Reaction $\pi^-+p \rightarrow \pi^-+\pi^++n$ from 360 to 800 MeV*†

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The reaction $\pi^-+p\rightarrow\pi^-+\pi^++n$ is studied in the Lawrence Radiation Laboratory's 72-in. hydrogen bubble chamber. Events are located by scanning the pictures for π^+ tracks. Cross sections, Dalitz plots, and $\pi^+\pi^-$ and $\pi^\pm n$ mass spectra are given at 360-, 430-, 460-, 480-, 555-, 605-, 673-, and 780-MeV beam energies. No clear evidence is found for $\pi^+\pi^-$ resonances between threshold and 680 MeV. However, there is a strong preference for high $\pi^+\pi^-$ effective masses, especially at the lowest beam energies. Arguments are given to ascrib this anomaly to the $I=0$ state of the $\pi-\pi$ system. The $N_{3/2}^*(1238)$ isobar is observed in its negative charge state. The angular distribution of its production is discussed.

In this paper we report the cross sections, angular distributions, and two-body mass spectra for the reaction

$$\pi^-+p\rightarrow\pi^-+\pi^++n \tag{1}$$

at beam energies of 360, 430, 460, 480, 555, 605, 673, and 780 MeV. At the lowest beam energies, the $\pi^+\pi^-$ mass spectra are strongly peaked near the upper kinematic limit. At higher beam energies, the 3-3 π-N resonance $N^*(1238)$ is the dominant feature of the reaction. No clear evidence is found for $\pi^+\pi^-$ resonances over the range 280 MeV$\leqslant M_{\pi\pi}\leqslant$680 MeV.

The Lawrence Radiation Laboratory 72-in. hydrogen bubble chamber was used in conjunction with π^- beams obtained through the channel designed for 1- to 2-BeV/c K^- mesons.[1] The 40 000 pictures analyzed yielded 300 to 600 events of reaction (1) at each of the 8 momenta.

This type of event can be easily identified on the scanning table in this energy region, because it is, essentially, the only one with two charged outgoing tracks in which the positive track is a π^+. As the beam momentum increases, visual separation becomes somewhat less efficient. This is due to lightly ionizing fast protons from reactions

$$\pi^-+p\rightarrow\pi^-+p \tag{2}$$

and

$$\pi^-+p\rightarrow\pi^-+\pi^0+p, \tag{3}$$

and also due to increasing contamination from

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

events.

To obtain a clean sample of events of reaction (1), the film was scanned twice, yielding an efficiency ranging from 98% at 360 MeV to 95% at 780 MeV; then each candidate was measured on the Franckenstein and processed on the track-reconstruction and fitting program Package. In about 15% of the cases the program was unable to make a definite and unique fit to any one of the reactions (1), (2), or (3). However, by looking at these events on the scanning table, it was possible to reduce the number of ambiguities to 1 to 3%.

To obtain cross sections for reaction (1), a special scan and second scan were performed on part of the film. This time, all interactions were recorded. After corrections for small-angle elastic scattering and for scanning efficiency, the total number of events found was normalized to counter measurements of the π^-p total cross section.[2] This method also allows us to determine the fraction of the total cross section that yields all neutral secondaries. The results are summarized in Table I.

The three-body data may be best analyzed by using Dalitz plots, because this method does not obscure the kinematic reflection of resonances in other pairings of final-state particles. Figure 1 shows the 360-MeV data; Fig. 2 shows the corresponding plot for 480 MeV. To facilitate quantitative observations in Figs. 3 and 4, we present projections of the Dalitz plots at each of the beam energies. These show the effective masses of the $\pi^+-\pi^-$ and $\pi^\pm-n$ systems. The curves correspond to

Table I. Cross sections.[a]

T^b (MeV)	σ_T (assumed)[c] (mb)	$\sigma_{\pi^-\pi^+n}$ (mb)	σ_{neutrals} (mb)
365	28.0	1.93±0.16	15.5±0.5
435	29.0	3.7 ±0.3	12.9±0.5
466	30.0	4.0 ±0.3	12.9±0.5
480	30.5	5.0 ±0.3	11.3±0.5
560	41.0	5.8 ±0.5	14.4±0.7
610	46.0	6.1 ±0.4[d]	12.9±0.6
678	39.0	6.1 ±0.6[d]	12.3±0.7

[a] Errors shown are statistical only.
[b] Beam energies are 5 MeV above those for the rest of the experiment because of the choice of a more restricted bubble chamber volume.
[c] See reference 2.
[d] The reaction $\pi^-+p\rightarrow\pi^-+\pi^++n+\pi^0$ occurs with an *additional* ≈0.5 mb at these energies, whereas its contribution below 560 MeV is less than 0.1 mb. Note that threshold for the process $\pi^-+p\rightarrow\eta+n$ is near 560 MeV.

