production from the $^1P_1$ level seems to be suppressed. Moreover from the analysis of the ratios of BR as a function of the target density, important information on annihilation dynamics has been obtained.

The results on two body BR have been used to evaluate the initial state distribution of the $\bar{p}p$ system. The observation of the process $\bar{p}p \to K_SK_L$ in low pressure targets has shown that there must be some S-wave annihilation in low density targets. Furthermore all the BR have been fitted together giving for the first time an evaluation of the initial states annihilation probabilities.

Finally a promising new method, that allows to disentangle for the first time the atomic from the nuclear part of the BR, has been discussed. This approach, based on the study of annihilations in flight at very low momentum, has been used to obtain promising preliminary results on the K_SK_L channel, and can be extended to many two body final states. Nevertheless more accurate and precise measurements to test its validity are needed.

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Reactions	$^1S_0$, 0^{-+}	$^3S_1$, 1^{--}	$^1P_1$, 1^{+-}	$^3P_0$, 0^{++}	$^3P_1$, 1^{++}	$^3P_2$, 2^{++}
$\pi^+\pi^-$	N	$I^G = 1^+$	N	$I^G = 0^+$	N	$I^G = 0^+$
$\pi^o\pi^o$	N	N	N	$I^G = 0^+$	N	$I^G = 0^+$
$\pi^o\eta$	N	N	N	$I^G = 1^-$	N	$I^G = 1^-$
$\eta\eta$	N	N	N	$I^G = 0^+$	N	$I^G = 0^+$
K^+K^-	N	$I^G = 0^-, 1^+$	N	$I^G = 0^-, 1^+$	N	$I^G = 0^-, 1^+$
K_SK_L	N	$I^G = 0^-, 1^+$	N	N	N	N
K_SK_S	N	N	N	$I^G = 0^-, 1^+$	N	$I^G = 0^-, 1^+$
$\phi\pi^o$	N	$I^G = 1^+$	$I^G = 1^+$	N	N	N
$\omega\pi^o$	N	$I^G = 1^+$	$I^G = 1^+$	N	N	N
$\phi\eta$	N	$I^G = 0^-$	$I^G = 0^-$	N	N	N

Table 1: Selection rules for two body final states. N means forbidden by P or C conservation rules.

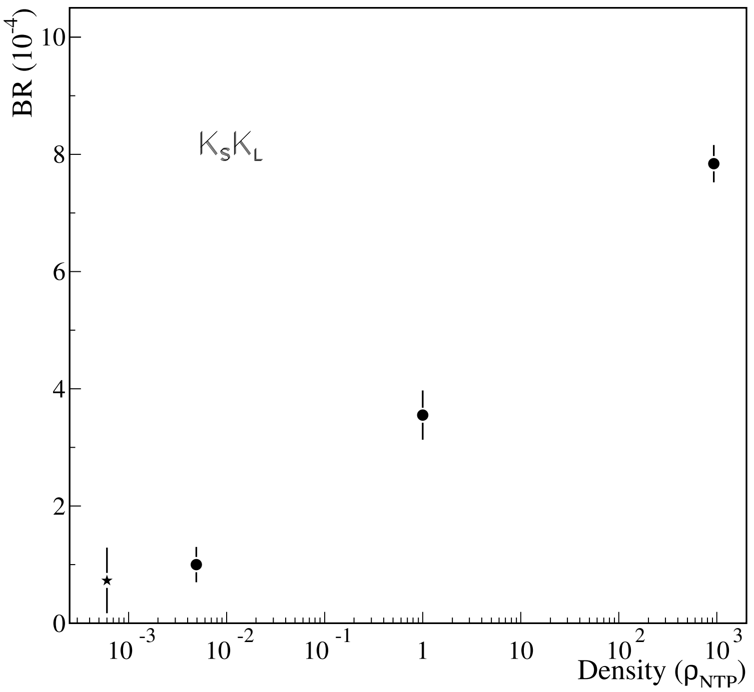

Figure 1: The BR of the K_SK_L final state as a function of the target density. The star indicates a measurement in coincidence with X-ray, the position in the horizontal scale is arbitrary. The target density is expressed as a function of the hydrogen density in NTP conditions ρ_{NTP}.

