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Experimental Study of Double-Charged Pion Production in (π^-,p) Collisions at 900 MeV*

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Eight hundred and forty events of the kind $\pi^-+p\rightarrow\pi^-+p+\pi^-+\pi^+$ produced in the 20-in. BNL hydrogen bubble chamber by 900-MeV pions have been unambiguously identified using spatial reconstruction and kinematic fitting programs as well as ionization density estimates. The π^+,π^- and π^-,π^- combined mass distributions can be fitted by smooth curves, with no deviation beyond statistical fluctuations; no indication has been found of any prominent pion-pion resonance in this interaction, which covers a mass range up to 610 MeV. The π^+,p combined mass distribution differs markedly from the four-body phase-space curve, but can be well fitted by weighting the π^+,p total cross-section curve at each point according to the amount of phase space available for production of an isobar of corresponding mass. Assuming that the interaction proceeds exclusively via formation of the (π^+,p) isobar, one can get a good fit to the π^-,π^- mass spectrum. This isobar model is also consistent with all of the observed angle and momentum distributions for both pions and protons. The momentum distributions show no indication of any pion-pion-proton resonance in the range up to 1550 MeV, or of any three-pion resonance in the range up to 750 MeV. The cross section for the events studied was measured and found to be (0.33 ± 0.04) mb.

I. GENERAL DESCRIPTION OF THE INVESTIGATION

THE object of the investigation was to get experimental data on pion-pion interactions and other information obtainable from a study of double-charged pion production in (π^-,p) collisions at 900 MeV. The reaction studied was $\pi^-+p\rightarrow\pi^-+p+\pi^-+\pi^+$. Use was made of film taken with the 20-in. hydrogen bubble chamber at Brookhaven, exposed to a beam of negative pions of 1025 ± 10 MeV/c momentum (as determined from wire measurements).

About 100 000 pictures were scanned. Events with four outgoing visible prongs were measured, except those with obvious Dalitz pairs. The setting accuracy was of the order of 50 μ in space. The measured events were put through a spatial reconstruction program which computed the direction and momentum of each track at the production vertex, and which eliminated background events (for instance those in which the incident track was not a beam track). The remaining events were analyzed by means of a kinematic fitting program, including a modified version of GUTS.[1] The kinematic program was supplemented by ionization density estimates made on the scanning table, and used for identification of the positive tracks: At the energy used, protons can be differentiated from pions most of the time on the basis of bubble density of the track.

Of 1027 events which were put through the kinematic fitting program, 840 were identified without track ambiguity as $\pi^-+p\rightarrow\pi^-+p+\pi^-+\pi^+$; 15 were identified without track ambiguity as $\pi^-+p\rightarrow\pi^-+p+\pi^-+\pi^+ +\pi^0$; 2 were identified without track ambiguity as $\pi^-+p\rightarrow\pi^-+n+\pi^-+\pi^++\pi^+$; 6 were rejected because the positive tracks could not be identified unambiguously; 164 were rejected because they could not be identified with any of the previous reactions (a large number of them probably contained Dalitz pairs).

The 840 events which had been clearly identified as double-charged pion production were then analyzed by means of a histogram program specially devised for this study: Computations were made of all pion-pion and pion-proton combined masses, and of all momenta and angles in the center-of-mass system; histograms of the computed quantities were then plotted automatically.

II. A CHECK ON THE ACCURACY OF MASS DETERMINATION

It was desirable to check the over-all accuracy of the method of analysis, and to determine the resolution function of mass determination. To this effect, use was made of two hundred events in the same film which were known to correspond to the associated production reaction $\pi^-+p\rightarrow K^0+\Lambda^0$. These events were treated as if they were ordinary four-prong events: that is, the neutral tracks were disregarded and the decay tracks of the K^0 and Λ^0 were fitted to a common vertex. The

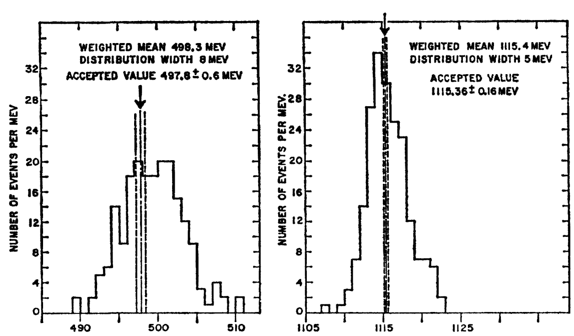

FIG. 1. Distributions of the K^0 and Λ^0 masses obtained from an analysis of 200 events known to be $\pi^-+p\rightarrow K^0+\Lambda^0$, and treated as ordinary four-prong events.