* Work done under the auspices of the U. S. Atomic Energy Commission.

† *Note added in proof*. For a more detailed account of this experiment see Janos Kirz (Ph.D. thesis), Lawrence Radiation Laboratory Report UCRL-10720, 1963 (unpublished).

[1] We wish to thank Professor Harold K. Ticho, Dr. George R. Kalbfleisch, Dr. Janice B. Shafer, and other members of the K^- experiment for their help and use of the beam, and Professor Frank S. Crawford, Jr., for providing the 780-MeV film.

[2] We used the data obtained by J. C. Brisson, J. F. Detoeuf, P. Falk-Vairant, L. Van Rossum, and G. Valladas, Nuovo Cimento 19, 210 (1961), and T. J. Devlin, B. J. Moyer, and V. Perez-Mendez, Phys. Rev. 125, 690 (1962).

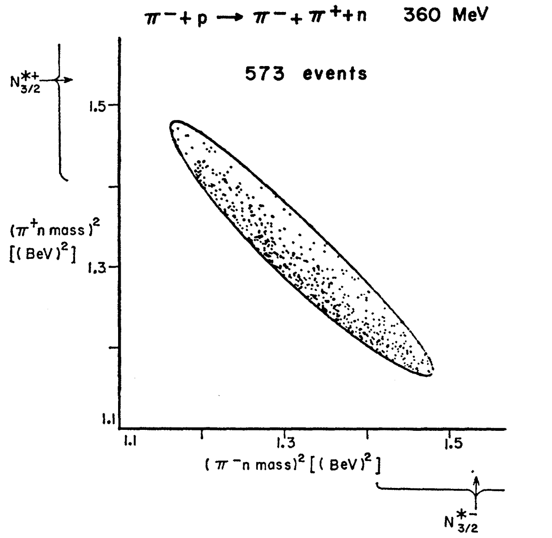

FIG. 1. Dalitz plot for reaction (1) at 360-MeV beam energy. The position and width of $N^*(1238)$ are indicated in both charge states.

phase-space prediction (uniform population on the Dalitz plot).

Consider first the data in terms of the di-pion pairing. The most striking effect in Fig. 3 is the very significant deviation from phase space that appears strongly at the lowest beam energy. The production process favors di-pions of a mass $M_{\pi\pi} \approx 400$ MeV. This behavior has been noted previously in this and other experiments.[3–5]

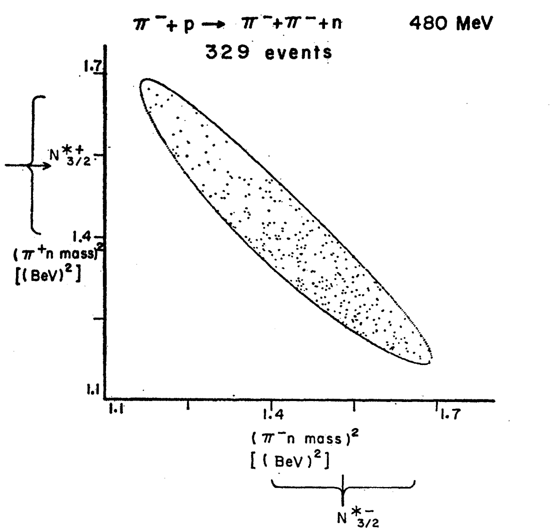

FIG. 2. Dalitz plot for reaction (1) at 480-MeV beam energy. The position and width of $N^*(1238)$ are indicated in both charge states.

