Two-body branching ratios; an experimental review

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Recent measurements of two-body Branching Ratios for $\bar{\rm p}$p and $\bar{\rm p}$d annihilations at rest are reviewed, with an emphasis on the consistency of the data and possible discrepancies. Their use for determining the probability for P-state annihilation as a function of target density is discussed and the results of a recent analysis of $\bar{\rm p}$p data are presented. These results also show clear evidence for the presence of dynamical selection rules.

1. INTRODUCTION

The Branching Ratio $BR(ch, \rho)$, or annihilation frequency as it is sometimes called, is the probability that a particular channel ch will be produced in a $\bar{\rm p}$p (protonium) or $\bar{\rm p}$d annihilation. It is usually the quantity measured experimentally and is a function of the target density ρ. The Partial Branching Ratio $B(ch, {}^{2S+1}{\rm L}_J)$ is the probability that the channel ch is produced by an annihilation from the initial state ${}^{2S+1}{\rm L}_J$ of the $\bar{\rm p}$p or $\bar{\rm p}$d system. The partial branching ratio is independent of the atomic physics effects occuring during the cascade of the $\bar{\rm p}$p or $\bar{\rm p}$d atom and so does not depend on the target density. It is this quantity which normally should be compared with predictions from theoretical models of the annihilation process.

Here we only discuss two-body branching ratios. These are of interest for studies of the annihilation mechanism. In section 5.2 the topic of dynamical selection rules (DSR) is discussed, where for some channels two-body annihilation from particular initial states (${}^{2S+1}{\rm L}_J$) is suppressed, even though not forbidden by conservation laws. The use of two-body branching ratios to study violation of the OZI rule and the possible presence of strangeness in the proton has been discussed elsewhere at this meeting.

The use of branching ratios for two-body final states to understand the composition of the protonium initial state from which annihilation occurs and in particular the fraction of S- and P-state annihilation as a function of target density has recently received considerable attention. This information is particularly relevant to partial wave analyses of more complicated final states in terms of meson resonances, especially where data is available at more than one target density.

Here we discuss two-body branching ratios for channels involving *narrow* mesons (π, K, η, η', ω and ϕ). Branching ratios for broader states usually have considerable uncertainties due to the need for subtraction of overlapping background and other experimental difficulties.

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In the following section we discuss the $\bar{p}p$ atom cascade, the role of the fine structure levels and the need for *enhancement* factors (section 2.1). Determination of the fraction of P-state annihilation is discussed in section 3. Recently published branching ratio measurements are reviewed in section 4 and the $\bar{p}p \rightarrow \pi^0\pi^0$ branching ratio is discussed in detail in section 4.1. A recent analysis of two-body branching ratios for $\bar{p}p$ atoms is presented in section 5 with emphasis on the fraction of P-state annihilation (section 5.1) and partial branching ratios and DSR (section 5.2). Section 6 comments on $\bar{p}d$ branching ratios and the determination of the P-state fraction in $\bar{p}d$ annihilation.

2. THE $\bar{p}p$ ATOM CASCADE

Formation of the $\bar{p}p$ atom and its atomic cascade has been discussed elsewhere (See ref. [1] for a review). Briefly, the capture of the $\bar{p}$ typically occurs at a principal quantum number $n \approx 30$. De-excitation then takes place by a number of processes including radiative transitions with the emission of X-rays and the external Auger effect involving the ionisation of a neighbouring H_2 molecule. Finally the $\bar{p}$ reaches an atomic state with angular momentum $\ell = 0$ or 1 when annihilation occurs. Annihilation from states with $\ell \geq 2$ can be ignored due to the negligible overlap of the $\bar{p}$ and p atomic wavefunctions during the cascade process.

In addition, except at very low target densities, the Stark effect gives mixing of the angular momentum states ℓ at high n allowing the antiprotons to transfer to S- and P-states where they can annihilate before reaching the low-n states. The Stark mixing is proportional to the target density and for liquid targets the rate is very high. In this case it is important to consider the effects of the fine structure of the atomic states. For $\bar{p}p$ atoms, the states with $\ell < 2$ are $^1S_0$, $^3S_1$, $^1P_1$, $^3P_0$, $^3P_1$ and $^3P_2$ with the corresponding $J^{PC} = 0^{-+}, 1^{--}, 1^{+-}, 0^{++}, 1^{++}$ and 2^{++}. No direct measurements of the strong interaction widths of all these states are at present available. In table 1 the predictions of Carbonell et al.[2] using potentials for the $\bar{p}p$ interaction due to Dover and Richard (DR1 and DR2) and Kohno and Weise (KW) are given. A particular feature of these predictions is the very large width of the $^3P_0$ state. This large width for the $^3P_0$ state relative to the other P-states is confirmed by the measurements of the PS207 collaboration reported at this conference by Gotta [3].