$\bar{p}p \to xy$	Ann. Freq. LH	Ref.	Ann. Freq. GH	Ref.	Ann. Freq. LP	Ref.
$\pi^+\pi^-$	31.4 ± 1.1	WA	43.0 ± 1.2	WA	42.6 ± 1.1	[30]
			48.1 ± 4.9	2P		
$\pi^o\pi^o$	4.8 ± 1.0	[10]	12.7 ± 1.3	[22]		
	6.0 ± 1.0	[11]				
	2.5 ± 0.3	[12] [13]				
	2.06 ± 0.14	[14]				
	6.93 ± 0.47	[15]				
$\pi^o\eta$	2.9 ± 1.5	[12]	3.4 ± 0.7	[23]		
	1.33 ± 0.25	[16]				
	2.12 ± 0.12	[15]				
	2.01 ± 0.29	WA				
$\eta\eta$	1.6 ± 0.8	[17]	2.7 ± 0.7	[23]		
	0.81 ± 0.31	[16]				
	1.64 ± 0.10	[15]				
	1.56 ± 0.24	WA				
K^+K^-	10.0 ± 0.4	WA	6.92 ± 0.41	[24]	4.6 ± 1.3	[30]
			2.87 ± 0.51	2P		
K_SK_L	6.1 ± 0.9	[18]	3.6 ± 0.6	[25]	1.0 ± 0.3	[21]
	8.0 ± 0.5	[19]	3.5 ± 0.5	[21]		
	9.0 ± 0.6	[20]	0.73 ± 0.56	2P		
	7.8 ± 0.7	[21]				
	8.0 ± 0.5	WA	3.5 ± 0.4	WA		
K_SK_S	0.04 ± 0.03	[18]	0.3 ± 0.1	[25]		
			0.37 ± 0.14	2P		
$\phi\pi^o$	5.5 ± 0.7	[20]	1.9 ± 0.5	[26]	0.85 ± 0.25	[28]
			2.33 ± 0.24	[27]		
			2.25 ± 0.22	WA		
$\omega\pi^o$	52.0 ± 5.0	[13]	21.9 ± 3.9	[23]		
	57.3 ± 4.7	[15]				
	54.8 ± 3.4	WA				
$\phi\eta$	0.66 ± 0.19	[20]	0.37 ± 0.09	[26]		
			0.41 ± 0.16	2P		

Table 2: Experimental situation for some two body final states. The branching ratios are expressed in units of 10^{-4} The symbol WA indicates an average of values. Moreover 2P indicates those cases when the BR was measured in coincidence with the L X-rays, so that annihilation only occurs from 2P-states.

Density	$W(^1S_0)$ (%)	$W(^3S_1)$ (%)	F_S (%)	$W(^1P_1)$ (%)	$W(^3P_0)$ (%)	$W(^3P_1)$ (%)	$W(^3P_2)$ (%)	F_P (%)
LH	22.7	65.4	88.1	2.5	2.5	2.1	4.8	11.9
GH	11.4	33.1	44.5	13.5	6.0	12.9	23.1	55.5
LP	3.6	10.2	13.8	21.5	7.3	21.4	36.0	86.2

Table 3: Results on annihilation probabilities as a function of the target density

Ref.	Γ ($^3S_1$) (keV)	3/4 $\beta\sigma^T$ (mbarn)	B_1--(K_SK_L) ($Units$ 10^{-3})	$W(^3S_1, LH)$ (%)	$W(^3S_1, GH)$ (%)	$W(^3S_1, LP)$ (%)
Expr. [41]	0.77 ± 0.15	23.3 ± 4.1	2.1 ± 0.6	36.6 ± 9.8	16.6 ± 4.8	4.7 ± 1.8
[42]	0.88	26.3	1.9	41.3	18.7	5.3
[43]	0.92	27.4	1.83	42.8	19.4	5.5
[44]	1.4	39.2	1.27	61.7	28.0	7.9
[45]		31.3	1.60	49.0	22.2	6.3
T. A.			1.34 ± 0.15	65.4 ± 1.8	33.1 ± 3.1	10.2 ± 3.6

Table 4: Antiprotonic triplet widths and triplet S-wave annihilation cross sections. In the second part are also reported the K_SK_L elementary BR and the obtained annihilation probabilities. T. A. refers to the results obtained in section 3 of this article.

