A STUDY OF THE ANNIHILATION OF STOPPED ANTIPROTONS IN HYDROGEN: THE REACTION $\bar{p}+p\rightarrow\pi^{+}+\pi^{-}+\pi^{0}$

G. B. Chadwick, W. T. Davies, M. Derrick, C. J. B. Hawkins, J. H. Mulvey, D. Radojicic and C. A. Wilkinson

Clarendon Laboratory, University of Oxford, Oxford

M. Cresti, S. Limentani and R. Santangelo

Istituto di Fisica, Università di Padova, Padova

(presented by M. Derrick)

This report describes a study of the reaction

$$\bar{p}+p\rightarrow\pi^{+}+\pi^{-}+\pi^{0} \qquad (1)$$

for antiprotons stopping in the Saclay 81 cm hydrogen bubble chamber. A total of 4148 annihilations giving two prong events have been measured and analysed. We estimate that about 93% of the events in the fiducial volume used were from the annihilation of protonium, the remaining 7% being annihilations in flight. An analysis of the entire sample of events will be given elsewhere.

All possible candidates for reaction (1), selected by an inspection of the missing mass, were tried in a least squares kinematic fitting programme [1]. In the fitting programme all possible combinations of two or three mesons (π and K) satisfying charge and strangeness conservation were tried as hypotheses. Events satisfying more than one hypothesis were rejected [2] and an upper χ^2 limit of 4 for the $\pi^{+}\pi^{-}\pi^{0}$ final state was imposed. 605 events satisfied these criteria.

We have tried to make an approximate estimate of the contamination of fits from $\pi^{+}\pi^{-}2\pi^{0}$ events by analysing four prong annihilations: 1100 such events have been put through the same selection and fitting procedure as used for the two prong events. Of the 4400 $\pi^{+}\pi^{-}$ combinations, 47 satisfied the single neutral pion hypothesis.

These " events " came predominantly from the type

$$p+\bar{p}\rightarrow 2\pi^{+}+2\pi^{-} \qquad (2)$$

which are about 12.5% of all four prong events, according to our measurements. Using isotopic spin weights to estimate the rate of

$$p+\bar{p}\rightarrow\pi^{+}+\pi^{-}+2\pi^{0} \qquad (3)$$

from the measured rate of reaction (2), gives a contamination from this source of 13.8%. This procedure neglects the presence of two and three pion resonances. An estimate including the rate of ρ^0 production in events of type (2) indicates that the contamination estimate could be as much as 20%. We have no way of estimating the effect of ω^0 meson production which can occur for reaction (3) but not for reaction (2). The absolute rate of the three pion annihilation is then $(5.4\pm1.0)10^{-2}$.

The results of this experiment are shown on the Dalitz plot in Fig. 1. The kinetic energy spectra of the π^{-}, π^{+} and π^{0} mesons are shown in Figs. 2 a, 2 b and 2 c respectively. The peaks at 650 MeV are due to the ρ-meson. The same effect is seen on the Dalitz plot as the accumulation of points within three bands parallel with the sides of the diagram, as indicated in Fig. 1. These bands contain events corresponding to the processes:

$$\bar{p}+p\rightarrow\rho^{\pm}_{0}+\pi^{\mp}_{0} \qquad (4)$$

The production of the ρ-meson appears to be a dominant feature of the annihilation to three pions. By counting the number of points within the bands shown

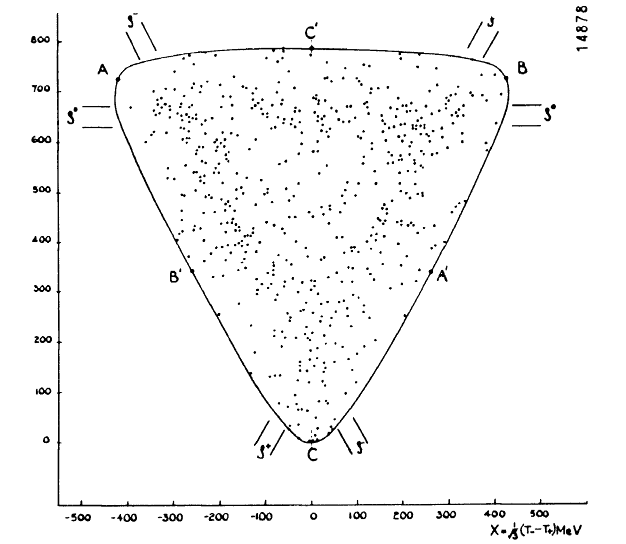

Fig. 1 The Dalitz plot for the events from reaction (1). The kinetic energy of the positive pion is zero at *B* and a maximum at *B*′, and similarly for the negative pion at *C* and *C*′. The bands labelled ϱ^+, ϱ^- and ϱ^0 indicate the two body process $p+\bar{p}\to\varrho^{\pm}_{0}+\pi^{\mp}_{0}$ with mass for the ϱ of 755 MeV and with a width of ± 55 MeV.

on the Dalitz plot the numbers obtained for ρ^+, ρ^- and ρ^0 are 92, 100 and 100 respectively.

