Interactions at High Energies, Stanford University (to be published); M. Braunschweig, D. Husman, K. Lübelsmeyer, and D. Schmitz, Phys. Letters 22, 705 (1966).

[15]H. Primakoff, Phys. Rev. 81, 899 (1951); see also C. Chiuderi and G. Morpurgo, Nuovo Cimento 19, 497 (1961); V. Glaser and R. A. Ferrell, Phys. Rev. 121, 886 (1961); S. M. Berman, Nuovo Cimento 21, 1020 (1961). For π^0 lifetime, we took the value $(0.74 \pm 0.11) \times 10^{-6}$ sec given by G. Belletini, C. Bemporad, P. L. Braccini, and L. Foa, Phys. Letters 18, 333 (1965).

[16]This behavior is accounted for by the presence of ω exchange in Regge-pole fits. For a recent discussion see J. P. Adler, M. Capdeville, and Ph. Salin, to be published.

DI-PION PRODUCTION IN HIGH-ENERGY $\pi^- p$ COLLISIONS*

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(Received 15 September 1967)

We report here the observation of the two processes $\pi^- + p \to \pi^- + \pi^0 + p$ and $\pi^- + p \to \pi^- + \pi^+ + n$ at bombarding energies of 7.0 and 25 BeV. A process in which the nucleon is dissociated seems to be present at 7.0 BeV and is dominant at 25 BeV. Arguments are presented to show that the results are consistent with diffraction dissociation.

We present here results of experiments with 7- and 25-BeV/c π^-. The experiments were done using the 30-in. Midwestern Universities Research Association-Argonne National Laboratory chamber and the 80-in. Brookhaven National Laboratory chamber.

Our data are very similar in several respects to counter data obtained by various groups at CERN and at Brookhaven.[1] In those experiments high-energy protons and π's are incident on target protons, but of the final-state particles, only the high-energy scattered particle is detected. Thus a "missing-mass" spectrum is obtained. It was found that the missing-mass spectrum is very dependent on the momentum transfer between the incident and outgoing particle. The counter experiments have detected a peak in the missing-mass spectrum at 1.4 BeV/c^2 which has been identified with the P_{11} resonant state of the nucleon. This peak is prominent only for small momentum transfers. In the case of the data presented here, we have made cuts on the momentum transfer between incoming and outgoing π^-.

At low energies, studies of the reactions (a) $\pi^- + p \to \pi^- + \pi^+ + n$ and (b) $\pi^- + p \to \pi^- + \pi^0 + p$ are dominated by the production of the ρ meson in the one-pion-exchange process. As the bombarding energy is increased, the cross section for the one-pion-exchange process should fall approximately as $1/p_{\mathrm{lab}}^2$.

That ρ^0 and f^0 production actually is less important at higher energy can be surmised by examining the Dalitz plots in Fig. 1. In the plot of the 7-BeV/c data one can see the familiar ρ^0 and f^0 bands. However, in the 25-BeV/c data the production of ρ and f^0 while present is less important than the process giving rise to the low-mass π-nucleon combination.

In Fig. 2, we show the projections from the Dalitz plot on the π^+-n and π^0-p axes. At both the energies the π-nucleon mass distribution is peaked in the 1.3-to 1.4-BeV region. There is also some enhancement in the energy region of the well-known $I = \frac{1}{2}$ states at 1520 and 1688 MeV/c^2. The curve shown is a slight modification of an expression given by Stodolsky.[2]

If we have the production of an $I = \frac{1}{2}$ state, we expect a 2:1 ratio for the production of π^+-n and π^0-p states. In the region of the peak at 1.35 BeV this 2:1 ratio does not seem to hold at either energy. This could result from an impure sample of events produced by measuring difficulties at high momentum. However, a nonunique isospin might be anticipated if the π-nucleon state were produced through diffraction dissociation of the nucleon.[3]

The energy dependence of the amplitude for the process giving rise to the low-mass π-nucleon state is of importance in determining the nature of the process. In comparing the cross sections at the two different energies we compare the processes for $\pi^- + p \to \pi^- + \pi^+ + n$ and take events for which the π^+-n mass is less than 1.4 BeV/c^2. The cross section is found to fall by a factor of 1.4 ± 0.3 as the energy is increased from 7.0 to 25 BeV. When we look at the process $\pi^- + p \to \rho^0 + n$, we find a decrease of 7 ± 2 in the cross section for the corresponding energy increase.