A similar effect has been observed near this beam energy in the reaction[4] $\pi^- p \rightarrow \pi^0 \pi^0 n$ but not in the reaction[6] $\pi^- p \rightarrow \pi^- \pi^0 p$ nor in the reaction[7] $\pi^+ p \rightarrow \pi^+ \pi^+ n$; this leads to the conclusion that the $I=0$ state of the di-pion system plays an important role in the anomaly. This view is further supported by the observation that the di-pion channels, in which the effect is observed, are much more copiously produced than are the latter two channels. The simplest interpretation of this anomaly

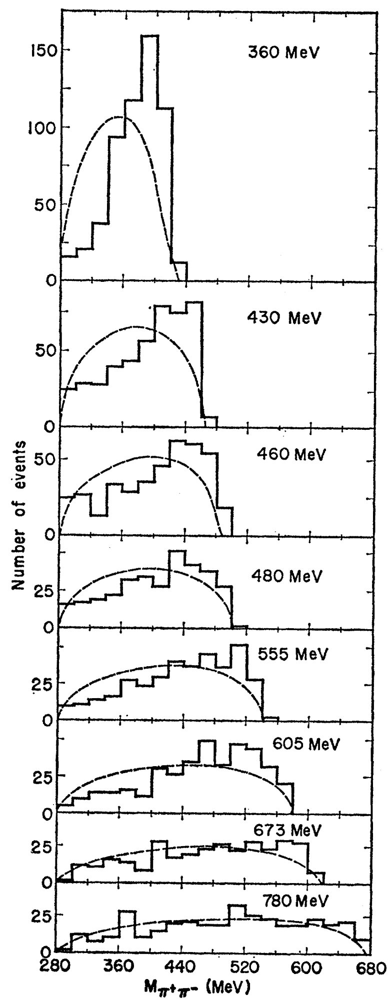

FIG. 3. $\pi^+\pi^-$ effective-mass distribution at each beam energy. The dashed curves represent phase space.

would be in terms of a strong di-pion interaction or a resonance in this mass region, as suggested by other

[3] J. Kirz, J. Schwartz, and R. D. Tripp, Bull. Am. Phys. Soc. **7**, 48 (1962); J. Schwartz, J. Kirz, and R. D. Tripp, *ibid.* **7**, 282 (1962).

[4] B. C. Barish, R. J. Kurz, V. Perez-Mendez, and J. Solomon, Bull. Am. Phys. Soc. **7**, 280 (1962); R. J. Kurz, thesis, Lawrence Radiation Laboratory Report UCRL-10564, 1962 (unpublished).

[5] L. I. Lapidus, in *Proceedings of the 1962 International Conference on High-Energy Physics at CERN* (CERN, Geneva, 1962), p. 115.

[6] B. C. Barish, thesis, Lawrence Radiation Laboratory Report UCRL-10470, 1962 (unpublished).

[7] J. Kirz, J. Schwartz, and R. D. Tripp, Phys. Rev. **126**, 763 (1962).

experiments.[8,9] However, as one proceeds to the higher beam energies, the enhancement, rather than remaining at the same di-pion mass, continues to appear near the kinematic limit as it diminishes in strength. We have no explanation for this behavior.

In view of the evidence for another strong $I=0$ interaction at a mass in the vicinity of the di-pion threshold (280 MeV),[10] a π-π cross-section calculation for

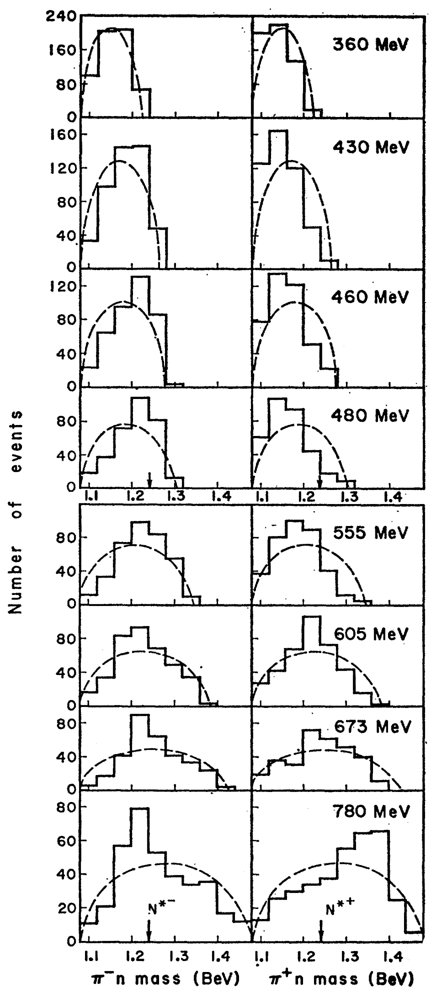

FIG. 4. π^+n and π^-n effective-mass distribution at each beam energy. The dashed curves represent phase space. The arrows point to the position of the N^* mass of 1238 MeV.