* This work is supported in part by the United States Atomic Energy Commission.
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[1] J. P. Berge, F. T. Solmitz, and H. D. Taft, University of California Radiation Laboratory Report UCRL-9097, 1960 (unpublished).

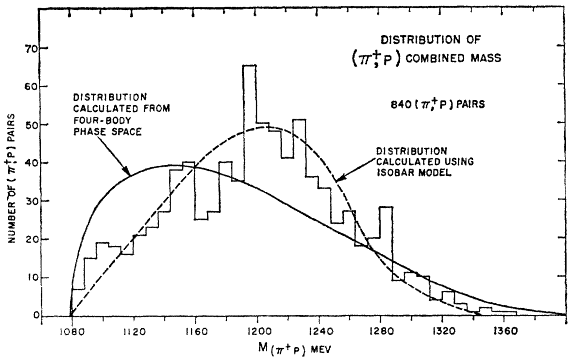

FIG. 2. Distribution of the combined masses for the 840 (π^+,p) pairs.

events were then put through the same programs as the regular four-prong events. The combined mass of any pion-pion pair coming from the decay of a K^0 should be equal to the mass of the K^0 particle, and the combined mass of any pion-proton pair coming from the decay of a Λ^0 should be equal to the mass of the Λ^0 particle.

Figure 1 shows the distributions of the K^0 and Λ^0 masses measured in the manner just described. The weighted means obtained were 498.3 MeV for the K^0 and 1115.4 MeV for the Λ^0; the distribution widths were 8 and 5 MeV (that is, ±4 and ±2.5 MeV). The measured masses agree with the accepted values (497.8 ± 0.6 and 1115.36 ± 0.16 MeV).[2] The resolution function of the experiment is indicated by the distribution widths given above; the 8 MeV for the K^0 mass corresponds to a Q value of 200 MeV, and the 5 MeV for the Λ^0 mass to a Q value of 40 MeV.

III. PION-PROTON MASS DISTRIBUTIONS

Figure 2 shows a histogram of the combined masses for the 840 (π^+,p) pairs. The solid curve represents the distribution calculated from the four-body phase space and normalized to the 840 events[3]; obviously it differs markedly from the data. The broken line represents a

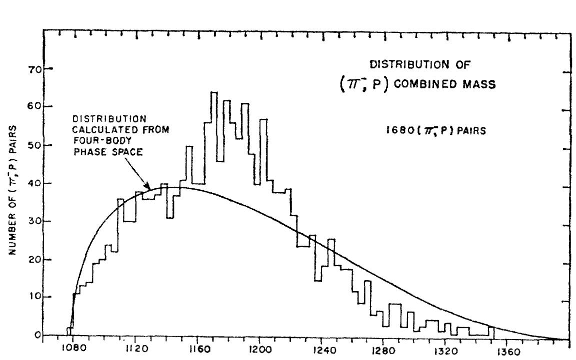

FIG. 3. Distribution of the combined masses for the 1680 (π^-,p) pairs.

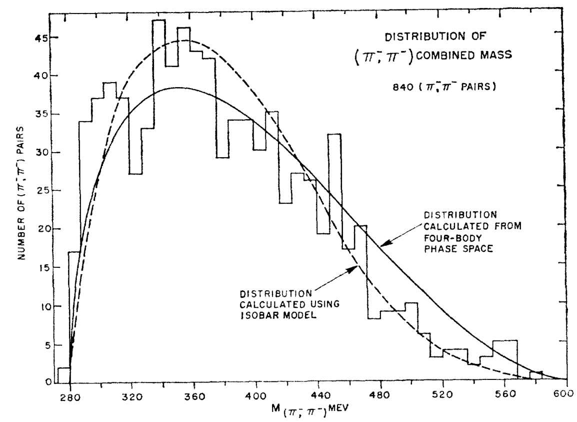

FIG. 4. Distribution of the combined masses for the 840 (π^-,π^-) pairs.

normalized distribution calculated assuming a (π^+,p) isobar model; it was obtained by weighting the π^+,p total cross-section curve, at each point, according to the amount of phase space available for production of an isobar of corresponding mass. This is similar to the method employed by Lindenbaum and Sternheimer in their calculations on pion production processes in N–N and π–N collisions.[4] The curve thus obtained fits the histogram very well; one may note that because of the weighting process described, it peaks below the 1240-MeV peak value of the $\frac{3}{2}$, $\frac{3}{2}$ resonance. It appears that the reaction studied can be considered to be dominated by isobar formation; that is, it proceeds in two steps: $\pi^-+p\rightarrow\pi^-+\pi^-+$isobar, and isobar$\rightarrow p+\pi^+$.

