Antiproton-Proton Inelastic Interactions at 1.61 Bev/c and Their Use for a Test of Charge-Conjugation Invariance in Strong Interactions*

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The reactions $\bar{p}+p\rightarrow\bar{p}+p+\pi^0$, $\bar{p}+n+\pi^+$, and $p+\bar{n}+\pi^-$ have been investigated for antiprotons of 1.61 Bev/c. The cross sections are measured and found to be 1.6 ± 0.3 mb, 1.15 ± 0.3 mb, and 0.96 ± 0.22 mb, respectively. The combined inelastic (nonannihilation) cross section is estimated to be 5.3 mb, and the annihilation cross section 51 ± 3 mb. The angular and energy distributions are presented. In all cases the antinucleons are peaked forward and the nucleons backward in the center-of-mass system.

These events can be used to check charge-conjugation invariance in strong interactions.

INELASTIC CROSS SECTION

THE following four reactions constitute the nonannihilation inelastic antiproton-proton interactions which produce one pion:

$$\bar{p}+p\rightarrow\bar{p}+p+\pi^0, \tag{1}$$

$$\bar{p}+p\rightarrow\bar{p}+n+\pi^+, \tag{2}$$

$$\bar{p}+p\rightarrow p+\bar{n}+\pi^-, \tag{3}$$

$$\bar{p}+p\rightarrow\bar{n}+n+\pi^0. \tag{4}$$

We have measured the cross section for reactions (1)–(3) for antiprotons of $1.61\pm.03$ Bev/c. Reaction (4) is difficult to observe alone, but some measurements of the charge-exchange cross section have included this reaction. The details of the beam used in this experiment are given in another paper.[1]

Because many antiprotons annihilate into two charged pions plus several neutral pions ($\bar{p}+p\rightarrow\pi^+ +\pi^-+n\pi^0$), it is extremely difficult to identify unambiguously reactions (1)–(3) from a random sample of two-prong events. Therefore, in order to study reactions (1) and (2) we have analyzed only those events in which the negative secondary produces a four- or a six-prong event. One of these connected events is shown in Fig. 1. A six-prong secondary event is nearly certain to be an annihilation of an antiproton. Since almost all secondary four-prong events produced by pions can have at most one associated neutral pion, they can be identified by kinematic analysis.

In a total of 21 000 antiproton interactions in the 72-in. hydrogen bubble chamber, there were 495 connected events of this type. A careful scanning-table measurement of these enabled us to identify almost all the elastic scatterings among these events. The Franckenstein measuring projector was used to measure the remaining 55 candidates for the inelastic reactions. Kinematic analysis of these, using program KICK[2] (supplemented by an ionization measurement of the positive track for a few events), yielded 25 events of $\bar{p}+p\rightarrow\bar{p}+p+\pi^0$, 17 events of $\bar{p}+p\rightarrow\bar{p}+n+\pi^+$, and 1 which fitted either reaction. The remaining 13 events were either elastic scatterings of antiprotons or pion interactions. In all subsequent statements we will treat the one ambiguous event as if it were one-half reaction (1) and one-half reaction (2).