This near equality is significant because the system $\rho^0\pi^0$ can be produced only from states of protonium with isotopic spin $I=0$, and the table shows that $\rho^0\pi^0$ production can occur only from the $^3S_1$ and $^1P_1$ states. The observation of equal rates for ρ^0, ρ^+ and $\bar{\rho}$ then strongly suggests that the annihilation to $\rho+\pi$ takes place predominantly from such states [5].

In earlier experiments it has been shown that the ρ-meson has isotopic spin 1 [3] and that the spin is consistent with 1 [4].

For a discussion of the properties of the final state we define the following system of reference: the dipion rest system in which the momentum of either pion is q and the relative angular momentum l, and the laboratory system in which the third pion has momentum P and angular momentum L relative to the dipion. In terms of these angular momenta some of the possible states (L, l) for three pions are listed in column three of the table [7].

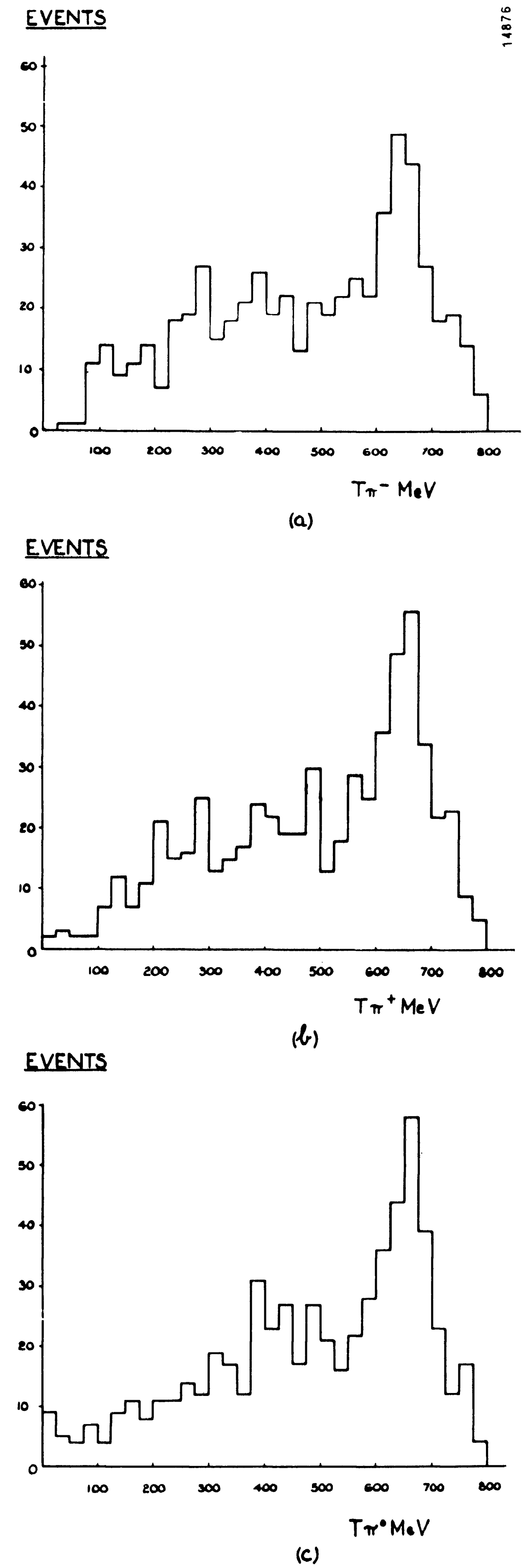

Fig. 2 The kinetic energy spectra of (a) the negative (b) the positive, and (c) the neutral pions.

Initial and Final States for Protonium Annihilation into three Pions

Initial State	Spin-Parity	I	C	G	Allowed final states (L, l)
$^1S_0$	0^-	1	+	−	(0,0), (1,1), (2,2) etc.
$^3S_1$	1^-	0	−	−	(1,1), (3,3), (5,5) etc.
$^1P_1$	1^+	0	−	−	(0,1), (2,1), (2,3) etc.
$^3P_0$	0^+	Annihilation to 3 π forbidden (Parity)			
$^3P_1$	1^+	1	+	−	(0,1), (1,0), (1,2) etc.
$^3P_2$	2^+	1	+	−	(1,2), (2,1), (2,3) etc.