Table 1
Predicted widths for $\bar{p}p$ atoms

Model	$^1S_0$ (keV)	$^3S_1$ (keV)	$^1P_1$ (meV)	$^3P_0$ (meV)	$^3P_1$ (meV)	$^3P_2$ (meV)
DR1	1.02	0.90	26	114	20	30
DR2	1.04	0.92	28	80	18	32
KW	1.26	0.98	26	96	22	36

At high n, in the case where Stark mixing is important, the fine structure levels are continually and rapidly repopulated according to their statistical weight. A fine structure level with a large annihilation width will therefore contribute more to annihilation than would be expected from its statistical weight only. This effect is particularly important for the $^3P_0$ level where the fraction of $\bar{p}p$ annihilations may be considerably enhanced over that expected from a purely statistical population of the level. Similar, but smaller, effects will also occur for the other fine structure P-states.

These deviations of the population of the fine structure states have been described [4] in terms of *enhancement factors* $E(^{2S+1}L_J, \rho)$ which are a function of the initial state and target density. Values of $E < 1$ correspond to a fraction of annihilations less than that expected on the basis of a purely statistical population of the level.

2.1. Enhancement factors

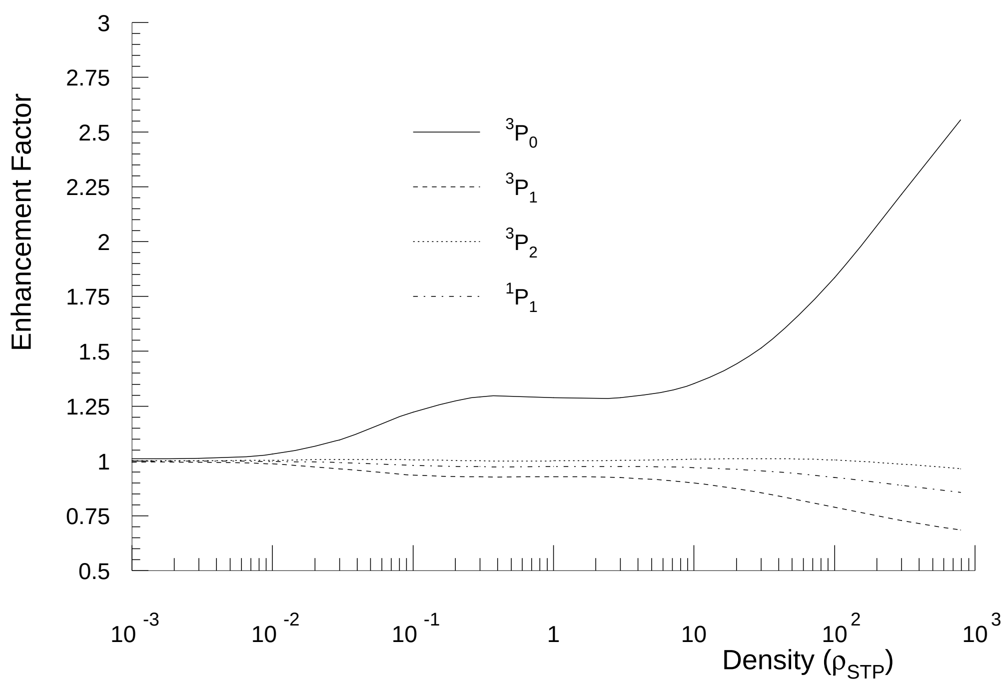

Figure 1. P-state enhancement factors from a cascade calculation [4] using annihilation widths from the DR1 potential in table 1.

Values of enhancement factors have been calculated [4] using a model for the atomic cascade which fits the available $\bar{p}p$ X-ray data covering the range of target densities from 0.016 to 10.0 ρ_{STP}, where ρ_{STP} is the density of H_2 gas at STP. Values of $E(^{2S+1}L_J, \rho)$ for P-states using the DR1 annihilation widths of table 1 are shown in fig.1. Enhancement factors for the S-states are generally close to 1. Values of E for the other annihilation models of table 1 are similar to those for the DR1 potential.[2]

[2]Tables of enhancement factors at a larger number of pressures than those given in ref.[4] are available from the author.