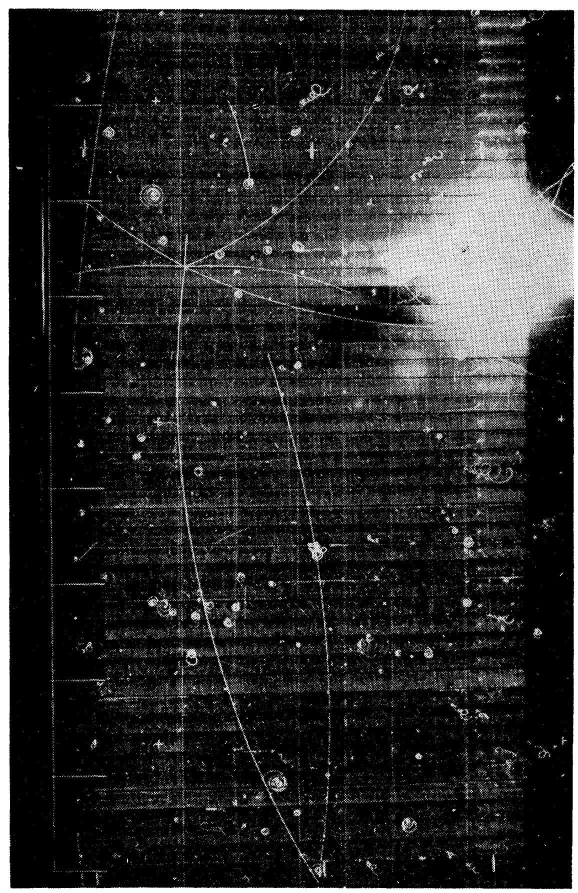

FIG. 1. A bubble chamber picture of one of the $\bar{p}+p\rightarrow\bar{p}+n+\pi^+$ events with the antiproton subsequently annihilating.

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[1] J. Button, P. Eberhard, G. R. Kalbfleisch, J. E. Lannutti, G. R. Lynch, B. C. Maglić, M. L. Stevenson, and N. H. Xuong, Phys. Rev. 121, 1788 (1961).

[2] A. H. Rosenfeld and J. N. Snyder, University of California Radiation Laboratory Report UCRL-9098, 1960 (unpublished).

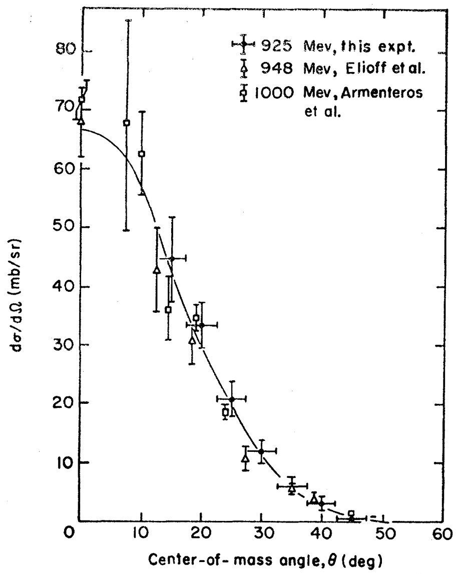

FIG. 2. The differential $\bar{p}$-p elastic scattering as measured by three experiments near 930 Mev. The solid curve is an optical-model fit to the data of the type described by Elioff *et al.*[4] (Ref. 4).

In order to study reaction (3), we analyzed the 81 two-prong events which were possible associated with three-, five-, or seven-prong stars. Many of these stars were found not to be associated with any visible interaction. Many others were associated with a zero-prong event in the same frame and were produced by antineutrons from the reaction $\bar{p}+p\rightarrow\bar{n}+n$. Careful kinematic analysis showed that only 19 of these events were the reaction $\bar{p}+p\rightarrow p+\bar{n}+\pi^-$.

To calculate the cross section of the inelastic processes from these events with secondary annihilations it was necessary to assign a weight to each event. This weight was equal to the reciprocal of the average probability that the antinucleon from such an event would produce an annihilation with more than two charged prongs in the 72-in. chamber. For an antiproton with a momentum equal to the beam momentum in this experiment, the calculation of this probability is straightforward because we have measured the fraction of antiproton interactions that are four- or six-prong events. To extend this to all energies we used the measured total $\bar{p}$-p cross sections[3] for reactions (1) and (2), and for reaction (3) we used the measured $\bar{p}$-n cross section,[4] assuming on the basis of charge independence that this is equal to the $\bar{n}$-p cross section. We took the annihilation cross section to be $\pi(\lambda\!\!\!^{-}+0.975\text{ f})^2$, a form which agrees with the experimental data. To predict what fraction of the annihilations had more than two charged prongs, we used a Lorentz-invariant Fermi statistical model with an interaction volume of five times the volume having a radius of one pion Compton wavelength. Such a statistical model fits fairly well the observed charged pion multiplicities.