One of the characteristics of the 1.4-BeV/c^2 mass region found by the counter groups is the rapid decrease in cross section with momentum transfer to the missing mass.[1] If we look at the momentum-transfer spectrum $\pi_{\text{in}}^- \to \pi_{\text{out}}^-$ at 7 BeV, we find that $d\sigma/d\Omega$ can be represented by an $e^{\alpha t}$ dependence. The constant α is very dependent on the π-nucleon mass. α varies from 15 $(\text{BeV}/c)^{-2}$ at 1.1 $(\text{BeV}/c)^2$ to 5 $(\text{BeV}/c)^{-2}$ at 1.5 $(\text{BeV}/c)^2$. This would seem to be an important signature of the production process.

Figure 3 gives the π-π angular distribution in the ρ^0 region at 7 BeV. We show the angular distribution in the π^--π^+ c.m. system corresponding to masses just below, just above, and overlapping the ρ. For the mass interval overlapping the ρ there is a very large sharp spike in the forwardmost angular interval. This spike does not appear in the adjacent intervals and is not consistent with the usual $\cos^2\theta$-dominated distributions expected in the energy region of the ρ. (See the recent tabulation of Walker et al.[4] for comparison.) We interpret this to be the result of interference between the ρ production amplitude and that amplitude giving rise to the π-nucleon state. The interference shows that this amplitude is dominantly imaginary since it interferes with the one-pion-exchange amplitude in the region where the π-π scattering amplitude has a large imaginary part.

We believe that the process giving rise to low-energy π-nucleon pairs is diffraction dissociation of the nucleon. This sort of process was first proposed by Feinberg and Pomerančuk[5] and Good and Walker.[3] Quantitative calculations on these sorts of processes have been made by Ross and his collaborators,[6] Stodolsky,[2] and others.[7-9]

The reasons that we can give for believing that the process is a diffraction process are as follows:

(1) The cross section for the production of the π-nucleon state falls very slowly with increasing energy. If the π-nucleon diffraction scattering is independent of energy, then the cross section for the diffraction dissociation should be nearly constant.

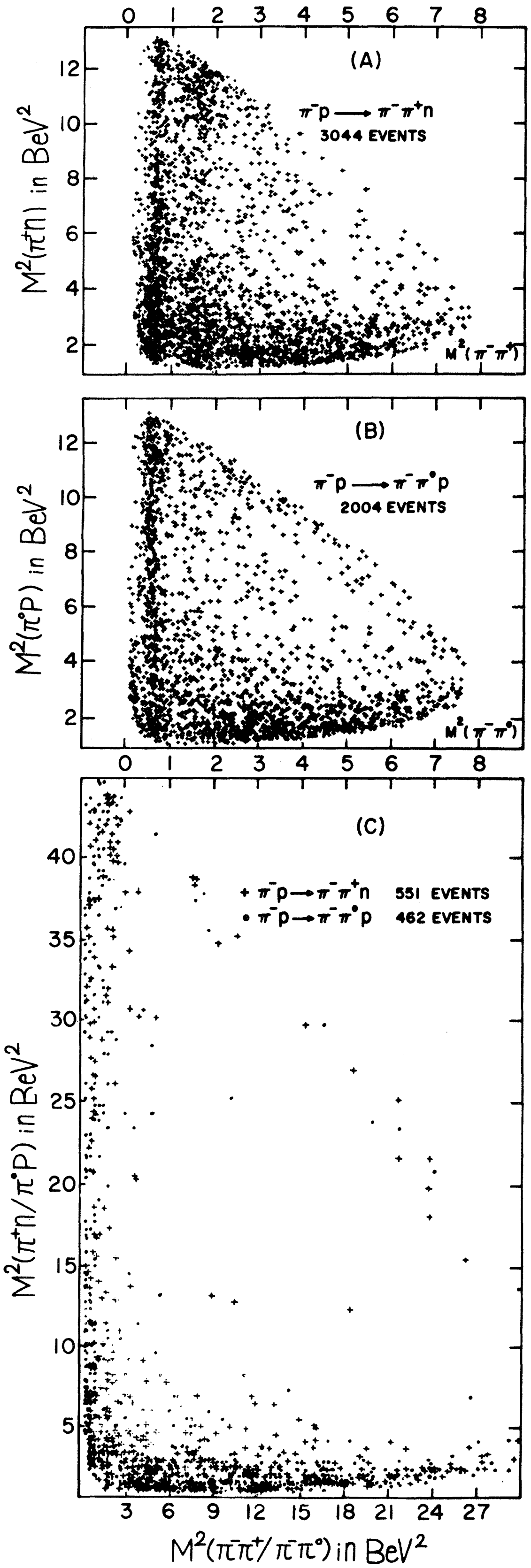

FIG. 1. Dalitz plots for the two processes (a) and (b) at 7 BeV/c and a combined plot for the data (c) at 25 BeV/c.