The branching ratio $\mathrm{BR}(ch,\rho)$ can then be written [4] in terms of the partial branching ratios $\mathrm{B}(ch,{}^{2S+1}\mathrm{L}_J)$ in the form

$$\begin{aligned}BR(ch,\rho) &= (1-\mathrm{f_P}(\rho))[\frac{1}{4}E({}^1\mathrm{S}_0,\rho)B(ch,{}^1\mathrm{S}_0)+\frac{3}{4}E({}^3\mathrm{S}_1,\rho)B(ch,{}^3\mathrm{S}_1)]+\\ &\qquad \mathrm{f_P}(\rho)\,[\frac{3}{12}E({}^1\mathrm{P}_1,\rho)B(ch,{}^1\mathrm{P}_1)+\frac{1}{12}E({}^3\mathrm{P}_0,\rho)B(ch,{}^3\mathrm{P}_0)+\\ &\qquad \frac{3}{12}E({}^3\mathrm{P}_1,\rho)B(ch,{}^3\mathrm{P}_1)+\frac{5}{12}E({}^3\mathrm{P}_2,\rho)B(ch,{}^3\mathrm{P}_2)]\end{aligned} \quad (1)$$

where $\mathrm{f_P}(\rho)$ is the fraction of P-state annihilation and the factors $\frac{1}{4},\frac{5}{12}$ etc. are the statistical weights of the states.

As will be shown in section 3 a good fit to two-body branching ratios requires the use of enhancement factors. With only a limited range of branching ratio measurements available it is not possible to determine the enhancement factors from a fit to the data and values calculated as discussed earlier have to be used. However we note that a study [5] of the reaction $\bar{\mathrm{p}}\mathrm{p}\rightarrow\eta\pi^0\pi^0\pi^0$ at rest, both in liquid and in gas at 12 ρ_{STP}, finds

$$r=\frac{E({}^3\mathrm{P}_0,liq)/E({}^3\mathrm{P}_0,12\ \rho_{\mathrm{STP}})}{E({}^3\mathrm{P}_2,liq)/E({}^3\mathrm{P}_2,12\ \rho_{\mathrm{STP}})}=2.46\pm0.15 \quad (2)$$

to be compared with the value $r\approx\ 1.7$ predicted by the potential models of table 1. In a simultaneous analysis [6] made for the reaction $\bar{\mathrm{p}}\mathrm{p}\rightarrow\eta\pi^0\pi^0$ of data taken in gas at 12 ρ_{STP} and in liquid hydrogen, the relative rates (gas/liquid) for annihilation from specific states (${}^1\mathrm{S}_0$,${}^3\mathrm{P}_1$, etc.) were constrained by predictions which include the enhancement factors discussed above.

3. DETERMINATION OF FRACTION OF P-STATE ANNIHILATION

Two-body final states are only allowed from certain initial states of the $\bar{\mathrm{p}}\mathrm{p}$ system as shown in table 2. For most channels this gives a considerable reduction in the number of free parameters $\mathrm{f_P}(\rho)$and $B(ch,{}^{2S+1}\mathrm{L}_J)$ in equ.(1) when fitting the branching ratio data $BR(ch,\rho)$. In some cases the branching ratio was measured in coincidence with L X-rays so that annihilation only occurs from 2P states. From (1) the expression for the branching ratio then becomes

$$BR(ch,\rho)_X = \frac{3}{12}B(ch,{}^1\mathrm{P}_1)+\frac{1}{12}B(ch,{}^3\mathrm{P}_0)+\frac{3}{12}B(ch,{}^3\mathrm{P}_1)+\frac{5}{12}B(ch,{}^3\mathrm{P}_2) \quad (3)$$

A fit [4] to the branching ratios available in 1996, for the channels $\pi^+\pi^-$, $\pi^0\pi^0$, $\mathrm{K_S^0K_S^0}$, $\mathrm{K_S^0K_L^0}$ and $\mathrm{K^+K^-}$ for a range of target densities from 0.002 ρ_{STP} to liquid $\mathrm{H_2}$, gave a P-state fraction in liquid of $\mathrm{f_P}(liq)=0.13\pm0.04$ with a χ^2 per degree of freedom χ^2/N = 7.1/5 using enhancement factors calculated with the DR1 potential (table 1). The partial branching ratios were constrained so that $B(ch,{}^{2S+1}\mathrm{L}_J)\ \geq\ 0$; values of $\mathrm{f_P}(\rho)$ at other densities are given in ref.[4]. If the enhancement effects were not taken into account, i.e. E = 1, then a significantly worse fit was obtained with χ^2/N = 14.5/6 and $\mathrm{f_P}(liq)=0.29\pm0.02$. An important component of the input data was the branching ratio