In Fig. 3 we show the angular distributions for the decay of the neutral and charged ρ-mesons, where θ is the angle between the direction of one meson in the dipion rest system and the line of flight of the dipion. The events were selected for these diagrams by choosing values of dipion mass between 700 and 820 MeV.

Two features of these results are the peaks at $|\cos\theta| = 0.67$ and the fall to zero at $\cos\theta = \pm 1$. The simplest matrix elements which may be constructed for $\rho^0+\pi^0$ production from the $^1P_1$ states of protonium would not vanish at $\cos\theta = 1$ in the angular distributions for ρ^0 in Fig. 3 [8]. The simplest interpretation of these results is therefore that they are consistent with very little contribution from the P states of protonium [10].

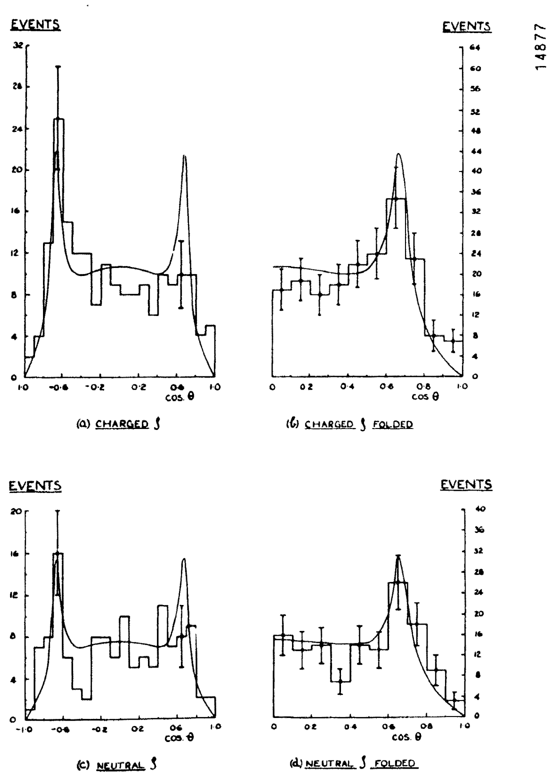

Fig. 3 The angular distribution of (a) the charged ρ and (c) the neutral ρ decays in their barycentric system. The distributions have been folded about $\cos\theta = 0$ in (b) and (d). The curves show the distributions expected for a $J = 1$ particle produced from the $^3S_1$ state. [11]

If the S-state annihilation dominates, one might expect that the $^1S_0$ channel should contribute to the production of three pions. The final state would be represented by a combination of states (0,0), (1,1), (2,2) etc. It is hard to understand why some of these states should be present and (1,1) not at all, as implied by the absence of any contribution to ρ^+ and ρ^- production. The fact that the angular distributions for $\rho^\pm$ approach zero at $\cos\theta = 1$, also suggests that the $^3S_1$ channel is predominant.

In view of these considerations we shall now discuss the $\rho+\pi$ production process under the assumption that only the $^3S_1$ state contributes. In this case the resonant final state is represented uniquely by one configuration of angular momentum, (1,1). Both the isotopic spin and angular momentum wave functions of this system are totally anti-symmetric. The consequences of this have been discussed by Bouchiat and Flamand [11], who write the amplitude for process (4) in the following way:

$$A = \mathbf{S}(\mathbf{q}_{+-}\times\mathbf{P}_0 f(q_0)+\mathbf{q}_{-0}\times\mathbf{P}_+ f(q_+)+\mathbf{q}_{0+}\times\mathbf{P}_- f(q_-)) \tag{5}$$

where $\mathbf{S}$ represents the protonium spin and

$$f(q) = \frac{\gamma m_\pi^2}{q^2 - q_r^2 + i\gamma[q^6/(q^2+m_\pi^2)]^{\frac{1}{2}}} \tag{5a}$$

$f(q)$ is an $l = 1$ resonance factor and the parameters are the value of q at the resonance, q_r, and the dimensionless quantity γ related to the width Γ_0 [12].

As expected for an $I = 0$ state of three pions, the interference between the amplitudes for the different charge configurations is constructive everywhere, and in particular at the point where two resonance factors become equal an enhancement occurs. This corresponds to the regions of the Dalitz plot where two bands cross and one pion can be in a resonant state with either of the other two.

This effect should be demonstrated in the angular distributions of Fig. 3, and the curves which have been drawn were computed using the amplitude given by equation 5. The data show the general characteristics expected on this model except that there appears to be some asymmetry. In the case of the charged ρ-mesons this may be an indication that the neglect of more complicated interference effects (involving the $^1S_0$ channel) is not completely justified.

These results suggest that the annihilation to $\rho+\pi$ is reasonably consistent with the conclusion that the $^3S_1$ channel is dominant, and with the assignment of spin 1 to the ρ-meson.