Figure 3 shows a histogram of the combined masses for the 1680 (π^-,p) pairs. The solid curve represents the distribution calculated from the four-body phase space and normalized to the 1680 events. The (π^-,p)

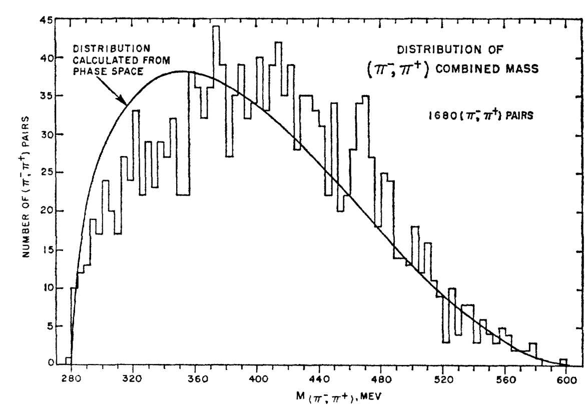

FIG. 5. Distribution of the combined masses for the 1680 (π^-,π^+) pairs.

[2] W. H. Barkas and A. H. Rosenfeld, in *Proceedings of the 1960 Annual International Conference on High-Energy Physics at Rochester*, edited by E. C. G. Sudarshan, J. H. Tinlot, and A. C. Melissions (Interscience Publishers, Inc., New York, 1960), p. 878.

[3] The four-body phase-space distributions of pion-proton and pion-pion masses shown in Figs. 2 to 5 were calculated and supplied to the authors by Dr. Theodore Kalogeropoulos. They were computed on the usual assumptions of Lorentz invariance and statistical distribution.

[4] S. J. Lindenbaum and R. M. Sternheimer, Phys. Rev. **105**, 1874 (1957); R. M. Sternheimer and S. J. Lindenbaum, *ibid.* **109**, 1723 (1958); **123**, 333 (1961).

histogram differs markedly from the four-body phase-space curve and also from the (π^+,p) histogram; if one accepts the (π^+,p) isobar model described previously, the discrepancies are accountable in terms of (π^-,p) kinematic correlations.

IV. PION-PION MASS DISTRIBUTIONS

The center-of-mass energy of the reaction is 1690 MeV; the upper limit of observable pion-pion combined masses is therefore 610 MeV.

Figure 4 shows a histogram of the combined masses for the 840 (π^-,π^-) pairs. The solid curve represents the

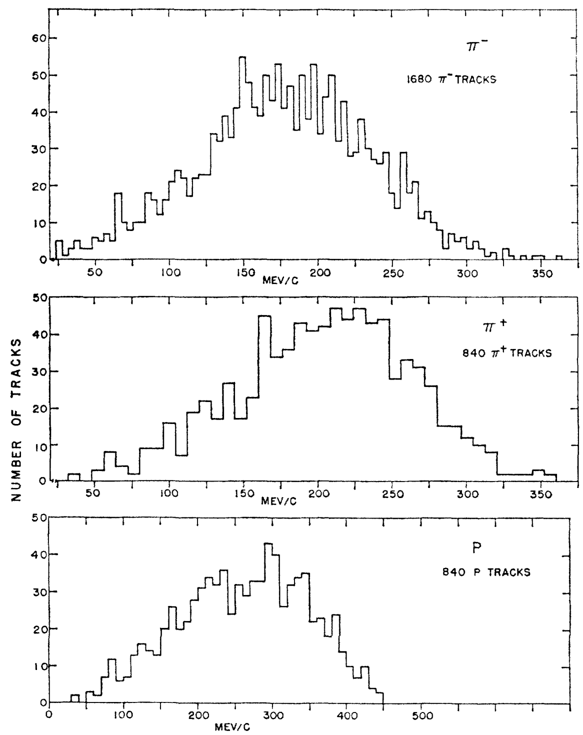

FIG. 6. Distributions of the momenta, in the center-of-mass system, of the outgoing negative pions, positive pions, and protons.

normalized distribution calculated from the four-body phase space. The broken line represents a normalized distribution calculated using the (π^+,p) isobar model described previously; it appears to fit the data better than the four-body phase space.