Table 2
Two body reactions

Final state	J^{PC} J^{PC}	Allowed initial states					
$\pi^0\pi^0$	0^{-+} 0^{-+}				$^3P_0$		$^3P_2$
$\pi^+\pi^-$	0^- 0^-		$^3S_1$		$^3P_0$		$^3P_2$
$K^0_SK^0_L$	0^- 0^-		$^3S_1$				
$K^0_SK^0_S$	0^- 0^-				$^3P_0$		$^3P_2$
K^+K^-	0^- 0^-		$^3S_1$		$^3P_0$		$^3P_2$
$^\star\eta(1440)$ prod.	0^{-+}	$^1S_0$					
$\phi\pi$	1^{--} 0^{-+}		$^3S_1$	$^1P_1$			
$\omega\pi$	1^{--} 0^{-+}		$^3S_1$	$^1P_1$			
$\phi\eta$	1^{--} 0^{-+}		$^3S_1$	$^1P_1$			
$\pi\eta$	0^{-+} 0^{-+}				$^3P_0$		$^3P_2$
$\eta\eta$	0^{-+} 0^{-+}				$^3P_0$		$^3P_2$
$\omega\omega$	1^{--} 1^{--}		$^3S_1$		$^3P_0$	$^3P_1$	$^3P_2$
$\omega\phi$	1^{--} 1^{--}		$^3S_1$		$^3P_0$	$^3P_1$	$^3P_2$

* $\bar{p}p \longrightarrow \eta(1440)\pi^+\pi^-$; $\eta(1440) \longrightarrow K^\pm K^0_L\pi^\mp$

$BR(\pi^0\pi^0, liq)$ for the reaction $\bar{p}p \to \pi^0\pi^0$ in liquid H_2, which had been measured [7,8] by the Crystal Barrel (CBAR) collaboration. This branching ratio was significantly larger than previously measured values.

4. RECENTLY PUBLISHED BRANCHING RATIO MEASUREMENTS

A number of two-body branching ratios measurements have been published since the analysis of ref.[4]. These include measurements by the Obelix collaboration [9] for the reaction $\bar{p}p \to K^0_SK^0_L$; $K^0_S \to \pi^+\pi^-$at three densities, $0.005\rho_{STP}$, ρ_{STP} and liquid. The latter value $BR(K^0_SK^0_L, liq) = (7.8 \pm 0.7 \pm 0.3)10^{-4}$ is in good agreement with that measured [10] by the Crystal Barrel collaboration, $BR(K^0_SK^0_L, liq) = (9.0 \pm 0.6)10^{-4}$, for the same reaction but with $K^0_S \to \pi^0\pi^0$. This good agreement is an important check on the consistency of measurements from the two experiments, and particularly on the detection efficiency for all neutral events in the Crystal Barrel detector.

The CPLEAR collaboration have measured [11] the ratio $BR(K^0_SK^0_S, \rho)/BR(K^0_SK^0_L, \rho)$ at densities of 15 ρ_{STP} and 27 ρ_{STP}. This latter measurement enables the P-state fraction $f_P(27\rho_{STP})$ to be determined for the first time.

Although not a two-body branching ratio, the production of $\eta(1440)$ at three target densities in the reaction $\bar{p}p \to \eta(1440)\ \pi^+\pi^-$; $\eta(1440) \to K^\pm K^0_L\pi^\mp$ has been determined [12] by the Obelix collaboration. This is a particularly useful measurement since production only occurs from the $^1S_0$ state of the $\bar{p}p$ system which does not contribute to the other channels listed in table 2.

At the HADRON97 conference, the Obelix collaboration presented a new measurement [13] of the branching ratio for $\bar{p}p \to \pi^0\pi^0$ in liquid hydrogen, $BR(\pi^0\pi^0, liq) = (2.8 \pm 0.4)10^{-4}$ in marked disagreement with the Crystal Barrel [7,8] value of $BR(\pi^0\pi^0, liq) = (6.93 \pm$

0.43)10^{-4} mentioned in section 3. The Obelix value gives significantly reduced P-state annihilation in liquid H_2 and there has been much activity over the past year to try to understand the discrepancy between these two measurements.

This is particularly important since the value of $BR(\pi^0\pi^0, liq)$ was used by the Crystal Barrel collaboration to normalise their other branching ratio measurements [8] for all neutral final states $\pi^0\eta$, $\pi^0\omega$, $\pi^0\eta'$, $\eta\eta$, $\eta\omega$, $\eta\eta'$, $\omega\omega$ and $\omega\eta'$. The resulting $BR(\omega\omega, liq) = (3.32 \pm 0.34)\%$ has also been used to normalise most Crystal Barrel analyses of 3 pseudoscalar data e.g. $\bar{p}p \to 3\pi^0$, $2\pi^0\eta$ etc..

Recently the $\bar{p}p \to \omega_1\omega_2$ branching ratio has been measured [14] by the Crystal Barrel collaboration with $\omega_1 \to \pi^+\pi^-\pi^0$, $\omega_2 \to \pi^0\gamma$. They obtain $BR(\omega\omega, liq) = (3.15 \pm 0.25)\%$ in agreement with their earlier result (see above), giving confidence in their measured $BR(\pi^0\pi^0, liq)$ used for the normalisation of all neutral final states and in their branching ratios for the 3 pseudoscalar data.