After weighting, we estimated the number of each of these events in the film. Reaction (1), 331±64; (2), 236±56; (3), 208±48. No event was observed for the reaction $\bar{p}+p\rightarrow\bar{p}+p+\pi^++\pi^-$ or for the reaction $\bar{p}+p\rightarrow\bar{n}+n+\pi^++\pi^-$ with a subsequent annihilation of the antinucleon with more than two charged prongs. This sets an upper limit of about 0.1 mb for the cross section of these reactions.

After correcting for scanning efficiency and making use of the known antiproton-proton cross section,[3] we obtained

$$\sigma(\bar{p}+p+\pi^0)=1.6\ \pm0.3\text{ mb},$$
$$\sigma(\bar{p}+n+\pi^+)=1.15\pm0.3\text{ mb},$$
$$\sigma(p+\bar{n}+\pi^-)=0.96\pm0.22\text{ mb}.$$

If either the isobaric model[5] or the statistical model[6] is assumed, the cross sections for reactions (1) and (4) are equal. On the basis of the assumption that they are indeed equal, the total inelastic cross section is $\sigma_{\text{inel}}=5.3\pm1$ mb. It is interesting to note that this value is small compared with the nucleon-nucleon inelastic cross sections. These cross sections[7] are 21±1 mb for the sum of the proton-proton inelastic reactions and 21±4 mb for the sum of the neutron-proton inelastic reactions at this energy.

The sum of the inelastic plus the annihilation cross sections at this energy has been measured[3] as 56±2 mb. Therefore the annihilation cross section is 51±3 mb.

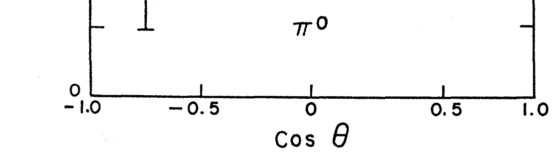

FIG. 3. Angular distribution of neutral pions from the reaction $\bar{p}+p\rightarrow\bar{p}+p+\pi^0$.

[3] T. Elioff, L. Agnew, O. Chamberlain, H. Steiner, C. Wiegand, and T. Ypsilantis, Phys. Rev. Letters **3**, 285 (1959); R. Armenteros, C. H. Coombes, B. Cork, G. R. Lambertson, and W. Wentzel, Phys. Rev. **119**, 2068 (1960).

[4] T. Elioff, thesis, University of California Radiation Laboratory Report UCRL-9288, 1960 (unpublished).

[5] S. J. Lindenbaum and R. M. Sternheimer, Phys. Rev. Letters **5**, 24 (1960).

[6] J. McConnell, Fordham University, New York (private communication).

[7] A. P. Batson, B. B. Culwick, J. G. Hill, and L. Riddiford, Proc. Roy. Soc. (London) **251**, 218 (1959). A. P. Batson, B. B. Culwick, H. B. Klepp, and L. Riddiford, Proc. Roy. Soc. (London) **A251**, 233 (1959).

Partly as a check on this method of measuring cross sections, we calculated the differential elastic cross section from the elastic events in this sample of connected events. In about 70% of these elastic events the recoil proton stopped in the chamber, and the scanning-table measurement of its range gave a determination of the center-of-mass angle to a precision of less than 1 deg. For those events in which the proton did not stop in the chamber, the accuracy of the center-of-mass angle determination was about 3 deg. Figure 2 shows how these measurements agree with previous measurements of the elastic-scattering differential cross section in the forward diffraction peak at this energy. In addition to these events in the forward peak, there were 10 events with center-of-mass angles fairly evenly distributed between 50 and 152 deg, and there were five events in the far backward region with center-of-mass angle greater than 152 deg, where the antiproton has such a low energy that it usually stops inside the chamber. The partial cross sections for these regions are $\sigma_{el}(50$ to 152 deg$)=1.4\pm0.5$ mb, and $\sigma_{el}(152$ to 180 deg$)=0.05\pm0.02$ mb.

