Annihilation of Antiprotons in Hydrogen at Rest. II. Analysis of the Annihilation into Three Pions*

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Analysis of 823 events attributed to the reaction $\bar{p}+p$ (at rest) $\rightarrow \pi^+ + \pi^- + \pi^0$ yields the following results: (a) The channel accounts for 7.8% of the annihilations; (b) 0.55±0.05 of the channel proceeds via ρ production, and the capture to $\rho\pi$ is from the $^3S_1$ state; and (c) 0.45±0.05 of the channel is nonresonant and this nonresonant production is from the $^1S_0$ state.

I. INTRODUCTION

THE presentation of results based on an exposure of the Columbia-BNL 30-in. H_2 bubble chamber to stopping antiprotons at the BNL AGS is continued[1] here with a discussion of the channel $\pi^+\pi^-\pi^0$. Experimental results on this reaction have previously been given by Chadwick *et al.*,[2] who showed that approximately one-half of the channel is nonresonant, that the other half proceeds via the production $\pi+\rho$, and that this latter part is due to capture from the triplet state. Our results are slightly more extensive numerically and we confirm the conclusions of Chadwick *et al.*[2] In addition, we analyze the nonresonant part of the channel and show that it is the result of capture from the $^1S_0$ state.

II. EXPERIMENTAL RESULTS

A. Selection Criteria and Contamination

The results presented here are based on the measurement of 10.3×10^3 two-prong annihilations, representing 22.6×10^3 stopped antiprotons. Of these, 9301 survived spatial reconstruction and of these 2560 were kinematically consistent with the hypothesis of annihilation into $\pi^+ + \pi^- + \pi^0$, with $\chi^2<6$, and 1815 of these events were in the fiducial volume chosen for this experiment. There is, however, the problem that the measurement accuracy is not quite good enough, and the remaining sample has a substantial contamination of events containing more than one π^0. The missing masses of the events as selected so far are shown in Fig. 1. We now impose the additional restriction that the square of the missing mass be within 0.1 BeV^2 of the square of the pion mass. This reduces the sample to 823 events. The remaining background of multi-π^0 events may perhaps be estimated using the events with four charged tracks. Using only the measurements of two of the four charged tracks, with four possible combinations per event we find that $\frac{3}{4}$% of these combinations fit the above acceptance criteria. Since the number of two prong events with more than one π^0 is roughly five times greater than those with only one π^0, we conclude that the multi-π^0 contamination is approximately 4%. In addition, we note that the two pronged events with two or more π^0's show less than 10% ρ^0 production; we have therefore neglected the ρ^0 contribution from the multi-π^0 background.

B. Absolute Rate Determination

We have 823 events after the various selection criteria have been applied, corresponding to 22.6×10^3 stopped antiprotons. The various efficiencies have been estimated to be as follows:

(a) Efficiency for survival in spatial reconstruction and fitting programs $\epsilon_{recon}=0.88\pm0.02$; (b) fraction of measurements in fiducial volume $\epsilon_{fid}=0.722 \pm0.02$; (c) fraction of events within mass region of π^0 $\epsilon_{mass\ cut}=0.73\pm0.07$.

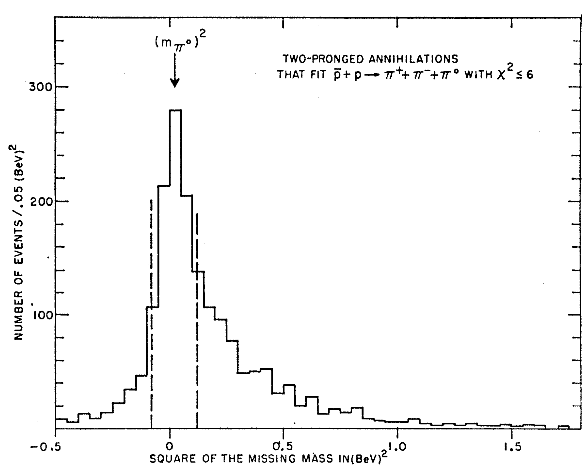

FIG. 1. Distribution in the square of the missing mass for 1815 two-pronged annihilations consistent with the hypothesis $\bar{p}+p\rightarrow\pi^++\pi^-+\pi^0$ with $\chi^2\leq6$.