4.1. Measurements of the branching ratio for $\bar{p}p \to \pi^0\pi^0$.

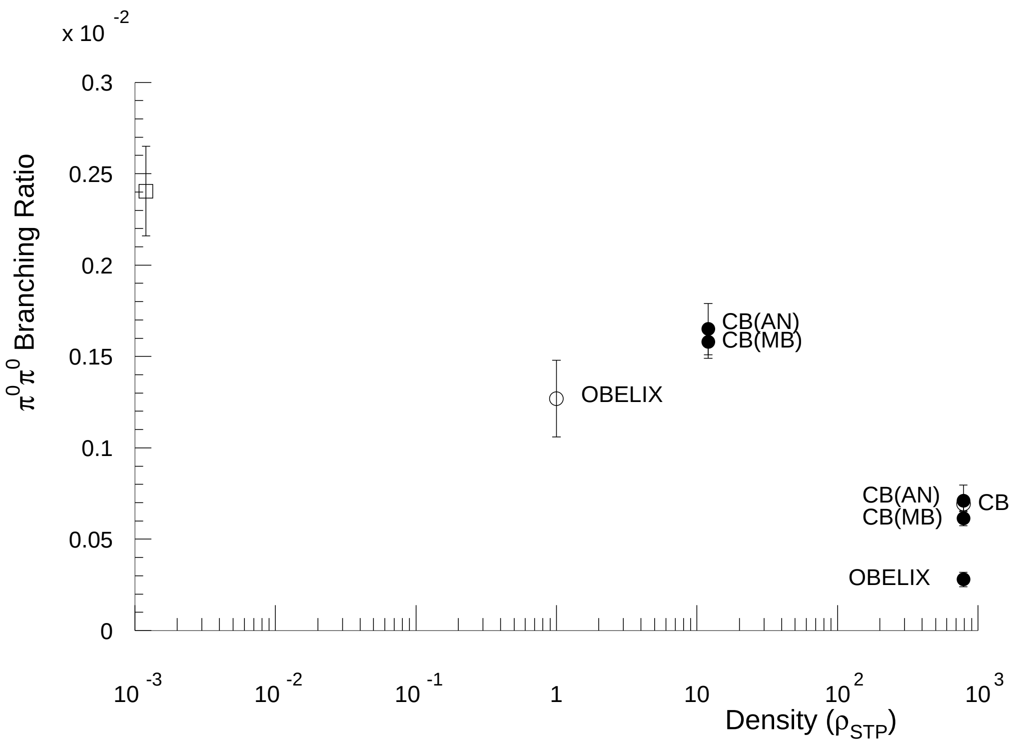

Figure 2. Values of the $\pi^0\pi^0$ branching ratio as a function of target density ρ. The points marked CB(AN) and CB(MB) are preliminary values from the Crystal Barrel "all neutral" and "minimum bias" analyses discussed in section 4.1.

The original Crystal Barrel measurement [8] of the $BR(\pi^0\pi^0, liq) = (6.93 \pm 0.22 \pm 0.37)10^{-4}$ was obtained from the analysis of 3.6 10^6 "minimum bias" events. A 4C kinematic fit to $\bar{p}p \to 4\gamma$ and the selection of any pairs of two photons which have the expected momentum of 928.5 MeV/c gave a very clean spectrum with 1112 ± 34 events. The overall detection efficiency as calculated by Monte Carlo simulation was $\epsilon = 0.49 \pm 0.01$.

The more recent Obelix measurement [13] used 6.4 10^6 events obtained with an "all neutral" trigger. Good agreement was obtained between the results obtained with 1C fits to $\bar{\mathrm{p}}\mathrm{p}\to\pi^0\gamma\gamma$ and 2C fits to $\bar{\mathrm{p}}\mathrm{p}\to\pi^0\pi^0$. However the calculated overall detection efficiencies were only $\epsilon = 0.112 \pm 0.001$ and 0.062 ± 0.001 respectively. The final $BR(\pi^0\pi^0, liq) = (2.8 \pm 0.1 \pm 0.4)10^{-4}$.

In an attempt to resolve this discrepancy the Crystal Barrel collaboration has recently made two further determinations of $BR(\pi^0\pi^0, liq)$ and $BR(\mathrm{K_S^0K_L^0}, liq)$. The latter value gives an important check on the consistency of the Obelix and Crystal Barrel results as mentioned earlier in section 4. It should be emphasised that the following results are *PRELIMINARY.*

The first of the analyses used 1.5 10^6 events taken with an "all neutral" trigger. The absolute normalisation used $\pi^0\pi^0$ events selected from 2 10^5 "minimum bias" trigger events taken in the same run period. After kinematic fitting to $\bar{\mathrm{p}}\mathrm{p}\to4\gamma$ the branching ratios $BR(\pi^0\pi^0, liq) = (7.17 \pm 0.86)10^{-4}$ with detector efficiency $\epsilon = 0.55$ and $BR(\mathrm{K_S^0K_L^0}, liq) = (8.75 \pm 1.18)10^{-4}$ with $\epsilon = 0.52$ were obtained. The errors shown are statistical only.