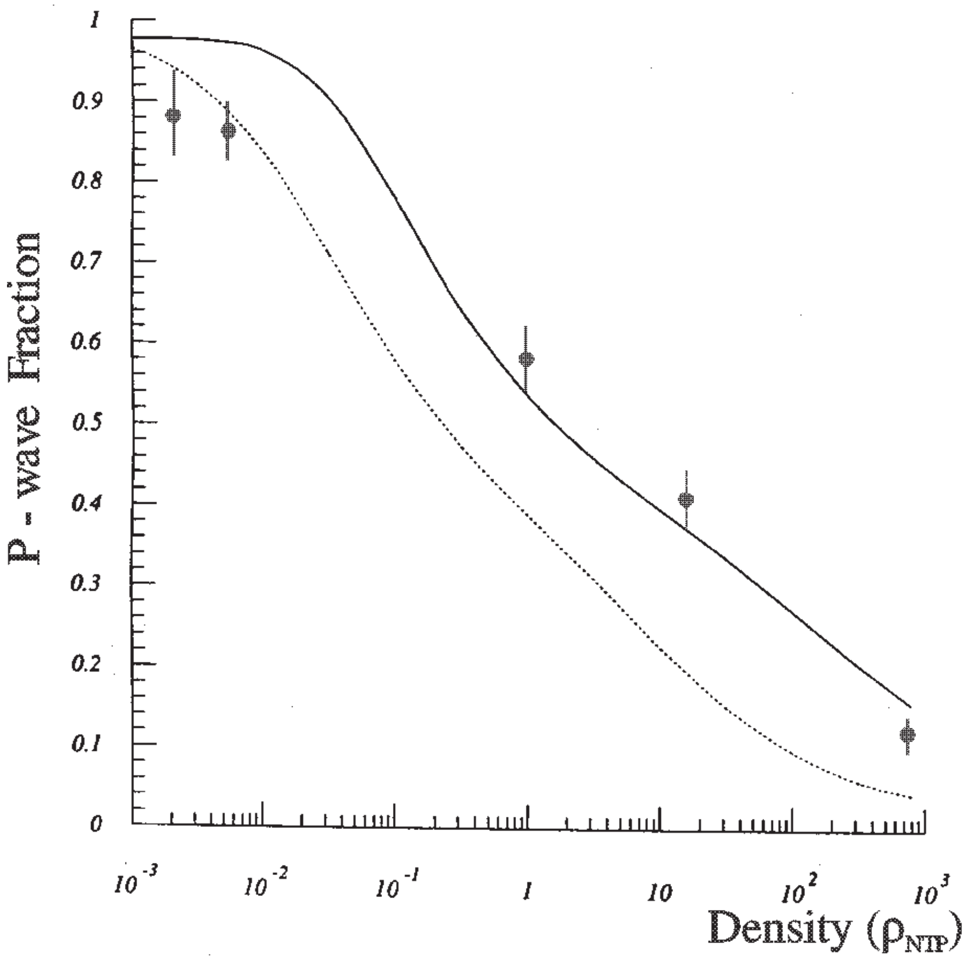

Figure 2: Fraction of P-wave annihilation as a function of the target density. The dashed and the continuous lines correspond respectively to the Mainz model [32] and the Borie-Leon model [31].

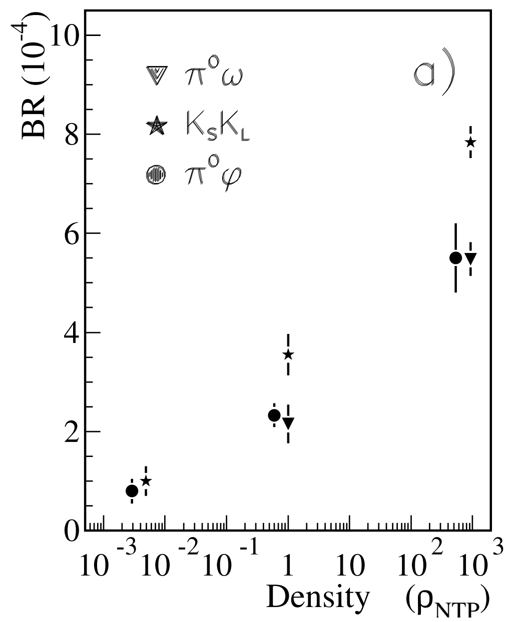

Figure 3: (a) The BR of the $\omega\pi^o$, $\phi\pi^o$ and K_SK_L final states as a function of the target density. The vertical scale must be multiplied by a factor 10 for the $\omega\pi^o$ channel. (b) The ratios of the two BR $\omega\pi^o$ and $\phi\pi^o$ respect to the K_SK_L one.

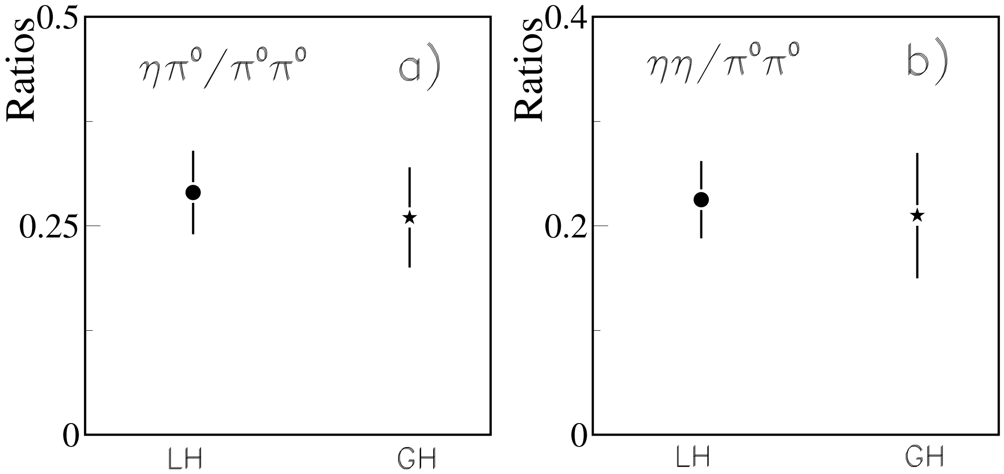

Figure 4: (a) Ratios of the BR $\pi^o\eta$ to $\pi^o\pi^o$ as a function of the target density. (b) Ratios of the BR $\eta\eta$ to $\pi^o\pi^o$ as a function of the target density. The results corresponding to the LH condition are taken from ref. [15].