We have therefore attempted to fit the distribution of M^*, the dipion mass, given in Fig. 4, by adding incoherently a contribution from the resonant state as described by Eq. (5) and a distribution corresponding to a simple phase space for three pions [14]. This treatment of the non-resonant contribution is an approximation since in general it will be a combination of states (1,1), (3,3), (5,5) etc. coherently added to the resonant amplitude. The two contributions have been added in the ratio 1: 1 to obtain the curve shown in Fig. 4; the resonance parameters used are a ρ-meson mass of 755 MeV and a width of 110 MeV (this width includes the experimental resolution). The fit is not good in the region 900 to 1500 MeV; this could be due to the high energy behaviour of the p-wave $\pi\pi$ cross-section or the over-simplified treatment of the background.

Finally, the absolute rate of annihilation to $\rho+\pi$ obtained by this means is $(2.7\pm0.6)\ 10^{-2}$.

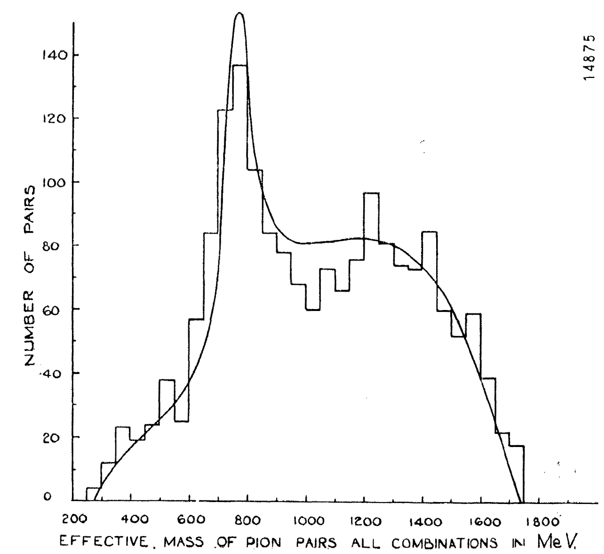

Fig. 4 The two pion mass distribution for events from reaction (1). The curve is an incoherent sum of equal proportions of the distribution calculated from equation 5 in the text, and a uniform phase space background.

LIST OF REFERENCES

1. The fitting programme was written by Mr. A. G. Wilson at the Rutherford Laboratory, N.I.R.N.S., Harwell. We are greatly indepted to Mr. Wilson for the programme and for all his generously given help.
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4. D. D. Carmony and R. T. Van de Walle: Phys. Rev. Letters, *8*, 73 (1962).
5. It has been suggested [6] that the rate for the decay of ω^0 into $\pi^++\pi^-$ by an electromagnetic interaction may be appreciable. The reaction $\bar{p}+p\rightarrow\omega^0+\pi^0$ may proceed only through the $^3S_1$ channel of isotopic spin 1 (if P states are excluded) and so any such contribution would be added coherently to the direct $^3S_1$, $\varrho^0+\pi^0$, amplitude. In this case the equality of the rates of production of ϱ^0, ϱ^+, ϱ^- would in general imply some contribution of $\varrho^\pm$ from, say, the $^1S_0$ state (unless the interference in the $^3S_1$ channel was so arranged as to lead to the equality). However, the angular distribution of $\varrho^\pm$ decay (Fig. 3) is also consistent with little contribution from the $^1S_0$ state.
6. S. Glashow, Phys. Rev. Letters, *7*, 469 (1961); J. Bernstein and G. Feinberg, BNL 6122 (1962).
7. This description in terms of l and L is correct only in the non-relativistic limit and so use of this representation in the present experiment, where the ϱ-meson has a momentum of 780 MeV/c, is an approximation.
8. The lowest $^1P_1$ state leading to ϱ^0-production is (0,1) $J = 1^+$. It has been discussed by Stevenson *et al.*[9] in connection with the ω^0 spin analysis.
9. M. L. Stevenson, L. W. Alvarez, B. C. Maglić and A. H. Rosenfeld; Phys. Rev. *125*, 687 (1962).
10. It is not possible to exclude completely the possibility of some P state contribution since interference between several (L, l) waves may occur in such a way as to allow the effect observed.
11. C. Bouchiat and G. Flamand, Nuovo Cimento *23*, 13 (1962).
12. The relation used is $\gamma = \Gamma_0\,(q_r^2+m_\pi^2)/2q_r^3$. Formula 5 (a) is a p-wave effective range approximation (See for example Lee and Vaughn).[13]
13. B. Lee and M. T. Vaughn, Phys. Rev. Letters, *4*, 578 (1960).
14. The contamination from the pseudo three pion events is included in this background.