TEST OF CHARGE-CONJUGATION INVARIANCE IN STRONG INTERACTIONS

Many experiments test parity conservation in strong interactions. But, as far as we know, there is still no experimental test of charge-conjugation invariance in strong interactions; that is to say, there is no published experimental result which is predicted by charge-conjugation invariance and is not also predicted by some other generally accepted symmetry principle.[8] Bernstein and Michel[9] have pointed out that one way of testing C conservation in strong interactions is to look for the decay of the π^0 into three photons. This decay mode is forbidden by charge-conjugation invariance. The experimental upper limit for the branching ratio for this decay mode is about 1%.[10] This limit is of insufficient accuracy to test C conservation in π^0 decay because one would expect the three-photon decay to be less than the two-photon decay by a factor of $e^2/\hbar c=1/137$ even if the C-conserving amplitude and the C-nonconserving amplitude were equal.

For an unpolarized beam and target, the $\bar{p}+p$ system is invariant under the operators CP or CR, where R is a rotation of 180 deg around any axis perpendicular to the direction of motion of both the p and $\bar{p}$. We assume R invariance to be true and therefore treat a test of CR as a test of C alone. For reaction (1), C and CP both make the following predictions in the center-of-mass system: (a) The angular distribution of the π^0 is symmetric about 90 deg; (b) the angular distribution of the proton is equal to the reflection of the angular distribution of the antiproton; and (c) the energy distributions of the proton and the antiproton are identical.

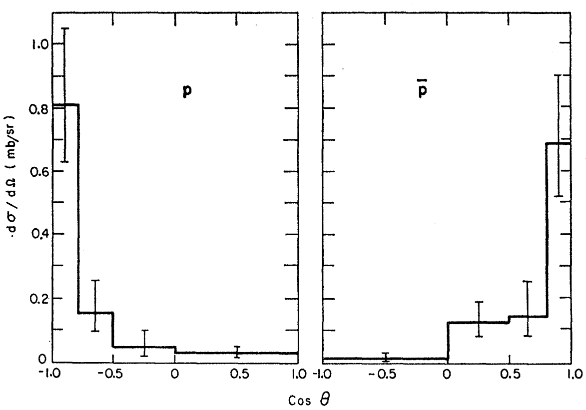

FIG. 4. Angular distributions of protons and antiprotons from the reaction $\bar{p}+p\rightarrow\bar{p}+p+\pi^0$.

Figures 3 and 4 show that the angular distributions agree very well with these predictions. The π^0 distribution seems to be isotropic. The other distributions are very anisotropic. The antiproton tends to go forward and the proton tends to go backward relative to the incident antiproton. Figure 5 is a Dalitz plot of the $\bar{p}+p+\pi^0$ events. There is fairly good agreement with the predictions of C and CP, which is that there will be symmetry about the diagonal line at which the proton and antiproton have the same energy.

The final states in reactions (2) and (3) are charge conjugates of each other. Pais has shown[11] that CP conservation predicts

$$W(E_{\bar{p}},\theta_{\bar{p}},E_n,\theta_n,\phi_{\bar{p}n})=W(E_p,\ \pi-\theta_p,\ E_{\bar{n}},\ \pi-\theta_{\bar{n}},\ \phi_{p\bar{n}}),$$

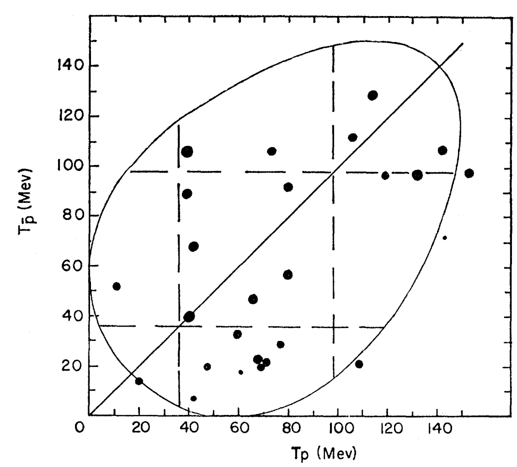

FIG. 5. Dalitz plot of $\bar{p}+p\rightarrow\bar{p}+p+\pi^0$. The area of each circle is proportional to the statistical weight assigned to the event. The dashed lines outline the horizontal and vertical bands corresponding to the energy of the recoil nucleon or antinucleon if an isobar in the 3-3 resonance is formed.

