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# PHOTOPRODUCTION OF $\pi^+$, $\pi^0$, AND $K^+$ NEAR $t=0$*

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It is shown that the coherent-droplet model with long-range $\pi$ exchange can account for the observed behavior with $-t$ of the high-energy, small-momentum-transfer differential cross sections for $\gamma+p\rightarrow\pi^++n$, $\gamma+p\rightarrow\pi^0+p$, and $\gamma+p\rightarrow K^++\Lambda$. As in $n$-$p$ charge-exchange scattering, the steep rise near $-t=0$ in $\gamma+p\rightarrow\pi^++n$ is the effect of long-range $\pi$ exchange. The dip near $-t=0$ in $\gamma+p\rightarrow K^++\Lambda$ is accounted for by the presence of large helicity-flip amplitudes. Experiments to check this are suggested.

Experiments with $E_\gamma$ from 700 MeV to 16 GeV[1,2] show that the differential cross section for

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

rises very steeply in the forward direction. A similar steep peak is observed in $n$-$p$ charge-exchange scattering.[3] Partial-wave analyses of the lower energy data account for this by explicitly including single-$\pi$-exchange terms [Figs. 1(a) and 1(b)].[4] In a previous publication,[5] it was shown that the steep peak in the high-energy $n$-$p$ charge-exchange data could similarly be understood as the effect of $\pi$ exchange in the "higher partial waves." The coherent-droplet model[6] was used for the small-impact-parameter collisions. In this model all possible strong-interaction processes occur indistinguishably in an interaction volume whose spatial extent (as function of impact parameter) is approximately given by the elastic-scattering diffraction peaks. The root-mean-square impact parameter for elastic scattering is $a \lesssim 0.7m_\pi^{-1}$.[6] We define as small impact parameters $b\lesssim 0.7m_\pi^{-1}$. Interactions which are appreciable in larger impact parameter collisions will be called long-range interactions. Figures 1(a) and 1(b) give long-range interactions. For large $b$, the partial-wave projections of helicity amplitudes[7] for Fig. 1(a) have the form[8]

$$\sim\frac{egm_\pi^2}{4\pi p\sqrt{s}}\left(\frac{\pi}{2}\right)^{1/2}\frac{\exp(-m_\pi b)}{(m_\pi b)^{1/2}}$$

$$\text{with } b\equiv(J+\tfrac{1}{2})/p>m_\pi^{-1}. \tag{2}$$

In this Letter, we show that the coherent-droplet model with long-range $\pi$ exchange included can account for the $-t$ dependence of the small-momentum-transfer $\pi^+$ photoproduction data. Including the Primakoff effect [Fig. 1(c)], we find that the model can also account for the small-momentum-transfer $\pi^0$ and $K^+$ photoproduction data. In $\gamma+p\rightarrow K^++\Lambda$, there is no known long-range interaction and indeed the data[1] indicate no peaking near $-t=0$. Instead they show

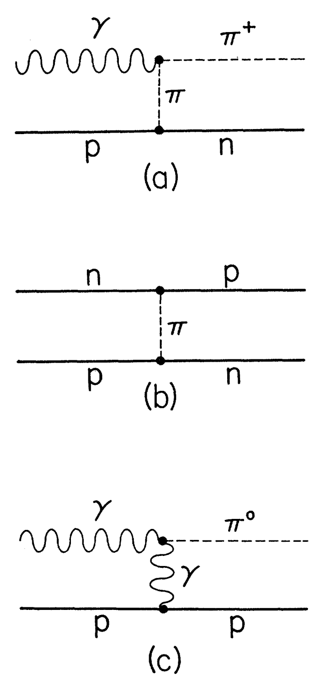


FIG. 1. (a), (b) Feynman diagrams for $\pi$ exchange; (c) diagram representing the Primakoff effect (Ref. 15).