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[1] N. Barash, P. Franzini, L. Kirsch, D. Miller, J. Steinberger, T. H. Tan, R. Plano, and P. Yaeger, Phys. Rev. 139, B1659 (1965).
[2] G. B. Chadwick, W. T. Davies, M. Derrick, C. J. B. Hawkins, J. H. Mulvey, D. Radojicic, C. A. Wilkinson, M. Cresti, S. Limentani, and R. Santangelo, Phys. Rev. Letters 10, 62 (1963); F. N. Ndili, Phys. Rev. 138, B460 (1965).

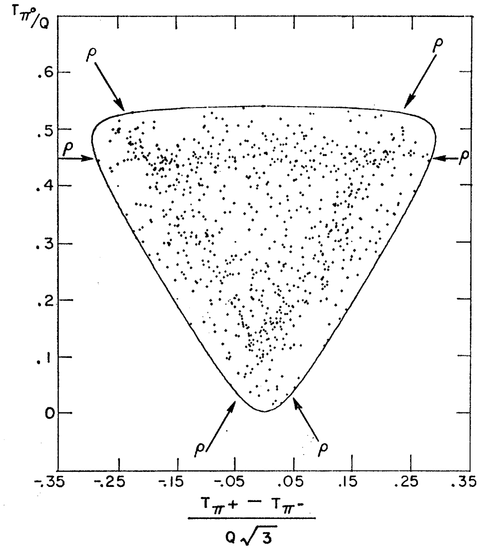

FIG. 2. Dalitz plot for 823 $\bar{p}+p \rightarrow \pi^+ + \pi^- + \pi^0$ events. Q is defined as $2m_p - 3m_\pi$.

This latter efficiency is estimated by assuming (this has been checked experimentally in similar situations) that the missing mass-squared distribution for a missing π^0 is symmetrical. We then find that the reaction $\bar{p}+p \rightarrow \pi^+ + \pi^- + \pi^0$ accounts for 0.078 ± 0.009 of stopped antiprotons.

C. Correlations in the Pions

The experimental results are presented in the form of the Dalitz plot in Fig. 2 and the three projections of the Dalitz plot in Fig. 3.

III. DISCUSSION AND ANALYSIS OF RESULTS

A. Comparison of ρ Production in Various Charge States

The projections (Fig. 3) show ρ production which is equal within statistics in all three pion combinations. The numbers of events in the bands corresponding to the ρ^+, ρ^-, and ρ^0 $(700 < M_{\pi\pi} < 850 \text{ MeV})$ on the Dalitz plot are 175, 184, and 186, respectively.

B. Dynamics of the Reaction

A theoretical discussion of this reaction has been given by Bouchiat and Flamand.[3] G-parity conservation limits the S-state annihilation into 3 pions to the two states ${}^3S_1$, $I=0$ and ${}^1S_0$, $I=1$. The simplest matrix elements for 3π and $\rho\pi$ production from these initial states can be written as

$$\Psi(3\pi \text{ from } {}^1S_0) \propto 1, \quad (1)$$

$$\Psi(3\pi \text{ from } {}^3S_1) \propto (\mathbf{P}_+ - \mathbf{P}_-)\times\mathbf{P}_0 + (\mathbf{P}_- - \mathbf{P}_0)\times\mathbf{P}_+ + (\mathbf{P}_0 - \mathbf{P}_+)\times\mathbf{P}_-, \quad (2)$$

[3] C. Bouchiat and G. Flamand, Nuovo Cimento **23**, 13 (1962).

$$\Psi(\rho\pi \text{ from } {}^1S_0) \propto \frac{(\mathbf{P}_+ - \mathbf{P}_0)\cdot\mathbf{P}_-}{(m_{+0} - m_\rho) - \frac{1}{2}i\Gamma_\rho} - \frac{(\mathbf{P}_0 - \mathbf{P}_-)\cdot\mathbf{P}_+}{(m_{0-} - m_\rho) - \frac{1}{2}i\Gamma_\rho}, \quad (3)$$

$$\Psi(\rho\pi \text{ from } {}^3S_1) \propto \frac{(\mathbf{P}_+ - \mathbf{P}_-)\times\mathbf{P}_0}{(m_{+-} - m_\rho) - \frac{1}{2}i\Gamma_\rho} + \frac{(\mathbf{P}_- - \mathbf{P}_0)\times\mathbf{P}_+}{(m_{-0} - m_\rho) - \frac{1}{2}i\Gamma_\rho} + \frac{(\mathbf{P}_0 - \mathbf{P}_+)\times\mathbf{P}_-}{(m_{0+} - m_\rho) - \frac{1}{2}i\Gamma_\rho}, \quad (4)$$