The second analysis used 1.6 10^6 "minimum bias" events obtained towards the end of the LEAR running period. To avoid possible biases due to kinematic fitting, the data were selected solely on the basis of an E vs $\mid \mathbf{p} \mid$ plot of 4γ events and the invariant mass of $\gamma\gamma$ combinations. This gave $BR(\pi^0\pi^0, liq) = (6.14 \pm 0.40)10^{-4}$ with detector efficiency $\epsilon = 0.63$ and $BR(\mathrm{K_S^0K_L^0}, liq) = (8.64 \pm 1.02)10^{-4}$ with $\epsilon = 0.51$. Again the errors are purely statistical. Values of the $\pi^0\pi^0$ branching ratio are plotted in fig.2 together with *VERY PRELIMINARY* branching ratios obtained by these two analyses for $12\rho_{\mathrm{STP}}$ gas.

The above preliminary values of $BR(\mathrm{K_S^0K_L^0}, liq)$ obtained with both "minimum bias" and "all neutral" triggers are in good agreement with the previous Crystal Barrel [10] and Obelix [9] results, giving confidence in the measured two-body branching ratios and calculated detection efficiency. The corresponding values of $BR(\pi^0\pi^0, liq)$ are also in good agreement with the earlier Crystal Barrel result [8]. As mentioned above, the recent Crystal Barrel determination of the $\bar{\mathrm{p}}\mathrm{p}\to\omega\omega$ branching ratio, with one of the ω decaying in its charged decay mode, also supports this latter result [8].

On the other hand, the much lower Obelix value for $BR(\pi^0\pi^0, liq)$ is consistent with earlier measurements (See ref. [13] for references to earlier work.) However Crystal Barrel and Obelix are the only two experiments to measure all photons and to fully reconstruct $2\pi^0$ events. The detection efficiency for 4 photon events is, however, much smaller for the Obelix experiment than for Crystal Barrel, where the efficiency approaches the "geometrical" value.

5. A RECENT ANALYSIS OF TWO-BODY BRANCHING RATIOS

In the present section we present the results of an analysis of two-body branching ratios using the formalism presented here and in [4]. The experimental data used are those given in [4] and the more recent results [9,11–13] discussed in section 4. The very preliminary values of the $\pi^0\pi^0$branching ratio at $12\rho_{\mathrm{STP}}$ were not included in the fit. Unless otherwise stated the enhancement factors derived using the DR1 potential (Table 1) were used. The fraction of P-state annihilation $\mathrm{f_P}(\rho)$ and the partial branching ratios $B(ch, {}^{2S+1}\mathrm{L}_J)$ were determined.

5.1. Fraction of P-state annihilation

If the Crystal Barrel value [8] for $BR(\pi^0\pi^0, liq) = (6.93 \pm 0.22 \pm 0.37)10^{-4}$ is used, together with the other measurements discussed above, then the analysis [4] gives a best fit with $\chi^2/\mathrm{N} = 9.4/8$, $\mathrm{f_P}(liq) = 0.12 \pm 0.03$ and $\mathrm{f_P}(\rho_{\mathrm{STP}}) = 0.59 \pm 0.04$. These and other values of $\mathrm{f_P}(\rho)$ obtained in this analysis are plotted in fig.3. However the fit to the Obelix measurement [15] of $BR(\pi^0\pi^0, \rho_{\mathrm{STP}})$ is relatively poor with $\chi^2 = 4.3$ for this one point. This measurement also seems to be inconsistent with the values at $12\rho_{\mathrm{STP}}$ plotted in fig.2. Removing it gives a significantly better fit with $\chi^2/\mathrm{N} = 4.3/7$ and little change to the values of $\mathrm{f_P}(liq) = 0.12 \pm 0.01$ and $\mathrm{f_P}(\rho_{\mathrm{STP}}) = 0.60 \pm 0.03$.