a dip. If correctly accounted for by the coherent-droplet model, it occurs because strong contributions from helicity-flip amplitudes produce a maximum near $-t=0.1\ (\mathrm{GeV}/c)^2$. A similar (but less pronounced) effect is seen in $\pi p$ charge-exchange scattering.[6]

Our treatment of single-$\pi$ exchange differs from previous ones in that we assume that the Born approximation [Figs. 1(a) and 1(b)] is valid only for large-impact-parameter collisions. Previous analyses included all the partial-wave amplitudes of Fig. 1(a); these give pole terms

$$\sim \frac{eg}{4\pi}\frac{1}{\sqrt{s}}\frac{t}{t-m_\pi^{\ 2}} \tag{3}$$

(for $t\cong -4p^2\sin^2\frac{1}{2}\theta \ll p^2$) which vanish at $\theta=0^0$. If only the long-range part of Fig. 1(a) is kept, one has a pole term which is not zero at $0^0$. We find (see below) that this term accounts for nearly half the observed differential cross section at $\theta=0^0$.

A remark regarding gauge invariance may be in order here. Although the Feynman diagram Fig. 1(a) is not gauge invariant, the residue at the pion pole is gauge invariant. Consequently, for very large $b$, (2) is gauge invariant. One has the theorem (proved in I) that if an amplitude is analytic in a neighborhood of $t=0$ for $s$ fixed in the physical region and the nearest singularity to $t=0$ is the pion pole, the position and residue of the pole uniquely determine the asymptotic behavior (as $J\to\infty$) of its partial-wave components. Therefore, the estimation (2) of the effect of long-range $\pi$ exchange is gauge invariant.

Our assumptions are more precisely stated by giving partial-wave amplitudes as functions of $b$. We assume that the partial-wave components of the physical amplitudes to which $\pi$ exchange may contribute have the asymptotic form (2) and, as functions of $b$, go over smoothly to the droplet form at small $b$. To estimate the "droplet" contribution, we use (see below) the same material thickness factor as in $\pi$-$p$ charge exchange.[6] We use the same method as in I to interpolate between $b \gg m_\pi^{-1}$ and $b \lesssim a$. The latter two assumptions are crude estimates. However, we shall confine our attention to small-momentum-transfer collisions, where the amplitudes as functions of $t$ depend only on the large-scale behavior with $b$ of their partial-wave components. The helicity amplitudes for the droplet contribution then have the form[9]

$$f_{\frac{1}{2};-\frac{1}{2},-1}\equiv f_{\frac{1}{2},\frac{1}{2}}\cong C_0 e^{\frac{1}{4}a^2t}\quad(\Delta\lambda=0), \tag{4a}$$

$$f_{\frac{1}{2};\frac{1}{2},1}\equiv f_{\frac{1}{2},-\frac{1}{2}}\cong C_1(-t)^{\frac{1}{2}} e^{\frac{1}{4}a^2t}\quad(\Delta\lambda=1), \tag{4b}$$

$$f_{\frac{1}{2};\frac{1}{2},-1}\equiv f_{\frac{1}{2},\frac{3}{2}}\cong C_{-1}(-t)^{\frac{1}{2}} e^{\frac{1}{4}a^2t}\quad(\Delta\lambda=-1), \tag{4c}$$

$$f_{\frac{1}{2};-\frac{1}{2},1}\equiv f_{\frac{1}{2},-\frac{3}{2}}\cong C_2(-t) e^{\frac{1}{4}a^2t}\quad(\Delta\lambda=2), \tag{4d}$$

where $C_{0,\pm1,2}$ are parameters to be determined by experiment and $a$ = root-mean-square impact parameter for $\pi p$ elastic scattering = 4.5 $(\mathrm{GeV}/c)^{-1}$.[6] The corresponding differential cross section is

$$\left(\frac{d\sigma}{dt}\right)_{\text{droplet}} \cong \frac{\pi}{2p^2}(A_0 - A_1 t + A_2 t^2)e^{10t}, \tag{5}$$