where $\mathbf{P}_+$, $\mathbf{P}_-$, $\mathbf{P}_0$ are the π^+, π^-, π^0 momenta, respectively; m_{+-} is the invariant mass of the π^+ and the π^- and similarly for the other charge combinations; m_ρ and Γ_ρ are the mass and width of the ρ meson.

A two-dimensional least-squares fit to the distribution of the events on the Dalitz plot was carried out in terms of these matrix elements. The best fit, with a ρ mass of 750 MeV and width of 90 MeV, yielded the relative intensities shown in Table I. If the ρ mass and width are allowed to vary, a better fit is obtained with a mass of 735 MeV and a width of 90 MeV, but the relative intensities for this fit are the same as shown in Table I.

The absence of $\rho\pi$ production from ${}^1S_0$ in in agreement with the fact that ρ^+, ρ^- and ρ^0 production is approximately equal. The ${}^1S_0$ state with $I=1$ can not go into $\rho^0\pi^0$; the ${}^3S_1$ produces equal amounts of ρ^+, ρ^-, and ρ^0. Since ρ production from ${}^1S_0$ and ${}^3S_1$ are incoherent, any contribution from ${}^1S_0$ would result in more $\rho^\pm$ than ρ^0 production. It may also be interesting to note that in both resonant and nonresonant production, a single initial state dominates, and that this state is the opposite for the two reactions.

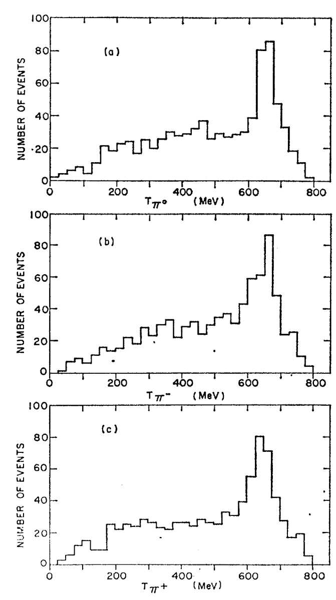

FIG. 3. Projections of the Dalitz plot on the T_{π^0}, T_{π^-}, and T_{π^+} axes.

TABLE I. Nonresonant and resonant three-pion annihilation rates.

Capture reaction	Fraction of $\pi^+\pi^-\pi^0$ channel	Fraction of all annihilations
3π from $^1S_0$	$45\pm5\%$	0.035 ± 0.06
3π from $^3S_1$	$<15\%$	<0.012
$\rho\pi$ from $^1S_0$	$<5\%$	<0.004
$\rho\pi$ from $^3S_1$	$55\pm5\%$	0.043 ± 0.06
All annihilations into $\pi^++\pi^-+\pi^0$	100%	0.078 ± 0.009

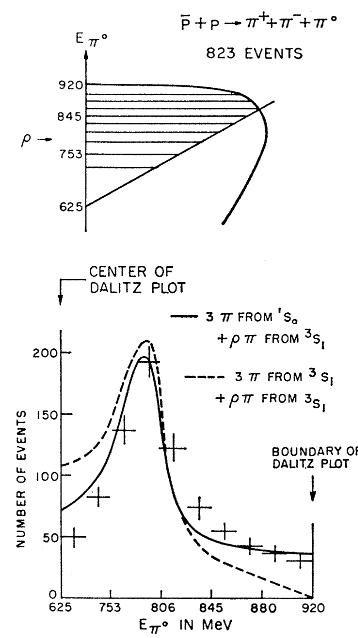

FIG. 5. Distribution of the events in the 10 equal areas of each sextant of the $\bar{p}+p\to\pi^++\pi^-+\pi^0$ Dalitz plot. The division of the sextants into 10 equal areas is shown in the sketch on top.

The projections of the Dalitz plot on the three dipion mass axes were the same within statistics; the three projections were added and are shown in Fig. 4. The superimposed curve corresponds to the best fit to the Dalitz plot, as described above, using $m_\rho=750$ MeV and $\Gamma_\rho=90$ MeV.