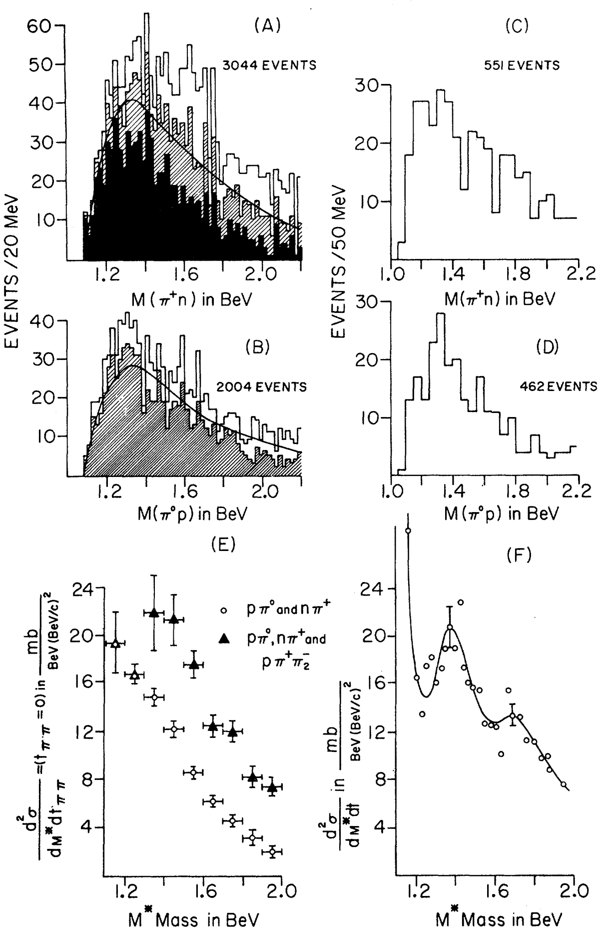

FIG. 2. Mass spectra of π+nucleon. (a), (b) $M(\pi^+n)$ and $M(\pi^0p)$ at 7 BeV/c. Shaded (cross-hatched) events correspond to center-of-mass cosine of beam-π^- scattering angle greater than 0.95 (greater than 0.98). The solid line is an arbitrarily normalized curve of an expression, a slight modification of one given by Stodolsky (Ref. 2): phase space $\times \vec{q} \times \exp(-\alpha t_0^2)/t_0^2$, where $t_0 = (M_{\pi N}^2 - M_p)/(2P_{\mathrm{lab}})$, and $\vec{q}$ is the momentum of π in a π-N rest frame. We used $\alpha = 9(\mathrm{GeV}/c)^{-2}$. (c), (d) $M(\pi^+n)$ and $M(\pi^0p)$ at 25 BeV/c. (e) $\partial^2\sigma/\partial M_{\pi N}\partial t_{\pi\pi}$, extrapolated to $t_{\pi\pi}=0$ using $e^{\alpha t}$ fit, at 7 BeV/c. Also shown are $\partial^2\sigma/\partial M_{\pi N}t_{\pi\pi} + \partial^2\sigma/\partial M_{\pi\pi p}\partial t_{\pi\pi}$ at $t_{\pi\pi}=0$. The second term comes from the process $\pi^-p \to \pi^-(\pi_2^-\pi^+p)$. (f) Data of K. J. Foley et al., Phys. Rev. Letters 19, 397 (1967), redrawn for comparison. This corresponds to $\pi^-p \to \pi^-(M^*)$ at 26.23 BeV/c, with c.m. scattering angle 5-10 mrad.

(2) The general shape of the mass spectrum is in qualitative agreement with an expression dominated by a factor[2] $(M^{-2} - M_N^2)^{-2}$.

(3) The dependence of the matrix element on momentum transfer is very strong, which is more characteristic of diffraction scattering than of some exchange process (ρ exchange).

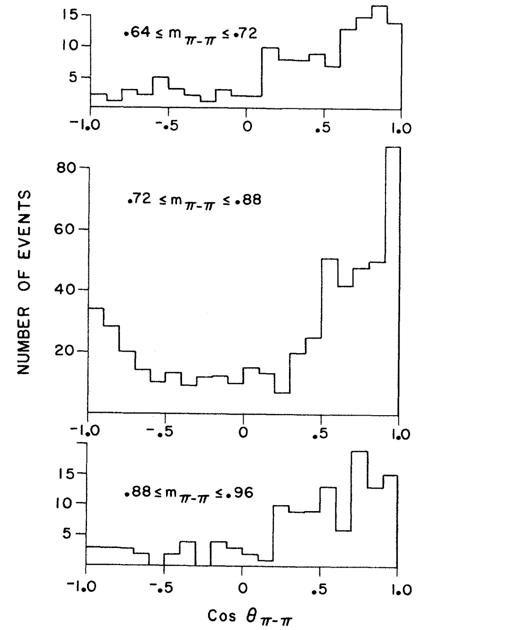

FIG. 3. Angular distribution for events in the ρ^0 region from 7-BeV/c data. $\theta_{\pi\pi}$ is the scattering angle of π^- in the di-pion center of mass with respect to beam.