[8] Gerson Goldhaber has communicated to us that his group is making a test of charge-conjugation invariance by looking at the pions from antiproton annihilations in propane.

[9] J. Bernstein and L. Michel, Phys. Rev. 118, 871 (1959).

[10] R. P. Ely and D. H. Frisch, Phys. Rev. Letters 3, 565 (1959).

[11] A. Pais, Phys. Rev. Letters 3, 242 (1959).

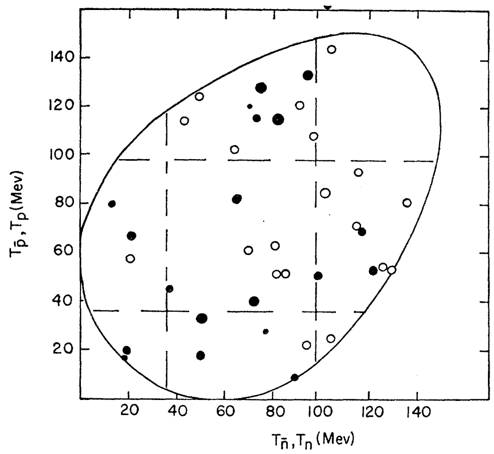

FIG. 6. Dalitz plot of the reactions $\bar{p}+p \rightarrow \bar{p}+n+\pi^+$ (solid circles) and $\bar{p}+p \rightarrow p+\bar{n}+\pi^-$ (open circles). The area of each circle is proportional to the statistical weight assigned to the event. The dashed lines are the same as those in Fig. 5.

and that CR conservation predicts

$$W(E_{\bar{p}},\theta_{\bar{p}},E_n,\theta_n,\phi_{\bar{p}n}) = W(E_p,\ \pi-\theta_p,\ E_{\bar{n}},\ \pi-\theta_{\bar{n}},\ -\phi_{p\bar{n}}),$$

where E and θ are the energy and center-of-mass angle; ϕ_{12} is the azimuthal angle in the plane normal to the incident antiproton direction between particle 2 and particle 1; $W(E_1,\theta_1,E_{21},\theta_2,\phi_{12})$ represents the relative probability of finding particles 1 and 2 with these energies and angles. By integrating over all or some of the variables we get the relations

$$\sigma(\bar{p}+n+\pi^+) = \sigma(p+\bar{n}+\pi^-).$$

$$W(E_{\bar{p}},E_n) = W(E_p,E_{\bar{n}}),$$

$$W(\theta_{\bar{p}}) = W(\pi-\theta_p);\quad W(\theta_n) = W(\pi-\theta_{\bar{n}})$$

as predictions of either C or CP. If CP is conserved, we have $W(\phi_{\bar{p}n}) = W(\phi_{p\bar{n}})$, whereas if C is conserved, we have $W(\phi_{\bar{p}n}) = W(-\phi_{p\bar{n}})$. In this analysis any two of the three particles could have been used. Therefore the prediction $W(\theta_{\pi^+}) = W(\pi-\theta_{\pi^-})$ is also made by C and CP.

We have already seen that the two cross sections are in agreement as predicted. Figure 6 is a Dalitz plot of

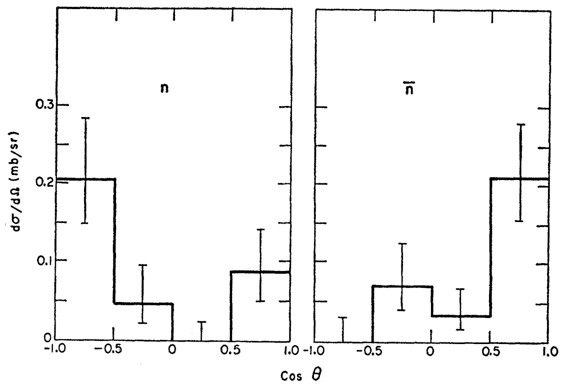

FIG. 8. Angular distributions of neutrons and antineutrons from the reaction $\bar{p}+p \rightarrow \bar{p}+n+\pi^+$ and $p+\bar{n}+\pi^-$.

these two reactions. A good many more events have a high-energy π^+ than have a high-energy π^-. However, the difference between the two distributions does not seem to be statistically significant. Figures 7–9 show the angular distributions of all the products of these reactions. The symmetries predicted by C and CR are observed.