In order to display the difference between 3π production from $^1S_0$ and $^3S_1$ more sensitively, a plot similar to the radial density distribution of the Dalitz plot (Stevenson plot) was made. Since (a) the $\rho\pi$ contribution from $^1S_0$ is negligible, and the remaining matrix elements have a sixfold symmetry on the Dalitz plot, and (b) the experimental population of the sextants is equal within statistics, the entire Dalitz plot was folded into one sextant. This sextant was then divided into 10 equal areas by straight lines parallel to the ρ band. The distribution of the events in these 10 bins is shown in Fig. 5. The solid curve represents 55% $\rho\pi$ from $^3S_1$ and 45% 3π from $^1S_0$. The dashed curve is the best fit to both $\rho\pi$ and 3π from $^3S_1$. The preference of the data for the 3π coming from $^1S_0$ is clear.

The curves superimposed on Figs. 4 and 5 which correspond to the best two-dimensional fits to the Dalitz plot reproduce the general features of the distributions, but they do not fit very well in the regions which correspond to the center of the Dalitz plot (this is the 900- to 1300-MeV region in Fig. 4). An An attempt was made to understand this disagreement in terms of higher angular momentum states of the three pions coming from the $^1S_0$ state of $\bar{p}p$. The simplest matrix element for this state, Eq. (1), corresponds to the lowest allowed angular momentum states of the pions. More complex matrix elements, corresponding to $(l,L)=(1,1)$ were constructed. (l is the relative angular momentum of two of the pions, and L is the angular momentum of the third pion with respect to the first two.) These matrix elements, however, failed to remove the disagreement.

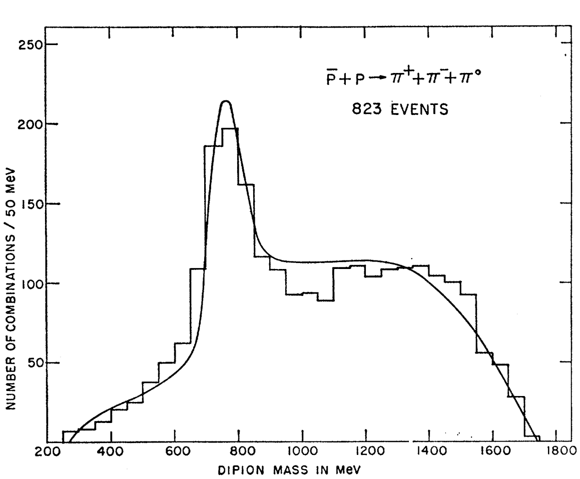

FIG. 4. Combined $\pi^+\pi^-$, $\pi^+\pi^0$, and $\pi^-\pi^0$ mass distribution.

The matrix elements used, Eqs. (1) to (4), could be multiplied by properly symmetrized and Lorentz-invariant, but otherwise arbitrary, functions of the pion energies. It may well be that such form factors are necessary to fit this reaction in detail. The conclusion that the annihilation into 3π proceeds primarily from the $^1S_0$ is not very sensitive to these form factors. No nonsingular multiplicative form factor can change the requirement that the distribution on the Dalitz plot fall off to zero along the boundary for the case of 3π coming from $^3S_1$. Figure 5 indicates that the distribution is constant and significantly different from zero as the boundary is approached, in agreement with the matrix element for 3π from $^1S_0$ [Eq. (1)].

IV. CONCLUSIONS

The $\bar{p}p$ annihilation at rest into $\pi^+\pi^-\pi^0$ proceeds in two approximately equally probable channels: $\pi\rho$ and nonresonating $\pi\pi\pi$. The former proceeds chiefly from the $^3S_1$ state, and the latter from the $^1S_0$ state. The rates are summarized in Table I.

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Annihilation of Antiprotons in Hydrogen at Rest. III. The Reactions $\bar{p}+p \rightarrow \omega^0+\pi^++\pi^-$ and $\bar{p}+p \rightarrow \omega^0+\rho^0$†

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The reactions (a) $\bar{p}+p \rightarrow \omega^0+\pi^++\pi^-(\pi^+\pi^-$ nonresonating), and (b) $\bar{p}+p \rightarrow \omega^0+\rho^0$ have been studied for antiprotons at rest. It is found that reaction (a) proceeds from the ^3S $\bar{p}p$ state, whereas reaction (b) is allowed only for the ^1S state. Reaction (a) accounts for 0.039 ± 0.005 of all annihilations, and reaction (b) for 0.007 ± 0.003 of all annihilations.