Figure 5 shows a histogram of the combined masses for the 1680 (π^-,π^+) pairs. The solid curve represents the normalized distribution calculated from the four-body phase space. The histogram differs markedly from the four-body phase-space curve, and also from the (π^-,π^+) histogram.

Both the (π^-,π^-) and (π^-,π^+) histograms can be fitted by smooth curves, with departures accountable as statistical fluctuations. There is no indication of any pion-pion resonance in the mass range up to 610 MeV in the reaction studied.

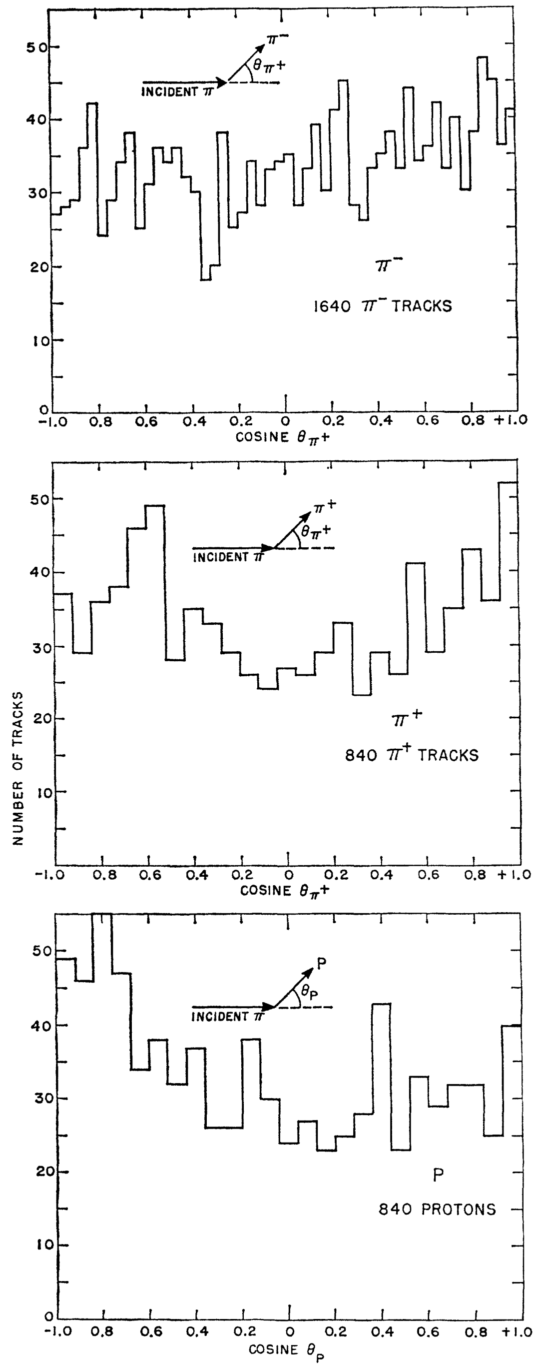

FIG. 7. Distributions of the angles, in the center-of-mass system, between the incident pion track and each outgoing track (negative pion, positive pion, and proton).

An anomaly at 310 MeV has been reported by Abashian, Booth, and Crowe, who studied the reactions $p+d\to He^3+\pi^++\pi^-$ and $p+d\to He^3+\pi^0+\pi^0$ at an incident proton energy ranging from 624 to 743 MeV[5]; and by Button *et al.*, who studied the reaction $\bar{p}+p\to$

[5] A. Abashian, N. E. Booth, and K. M. Crowe, Phys. Rev. Letters **5**, 258 (1960); **7**, 35 (1961); hereafter referred to as ABC.