(4) In the production processes considered here there are at least three important amplitudes (for explicit calculations, see the paper of West et al.[7]), one of which is the one-pion-exchange amplitude and two others involving a diffraction scattering. The diffraction amplitudes always have one diffraction-scattering vertex which, of course, is practically a pure imaginary amplitude. The observation of interference with the ρ production is thus consistent with the diffraction-dissociation model.

(5) The angular distribution of the π^+ in the π^+-n rest frame is strongly warped by the overlap with the ρ^0 and f^0 production amplitudes. If we remove those events we find a distribution which is nearly isotropic. Thus we seem to have the production of a $\frac{1}{2}^+$ or $\frac{1}{2}^-$ state. Such states would be preferentially produced according to the diffraction-dissociation picture.

Foley et al.[10] have noted the bump at 1.4 $(\mathrm{BeV}/c)^2$ in their missing-mass spectrum and noted that this indicates resonance production of the 1.4-$(\mathrm{BeV}/c)^2$, $\frac{1}{2}^+$ state. Although the data in our two experiments agree, we disagree with their conclusion in the following sense. It may be true that a resonant bump (such as the Roper resonance[10]) appears superimposed on this large background which is produced by the diffraction-dissociation mechanism. The fact that a bump appears invariant with respect to bombarding energy and particle should be true for the diffraction process as well as for resonance production. The data indicate production of a state of indefinite isospin which is also discouraging for a picture of pure resonance production.

We wish to express our gratitude to Dr. W. Fowler, Dr. H. Foelsche, Dr. R. Louttit, and Dr. R. Shutt for their cooperation and help with the 80-in. chamber and beam at Brookhaven. At Argonne we had the help and cooperation of J. Mark, R. Picha and Dr. L. Voyvodic in the course of two runs. We also wish to express our thanks to Miss Leah Arbelada for her help in the scanning measuring process.

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*Work supported in part by the U. S. Atomic Energy Commission under Contract No. AT(11-1)-881, COO-881-122.

[1]G. Bellettini, G. Cocconi, A. N. Diddens, E. Lillethun, J. P. Scanlon, A. M. Shapiro, and A. M. Wetherell, Phys. Letters 18, 167 (1965); E. W. Anderson, E. J. Bleser, G. B. Collins, T. Fujii, J. Menes, F. Turkot, R. A. Carrigan, R. M. Edelstein, N. C. Hien, T. J. McMahon, and I. Nadelhaft, Phys. Rev. Letters 16, 855 (1966).

[2]L. Stodolsky, Phys. Rev. Letters 18, 973 (1967).

[3]M. L. Good and W. D. Walker, Phys. Rev. 120, 1857 (1960). In this paper it was noted that isospin should be conserved in a diffraction dissociation process. This would be true if the absorptive processes giving rise to the diffraction dissociation are isospin independent. If any of these absorptive processes are isospin dependent, then the diffraction dissociation products will not have a definite isospin.

[4]W. D. Walker, J. Carroll, A. F. Garfinkel, and B. Y. Oh, Phys. Rev. Letters 18, 630 (1967).

[5]E. L. Feinberg and I. Pomerančuk, Nuovo Cimento Suppl. 3, 652 (1956).

[6]M. Ross and L. Stodolsky, Phys. Rev. 149, 1172 (1966). Also M. Ross and Y. Y. Yam, Phys. Rev. Letters 19, 546 (1967), and this contains references to other papers by Ross and collaborators.

[7]E. C. West, J. H. Boyd, A. R. Erwin, and W. D. Walker, Phys. Rev. 149, 1089 (1966), see Appendix A.

[8]Y. Nambu and E. Schrauner, Phys. Rev. 128, 862 (1962).

[9]S. M. Berman and S. D. Drell, Phys. Rev. 133, B791 (1964); U. Maor and T. O'Halloran, Phys. Rev. Letters 15, 281 (1965).

[10]K. J. Foley, R. S. Jones, S. J. Lindenbaum, W. A. Love, S. Ozaki, E. D. Platner, C. A. Quarles and E. H. Willen, Phys. Rev. Letters 19, 397 (1967).