$M_{\pi\pi}<340$ MeV was made by using the one-pion-exchange model and utilizing the data in the physical region up to a momentum transfer $p^2=6$. Results from

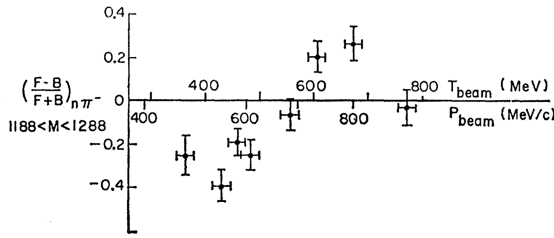

FIG. 5. The ratio $(F-B)/(F+B)$ for events with $1188 \leqslant M_{\pi^-n} \leqslant 1288$. F stands for the number of events for which the π^-n system is produced forward in the reaction center-of-mass system, B for those produced backward.

different beam energies ranged from 20 to 130 mb and corresponded to an $I=0$ scattering length of 0.6 to 1.5 F. Such a lack of agreement is to be expected on the basis of evidence for more complex phenomena such as isobar production discussed below. However, our lowest beam energy is slightly below $N^*(1238)$ threshold. Here the scattering length appears smallest and we find no evidence supporting a strong di-pion interaction near $M_{\pi\pi}=280$ MeV.

Let us now turn to the π-n pairings. Effects of $N^*(1238)$ are most clearly seen from the projections of Fig. 4. Production of the negatively charged isobar can be observed at every beam energy above N^* threshold. There is no evidence for production of the positive isobar, the enhancements at other π^+n masses being a reflection of N^{*-}. For production purely through an initial $I=\frac{1}{2}$ state a ratio $N^{*-}/N^{*+}=9$ is expected, although a suitable admixture of $I=\frac{3}{2}$ amplitude can lower or increase this ratio, depending on its relative phase. Since N^* is broad, it is difficult to estimate the fraction of pion production proceeding through isobar formation. At some energies it appears to be the dominant mechanism.

An analysis of pion production purely through isobar formation has recently been made by Olsson and Yodh.[11] This more complete treatment of the isobar model appears to reproduce deviations in π-N mass spectra. It also accounts for di-pion mass distributions in most charge states[12] but fails to account for the $\pi^+\pi^-$ spectra observed in this experiment.

By selecting those events for which the π^-n effective mass is 1238 ± 50 MeV, we obtain a sample in which the effects of the isobar appear most strongly. For these we assume a two-body production: $\pi^-p \rightarrow N^{*-}\pi^+$. As can be seen from Fig. 5, these "isobars" prefer the backward direction below 500 MeV, whereas around 600 to 700 MeV the majority is produced in the forward

[8] V. P. Samios, A. H. Bachman, R. N. Lea, T. E. Kalogeropoulos, and W. D. Shephard, Phys. Rev. Letters **9**, 139 (1962).

[9] C. Richardson, R. Kraemer, M. Mur, N. Nussbaum, A. Pevsner, R. Strand, T. Toohig, and M. Block, in *Proceedings of the 1962 International Conference on High-Energy Physics at CERN* (CERN, Geneva, 1962).

[10] N. E. Booth, A. Abashian, and K. M. Crowe, Phys. Rev. Letters **7**, 35 (1961). N. E. Booth, Lawrence Radiation Laboratory Report UCRL-10410, 1963 (unpublished).

[11] M. Olsson and G. B. Yodh, Bull. Am. Phys. Soc. **8**, 68 (1963); and Phys. Rev. Letters **10**, 353 (1963).