I. INTRODUCTION

It has been observed by Chadwick *et al.*[1] that a substantial fraction of $\bar{p}p$ annihilation into four charged and one neutral pion proceeds through intermediate ω^0 formation. It may be noted that this is the reaction, albeit for antiprotons in flight, in which the ω^0 was discovered.[2] Continuing our study of $\bar{p}p$ annihilation at rest[3] we present here a phenomenological analysis of the $\omega\pi\pi$ channel.[4]

II. EXPERIMENTAL RESULTS

From an exposure of the 30-in. Columbia-BNL hydrogen chamber to the separated low-energy antiproton beam at the BNL AGS, 16 700 "4-prong" events representing 35 600 stopped antiprotons have been analyzed. All events fitting the reaction $\bar{p}+p \rightarrow 2\pi^+ +2\pi^-$ were rejected. From the remaining 14 560 events, 7859 events could be fitted to the reaction $\bar{p}+p \rightarrow 2\pi^+ +2\pi^-+\pi^0$ (1-*C* fit). In Fig. 1 the distribution of the square of the missing mass $(M_m)^2$ of these events calculated from the unfitted quantities is presented. For the following analysis events with $(M_m)^2$ outside the interval -0.082 to 0.118 BeV^2 were rejected. We remain with a sample of 6353 events which is reasonably free from contaminations (less than 3%) and biases. Using the data of Fig. 1, and assuming that the asymmetry is due to multi-π^0 contaminations, the accepted mass interval contains 0.875 of the events corresponding to this channel.

Figure 2 shows the $\pi^+\pi^-\pi^0$ invariant mass $(M_{\pi^+\pi^-\pi^0})$ distribution around the ω^0 mass, where a large accumulation of events occurs. In order to determine the amount of $\omega\pi\pi$ production the experimental distribution of Fig. 2 has been fitted to a smoothly varying background plus a Gaussian of adjustable width. The mass of the ω^0 was taken to be 784.5 MeV. A best fit was obtained with 18.7-MeV half-width plus a second-order polynomial. To this fit there corresponds a total of $1250\pm95\omega^0\pi^+\pi^-$ events.

The partial rate for $\omega^0\pi^+\pi^-$ is then $1.14\times(1250\pm95)/(0.875\times35\,600)=0.046\pm0.0045$ per stopped antiproton. The factor 1.14 accounts for the neutral decay modes of the ω.[5]

The isometric Dalitz plot in the region $770\leq M_{\pi^+\pi^-\pi^0}\leq800$ is shown in Fig. 3. Figure 4(b) shows the projection of the experimental distribution on the T_{ω^0} axis of the Dalitz plot. Figures 4(a) and 4(c) show corresponding projections obtained from two control regions with $735\leq M_{\pi^+\pi^-\pi^0}\leq765$ MeV and $805\leq M_{\pi^+\pi^-\pi^0}\leq835$ MeV.

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[1] G. B. Chadwick, W. T. Davies, M. Derrick, C. J. B. Hawkins, P. B. Jones, T. H. Mulvey, D. Radojicic, C. A. Wilkinson, M. Cresti, A. Grigoletto, S. Limentani, A. Loria, L. Peruzzo, and R. Santangelo, in *1962 Annual International Conference on High-Energy Nuclear Physics at CERN*, edited by J. Prentki (CERN, Geneva, 1962), p. 73.

[2] B. Maglić, L. Alvarez, A. Rosenfeld, and M. Stevenson, Phys. Rev. Letters **7**, 178 (1961).

[3] N. Barash, P. Franzini, L. Kirsch, D. Miller, J. Steinberger, T. H. Tan, R. Plano, and P. Yeager, Phys. Rev. **139**, B1659 (1965).

[4] A more detailed account of antiproton annihilations into four and five pions will be presented later.

[5] C. Alff, D. Berley, D. Colley, N. Gelfand, U. Nauenberg, D. Miller, J. Schultz, J. Steinberger, T. H. Tan, H. Brugger, P. Kramer, and R. Plano, Phys. Rev. Letters **9**, 322 (1962).