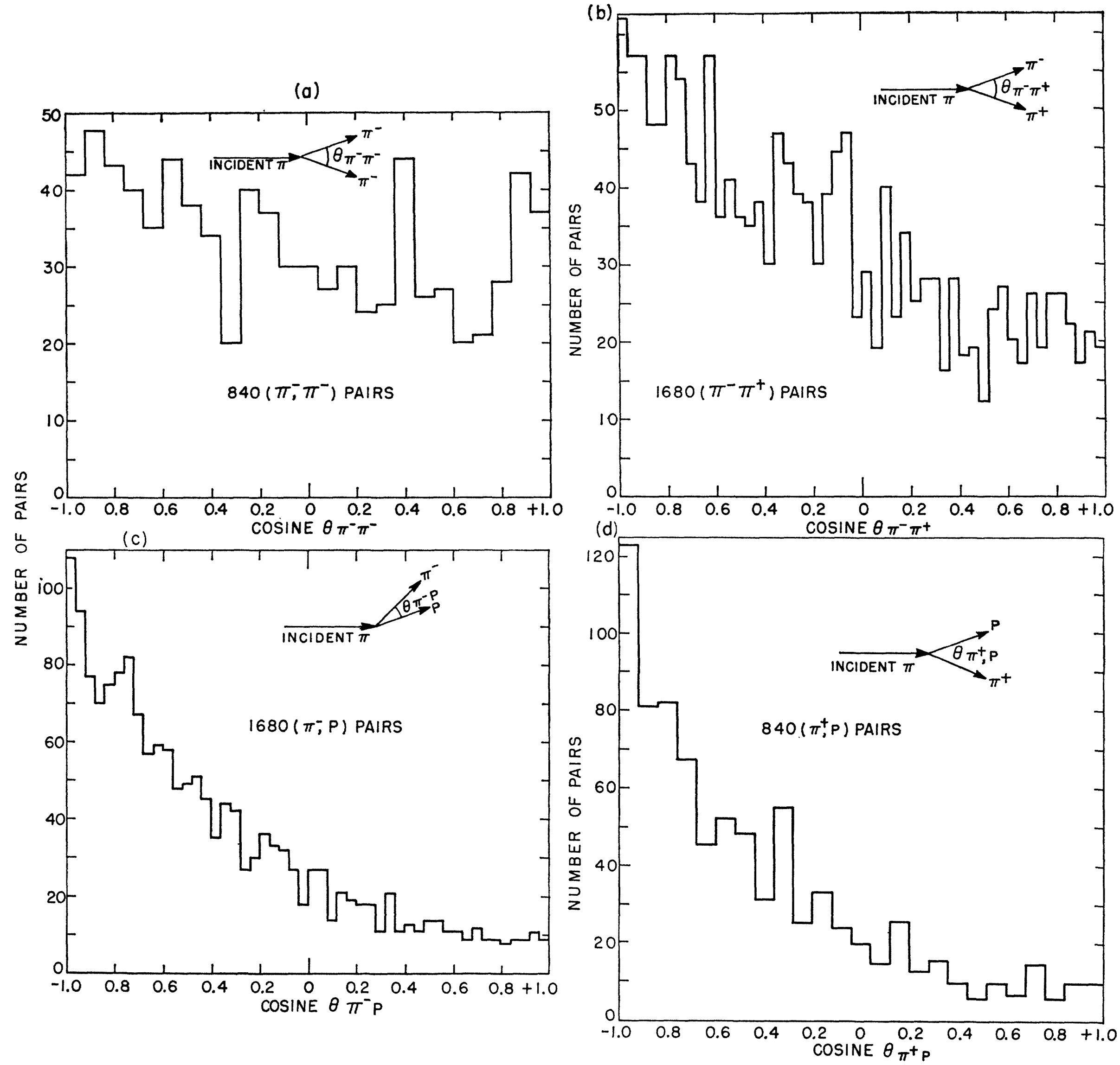

FIG. 8. Distributions of the angles, in the center-of-mass system, between the tracks of each pair of outgoing particles: (π^-,π^-), (π^-,π^+), (π^-,p), and (π^+,p).

$2\pi^+ + 2\pi^- + n\pi^0$ at an incident anti-proton momentum of 1.61 BeV/c.[6] A strong enhancement at a pion-pion mass above 340 MeV has been reported by Schwartz, Kirz, and Tripp, who studied the reactions $\pi^- + p \to \pi^- + \pi^+ + n$ and $\pi^+ + p \to \pi^+ + \pi^+ + n$ at an incident pion energy of 350 MeV.[7] A resonance at about 575 MeV has been reported by Barloutaud *et al.*, who studied the reactions $\pi^+ + p \to \pi^+ + \pi^0 + p$ and $\pi^+ + p \to \pi^+ + \pi^+ + n$ at incident pion energies of 820, 900, and 1050 MeV[8]; by Erwin *et al.*, who studied the reactions $\pi^- + p \to \pi^- + p + \pi^0$ and $\pi^- + p \to \pi^- + n + \pi^0$ at an incident pion energy of 1.89 BeV/c[9]; and by Zorn, who studied the reactions $p + p \to d + \pi^+ + \pi^0$ and $p + p \to d + \pi^+ + \pi^+ + \pi^-$ at an incident proton energy of 2.05 BeV.[10]

The ABC effect is believed to be due to an enhancement of the s-wave scattering; it is not considered as a resonance in the pion-pion system. Because of this, its effect might not be apparent in the present experiment since in the region of interest there are only about 20 (π^+,π^-) pairs per 4-MeV interval. At 350 MeV, there is no evidence for an enhancement of the kind reported

[6] J. Button, G. Kalbfleisch, G. R. Lynch, B. C. Maglić, A. H. Rosenfeld, and M. L. Stevenson, University of California Radiation Laboratory Report UCRL-9814, 1961 (unpublished).