In all the above tests the predictions of C and CP are identical. It is in the distribution in the angle ϕ that these predictions differ. Figure 10 shows the $\phi_{\bar{p}n}$ and the $\phi_{p\bar{n}}$ distributions. The prediction of C is that the two distributions should be reflections of each other. Within the statistics the data are in agreement with each of these predictions. Although these statistics do not make possible a very accurate test of charge conjugation, the results do illustrate a method for testing this symmetry principle in strong interactions.

INTERPRETATION OF THE RESULTS

A statistical-model calculation[6] predicts the ratio 4:5:5:4 for the cross sections of reactions (1), (2), (3), and (4). The isobaric model[5] predicts the ratio 2:1:1:2. To check how well our data agree with these predictions, we averaged the cross sections for reactions (2) and (3) (because these two must be equal by CP invariance)

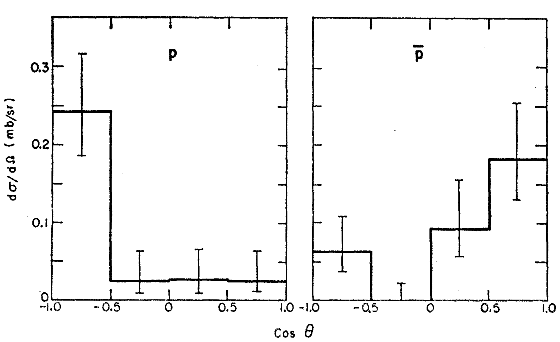

FIG. 7. Angular distributions of protons and antiprotons from the reactions $\bar{p}+p \rightarrow p+\bar{n}+\pi^-$ and $\bar{p}+n+\pi^+$.

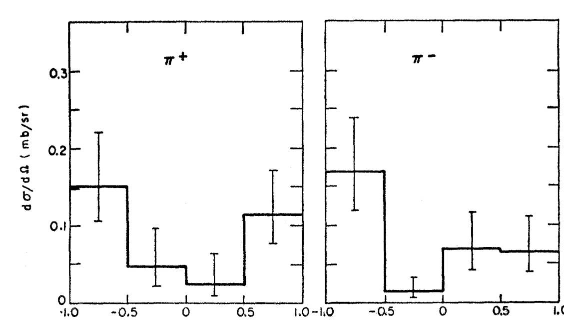

FIG. 9. Angular distributions of positive and negative pions from the reaction $\bar{p}+p \rightarrow \bar{p}+n+\pi^+$ and $p+\bar{n}+\pi^-$.

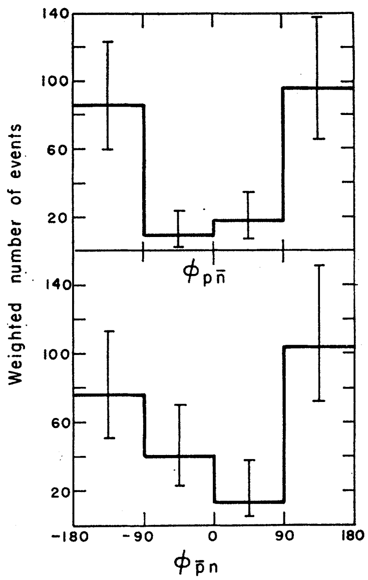

FIG. 10. Distributions in the angle ϕ for the reactions $\bar{p}+p\rightarrow\bar{p}+n+\pi^+$ and $p+\bar{n}+\pi^-$.