[12] C. N. Vittitoe, W. J. Fickinger, V. P. Kenney, J. G. Mowat, and W. D. Shephard, Bull. Am. Phys. Soc. **8**, 67 (1963); G. B. Yodh, T. B. Day, G. Quareni, A. Quareni-Vignudelli, R. A. Burnstein, J. Ashkin, I. Nadelhaft, and J. Oliver, *ibid.* **8**, 68 (1963); P. Newcomb, thesis, Lawrence Radiation Laboratory Report UCRL-10563, 1962 (unpublished); C. P. Poirier, E. D. Alyes, Jr., H. J. Martin, C. A. Tilger, Bull. Am. Phys. Soc. **8**, 68 (1963).

hemisphere. Since this change occurs in the energy region of the second nucleon isobar, $N^*(1512)$, it may perhaps be due to an interference between the rapidly varying resonant amplitude and nonresonant states of opposite parity.

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Extrapolation Methods and the Nucleon-Deuteron Breakup Reaction*

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The Chew-Low extrapolation as applied to the nucleon-deuteron breakup reaction is studied. Singularities of the amplitude and cross sections are located using perturbation theory and simple final-state interaction theory. The measured cross sections, whose kinematic singularities are exhibited, are expressed in terms of the invariant Chew-Low cross sections. The experimental procedure is outlined, and forms are suggested for the fitting curves.

1. INTRODUCTION

SINCE the paper of Chew and Low,[1] single-particle exchange models have been much exploited. One of the applications they suggested was to the determination of n-n scattering observables from n-d scattering: The differential or total n-n cross section could be found from the residue of a pole in the corresponding cross sections for the process $n+d\rightarrow n+p+n$. Some indication as to the practicality of this idea can be found by looking at the analogous reaction $p+d\rightarrow n+p+p$, using it to determine, in this way, the (known) p-p cross sections. This experiment is being done by Griffiths and Batty,[2] using the 30–50 MeV LINAC at the Rutherford Laboratory, Harwell. A modified Chew-Low procedure has already been used by Kuckes *et al.*,[3] and agrees qualitatively with the data.

The pole, which is of second order, occurs in a momentum transfer variable Δ^2; there is also a first-order pole at the same point. Apart from these, the cross section is, for purposes of extrapolation, usually expressed as a polynomial in Δ^2. But this is only justified if there are no other singularities in Δ^2 inside a circle, whose center is the Chew-Low pole, including a substantial part of the physical region. In other words, it will be difficult to separate out the effect of the single-particle exchange term if other processes are equally important in the same region of phase space: Rather, one ought to include terms in the extrapolation, or fitting, curve—for instance, additional poles—to take account of these processes.

The possibility of such singularities is something that can be examined, to some extent, theoretically. For example, Landshoff and Treiman[4] have pointed out that a three-point graph (see Sec. 3) could prejudice the determination of the $\pi\pi$ cross section from the $\pi p\rightarrow\pi\pi p$ data. The first step is to locate the singularities of the amplitude T; this is done in Sec. 3, in which poles, 2- and 3-point graphs are analyzed, and contributions from final-state interactions considered. In Sec. 4 the cross sections are defined in terms of T, and some of their singularities found.[5] Sections 3 and 4 use the kinematical results of Appendix A, which are dealt with descriptively in Sec. 2.

The conclusion of this analysis, so far as it goes, is that certain regions of phase space are likely to be "dangerous," being strongly influenced by final-state interactions. In Sec. 5 we show how to avoid these regions, treating in particular Griffith's experiment. Kinematical singularities are eliminated, and suggestions offered on the form of extrapolation curve to be used near the dangerous regions. No account of polarization effects is given.

2. NOTATION AND KINEMATICS

A.

For the five-particle process [Fig. 1(a)]

$$1+6\rightarrow 3+4+5$$

there are ten possible scalar products $p_ip_j(i\neq j)$ which

* Based, in part, on a thesis submitted to Cambridge University for the degree of Ph.D. Work performed partially under the auspices of the U. S. Atomic Energy Commission.

[1] G. F. Chew and F. E. Low, Phys. Rev. **113**, 1640 (1959), referred to as C-L.

[2] R. J. Griffiths and C. J. Batty (private communication).

[3] A. F. Kuckes, R. Wilson, and P. F. Cooper, Jr., Ann. Phys. (N. Y.) **15**, 193 (1961).

[4] P. V. Landshoff and S. B. Treiman, Nuovo Cimento **19**, 1249 (1961).

[5] I. T. Drummond, in a preprint received after this work was done, has also considered this problem.