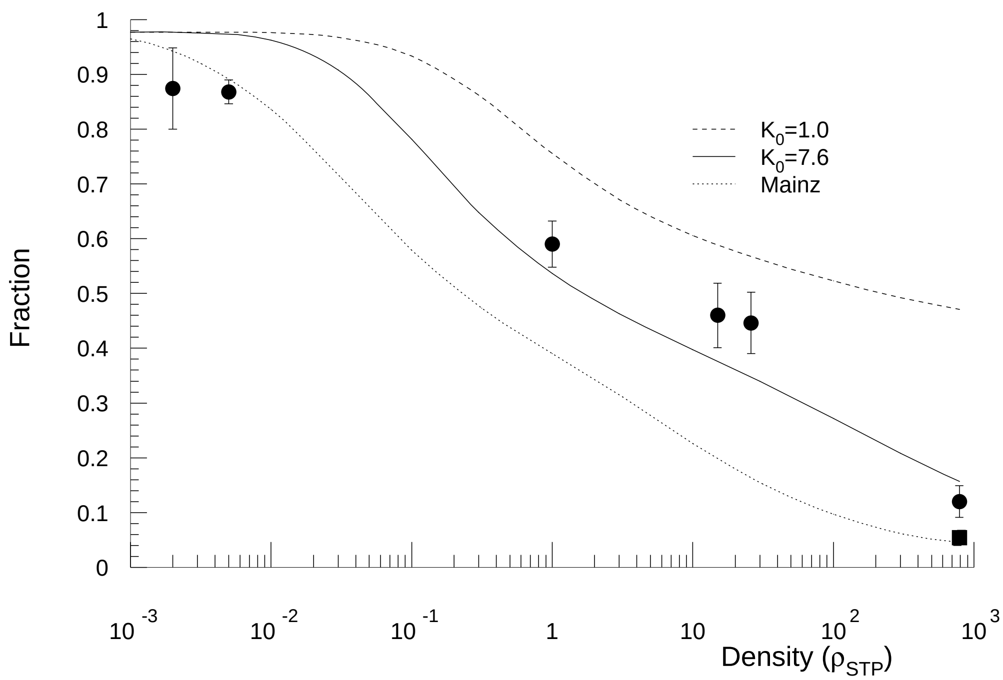

Figure 3. Fraction of P-state annihilation as a function of gas density determined by the analysis of section 5.1. The lines are the predictions of various atomic cascade models [4].

On the other hand if the Obelix value [13] of $BR(\pi^0\pi^0, liq) = (2.8 \pm 0.1 \pm 0.4)10^{-4}$ is used, but not the Crystal Barrel value [8], then the best fit has $\chi^2/\mathrm{N} = 6.9/8$ with $\mathrm{f_P}(liq) = 0.054 \pm 0.014$ and $\mathrm{f_P}(\rho_{\mathrm{STP}}) = 0.56 \pm 0.04$. A good fit to the Obelix value [15] of $BR(\pi^0\pi^0, \rho_{\mathrm{STP}})$ is also obtained. Thus the main effect of the two different values for the $\pi^0\pi^0$ branching ratio is a factor of two difference in the value of $\mathrm{f_P}(liq)$. The values of $\mathrm{f_P}(\rho)$ at lower densities (fig.3) are largely unaltered.

5.2. Partial branching ratios and DSR

The analysis also gives values of the partial branching ratios $\mathrm{B}(\mathrm{ch}, {}^{2S+1}\mathrm{L}_J)$ which are independent of atomic cascade effects. Results from an analysis using the data discussed earlier, with the Crystal Barrel value for $BR(\pi^0\pi^0, liq)$, together with values of the $\phi\pi$, $\omega\pi$, $\phi\eta$, $\pi\eta$ and $\eta\eta$ branching ratios taken from the literature, are given in table 3.

Table 3
Partial Branching Ratios (10^{-3})

Channel	J^{PC}	J^{PC}	^{3}S$_1$	^{1}P$_1$	^{3}P$_0$	^{3}P$_2$
$\pi\pi$	0^-	0^-	2.8 ± 0.3	X	28 ± 9	5.3 ± 1.9
K^+K^-	0^-	0^-	1.4 ± 0.1	X	4.3 ± 0.3	0.0 ± 0.01
$K^0\bar{K}^0$	0^-	0^-	1.4 ± 0.1	X	0.0 ± 0.01	0.19 ± 0.03
$\phi\pi$	1^{--}	0^{-+}	0.9 ± 0.1	0.06 ± 0.10	X	X
$\omega\pi$	1^{--}	0^{-+}	8.8 ± 0.5	0.0 ± 0.01	X	X
$\phi\eta$	1^{--}	0^{-+}	0.09 ± 0.02	0.12 ± 0.04	X	X
$\pi\eta$	0^{-+}	0^{-+}	X	X	10.7 ± 1.6	0.0 ± 0.01
$\eta\eta$	0^{-+}	0^{-+}	X	X	8.5 ± 1.2	0.0 ± 0.01

X   Channel forbidden from this initial state

Particularly noticeable are the values of $B(ch, {}^{2S+1}L_J)$ which for certain channels and specific initial states ${}^{2S+1}L_J$ are consistent with zero, giving clear evidence for dynamical selection rules [16]. The value for the ^{1}P$_1$ partial branching ratio, $B(\phi\eta, {}^1P_1)$, for the $\phi\eta$ channel is about a factor five lower than that recently obtained by the Obelix collaboration [17]. Note however that the value obtained in [17] for $BR(\phi\eta, \rho_{STP})$ is about a factor four larger than the ASTERIX measurement [18] which was used in the present analysis.