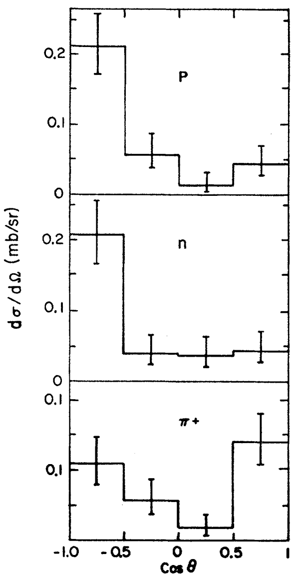

FIG. 11. Angular distributions of the products of $\bar{p}+p\rightarrow p+\bar{n}+\pi^-$ and $\bar{p}+n+\pi^+$ after combination according to the predictions of CR and CP.

and compared this average with the cross section for reaction (1). Our results are consistent with the isobar-model prediction, the probability being 0.36 that our data should deviate from the prediction of this model as much as they do. This confidence level corresponds to a discrepancy of 0.9 standard deviation for a Gaussian distribution. The data are rather inconsistent with the prediction of the statistical model, for which the probability is 0.026, which corresponds to a 2.2-standard-deviation discrepancy.

The Dalitz plots for the three reactions show a fairly uniform distribution of events. If a pion-nucleon (or pion-antinucleon) isobar corresponding to the 3-3 resonance were formed, the other antinucleon (or nucleon) would have a kinetic energy of 67 ± 31 Mev. This resonance is so broad that the horizontal and vertical bands which correspond to it (outlined by dashed lines on the plots) take up most of the area of the Dalitz plot. For this reason our energy distributions do not provide a very sensitive test of the isobar model.

In Fig. 11 the angular distribution of each particle has been combined with the angular distribution of its antiparticle in accordance with the predictions of C and CP. In this case the pions do not seem to be isotropically distributed. Just as in the $\bar{p}$-p-π^0 reaction, these reactions have the antinucleon going forward and the nucleon backward relative to the incident antiproton. The angular distributions of the protons and the neutrons look identical. This symmetry is not predicted by C, CP, nor charge independence alone. It would be predicted if the reactions proceeded through only one isospin channel, as is predicted in the isobaric model where the reaction must go through the $I=1$ channel. However, one could still obtain this symmetry if the reactions involved both the isospin channels (0 and 1) but there was no interference at any angle.

ACKNOWLEDGMENTS

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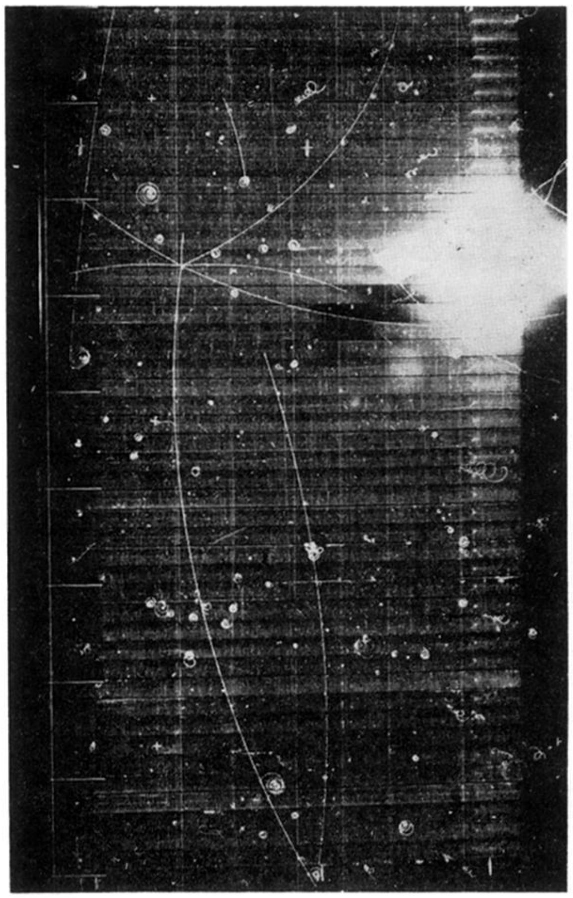

FIG. 1. A bubble chamber picture of one of the $\bar{p}+p \rightarrow \bar{p}+n+\pi^+$ events with the antiproton subsequently annihilating.