[7] J. Schwartz, J. Kirz, and R. Tripp, Bull. Am. Phys. Soc. **7**, 282 (1962).

[8] R. Barloutaud, J. Heughebaert, A. Leveque, and J. Meyer, Phys. Rev. Letters **8**, 32 (1962).

[9] A. Erwin, R. March, W. Walker, and E. West, Phys. Rev. Letters **6**, 628 (1961).

[10] B. S. Zorn, Phys. Rev. Letters **8**, 282 (1962).

by Schwartz *et al.*, but as those authors point out their experiment was performed in a region where isobar production could not occur and therefore any rather weak pion-pion interaction might be expected to be more prominent in their data than in the present investigation. The resonance reported at about 575 MeV is close to the edge of the phase space in the reaction studied here, and there is a conspicuous lack of any enhancement in the region above 550 MeV. Preliminary results from a study of four-prong events by a group at Yale agree well with those obtained in the present investigation and in particular the π^+,π^- spectrum is essentially featureless when allowance is made for the dominant role played by isobar formation.[11]

V. MOMENTUM DISTRIBUTIONS

Figure 6 shows the momentum distributions, in the center-of-mass system, of the outgoing particles: negative pions, positive pions, and protons. The histograms can be fitted by smooth curves, with departures accountable as statistical fluctuations. A pronounced peak in the negative or positive pion momentum distribution would have suggested the possibility of some three-body pion-pion-proton resonance in the range up to 1550 MeV; similarly a pronounced peak in the proton momentum distribution would have suggested the possibility of a three-pion resonance in the range up to 750 MeV. There is no indication of such three-body resonances.

VI. ANGULAR DISTRIBUTIONS

Figure 7 shows the distributions, in the center-of-mass system, of the angles between the incident pion track and each outgoing track (negative pion, positive pion, and proton). The protons tend to peak backward as if they tend to retain their backward momentum; the result does not conflict with the picture of a (π^+,p) isobar intermediate state.

Figure 8 shows the distributions, in the center-of-mass system, of the angles between the tracks of each pair of outgoing particles: (π^-,π^-), (π^-,π^+), (π^-,p), and (π^+,p). The (π^-,π^+) and (π^-,p) distributions show that the negative pions tend to go in a direction opposite to that of either positive pion or proton. The result does not conflict with the isobar model previously described: The π^-,p collision first produces two negative pions and the isobar; in the center-of-mass system, the negative pions in general will tend to go in a direction opposite to that of the isobar, and, therefore, of the particles into which the isobar decays. The (π^+,p) distribution definitely shows a peak at 180 deg, which is consistent with the isobar model: the two particles into which the isobar breaks up go in opposite directions in the isobar's own center-of-mass system; since in the over-all center-of-mass system the isobar moves slowly, the directions of its decay products in that system will also tend to diverge.

[11] J. Sanford (private communication).

VII. CROSS SECTION

A measurement was made of the cross section for the events studied. This was done by counting events occurring in a chosen fiducial region and measuring the corresponding total beam track length, taking account of muon and electron contamination. The cross section was found to be (0.33±0.04) mb.

VIII. CONCLUSIONS

In the reaction $\pi^-+p\rightarrow\pi^-+p+\pi^-+\pi^+$, at an incident pion energy of 900 MeV, no indication has been found of pion-pion resonance in the range up to 610 MeV, or of pion-pion-proton resonances in the range up to 1550 MeV, or of three-pion resonances in the range up to 750 MeV. The reaction seems to be dominated by the formation of an intermediate (π^+,p) isobar. The first step is: $\pi^-+p\rightarrow\pi^-+\pi^-+$isobar; the second step is: isobar$\rightarrow\pi^++p$. The distributions of combined masses, center-of-mass momenta and angles are all consistent with the isobar model. The cross section was found to be (0.33±0.04) mb.

ACKNOWLEDGMENTS

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