6. SOME COMMENTS ON p̄d BRANCHING RATIOS

The general features of the atomic cascade for p̄d atoms are very similar to those for p̄p atoms discussed in section 2. Whilst few calculations of the strong interaction fine structure effects in p̄d atoms are available, Wycech et al. [19] predict that the widths of the fine structure components for P-states are approximately equal. It is therefore to be expected that the enhancement factors will have values $E \approx 1$.

Due to the Fermi motion of the nucleons in deuterium, the p̄-nucleon angular momentum can be different from the angular momentum of the p̄ with respect to the deuteron center of mass. Hence the fraction of P-state annihilation in p̄d atoms could well be very different from that for p̄p atoms[20].

By charge independence, for p̄d atoms

$$BR(\pi^+\pi^-n, \rho) = \frac{1}{2}BR(\pi^-\pi^0p, \rho) + 2BR(\pi^0\pi^0n, \rho). \quad (4)$$

The reaction p̄d→$\pi^-\pi^0$p can only occur from S-states, whilst p̄d→$\pi^0\pi^0$ n only occurs from P-states. Several experiments (see ref.[21]) have determined the ratio

$$r = \frac{BR(\pi^-\pi^0\ p, liq)}{BR(\pi^+\pi^-n, liq)} \quad (5)$$

and argued that $\frac{1}{2}\,r$ is a direct measure of the fraction of annihilations in deuterium from S-states.

Following the notation used earlier equ. (4) can be written in the form

$$BR(\pi^+\pi^- n, liq) \;=\; \frac{1}{2}(1 - \mathrm{f_P}(liq))[\frac{3}{4}B(\pi^-\pi^0 p, {}^3\mathrm{S}_1)] + 2\mathrm{f_P}(liq)[\frac{1}{12}B(\pi^0\pi^0 n, {}^3\mathrm{P}_0) + \frac{5}{12}B(\pi^0\pi^0 n, {}^3\mathrm{P}_2)] \qquad (6)$$

and so $\mathrm{f_P}(\rho)$ cannot be determined from r since the partial branching ratios $B(ch, {}^{2S+1}\mathrm{L}_J)$ are unknown. In fact what r determines is the fraction of the *reaction* $\bar{\mathrm{p}}\mathrm{d}\to\pi^+\pi^-\mathrm{n}$ which proceeds from S-states; not the fraction of S-state annihilation in $\bar{\mathrm{p}}$d interactions at rest.

To summarise, two-body branching ratio measurements have the potential to give important information on the nucleon-antinucleon annihilation process and to make stringent tests of the interaction mechanism. Determination of partial branching ratios is an important part of this process. The data also allow the fraction of P-state annihilation to be determined as a function of density and compared with models for the $\bar{\mathrm{p}}$p atomic cascade. Reliability of the measured branching ratios is, of course, very important.

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REFERENCES

1. C. J. Batty, Rep. Prog. Phys. **52** (1989) 1165.
2. J. Carbonell, G. Ihle and J. M. Richard, Z. Phys. A **334** (1989) 329.
3. D. Gotta (These proceedings).
4. C. J. Batty, Nucl. Phys. A**601** (1996) 425.
5. A. Abele et al., Nucl. Phys. B**514** (1998) 45.
6. A. Abele et al., Phys. Lett. B (Submitted for publication).
7. C. Amsler et al., Phys. Lett. B**297** (1992) 214.
8. C. Amsler et al., Z. Phys. C**58** (1993) 175.
9. A. Bertin et al., Phys. Lett. B**386** (1996) 486 and **389** (1996) 781.
10. C. Amsler et al., Phys. Lett. B**346** (1995) 363.
11. R. Adler et al., Phys. Lett. B**403** (1997) 383.
12. A. Bertin et al., Phys. Lett. B**385** (1996) 493 and **395** (1997) 388..
13. A. Zoccoli, Proceedings HADRON 97 conference (eds. S-U. Chung and H. J. Willitzki) AIP conference proceedings **432** (1998) 347.
14. Crystal Barrel collaboration, (To be published).
15. M. Agnello et al., Phys. Lett. B**337** (1994) 226.
16. C. Amsler and F. Myhrer, Ann. Rev. Nucl. Part. Sci. **41** (1991) 219.
17. V. Alberico et al., Phys. Lett. B**432** (1998) 427.
18. J. Reifenröther et al., Phys. Lett. B**267** (1991) 299.
19. S. Wycech et al., Phys. Lett. **152B** (1985) 308.
20. R. Bizzarri et al., Nucl. Phys. B**69** (1974) 298.
21. A. Angelopoulos et al., Phys. Lett. B**212** (1988) 129.