with $t$ in $(\mathrm{GeV}/c)^2$ and

$$A_0=|C_0|^2,\quad A_1=|C_1|^2+|C_{-1}|^2,\quad A_2=|C_2|^2.$$

The Feynman diagram Fig. 1(a) contributes only to $f_{1/2,1/2}$ and $f_{1/2,3/2}$. These are amplitudes for which the total helicity either does not change ($\Delta\lambda=0$) or changes by two units ($\Delta\lambda=2$). Similarly, Fig. 1(b) contributes only to $\Delta\lambda=0$ and $\Delta\lambda=2$ amplitudes. At small $-t$, the contribution of the exponential (2) is, aside from the factor $(e/g)$, the same for $\pi^+$ photoproduction and $n$-$p$ charge exchange. This is because the partial-wave expansions of the helicity amplitudes contain the functions $d_{\mu\nu}^{\ J}(\theta)$ ($\Delta\lambda=\nu-\mu$). For large $J$ and small $\theta$, $d_{\mu\nu}^{\ J}(\theta)\approx J_{|\Delta\lambda|}((2J+1)\sin\frac{1}{2}\theta)$. Therefore, we can use the numerical results of I and include long-range $\pi$ exchange by adding the functions $(e/g)F$ and $(e/g)F_4$ to (4a) and (4d), respectively; $F$ and $F_4$ are displayed as functions of $t$ in I. Near $t=0$, for $-t\geq 0$

$$F\cong\frac{g^2}{4\pi}\frac{1}{\sqrt{s}}\frac{m_\pi^{\ 2}}{t-m_\pi^{\ 2}}\exp[-m_\pi a(1-t/2m_\pi^{\ 2})]. \tag{6}$$

Neglecting $F_4$,[10] one has

$$\left(\frac{d\sigma}{dt}\right)_{\pi^+} = \frac{\pi}{2p^2}[(e/g)^2F^2 + B(e/g)Fe^{5t}] + \left(\frac{d\sigma}{dt}\right)_{\text{droplet}}, \tag{7}$$

with $B=2\,\mathrm{Re}C_0$. The expression (7) is sensible only if the corresponding picture in $b$ space is consistent; i.e., one must fit (7) to the data, evaluate $|C_0|^2$ and $B$, and see if the corresponding partial-wave amplitude has a reasonable behavior with $b$. The partial-wave amplitude $\alpha(b)$ $[b=(J+\frac{1}{2})/p]$ corresponding to (3a) is $\alpha(b)=(2C_0/pa^2)e^{-b^2/a^2}$.

A fit of (7) to the data[1] is shown in Fig. 2. The interference term (proportional to $B$) is significant only for data in the neighborhood of $-t=0.01$. The fit was made with $B=0$ and it was found that

$$A_0=0.055s^{-1},\quad A_1=0.012a^2s^{-1},$$
$$A_2=0.011a^4s^{-1};\quad a=4.5\ (\mathrm{GeV}/c)^{-1}. \tag{8}$$

The corresponding $\Delta\lambda=0$ partial wave amplitude has the droplet form for $b<a$ and goes over to (2) for $b>a$. The term $F^2$ in (7) accounts for the steep peaking near $-t=0$; its contribution at $\theta=0^\circ$ to $s(d\sigma/d\Omega)_{\mathrm{c.m.}}$ is 9 $\mu$b GeV$^2$/sr. This is about half of the reported experimental value[11] of 21 $\mu$b GeV$^2$/sr. For $-t>m_\pi^2=0.02$, $F^2$ is very small. The relative flatness ($\sim e^{2t}$) of the data for $0.02<-t<0.3$ is accounted for in (7) by the contributions of the $|\Delta\lambda|=1$ and $\Delta\lambda=2$ amplitudes. Droplet-model fits to the charge-exchange data also required important contributions from helicity-flip amplitudes. For $-t\geq 0.3$, (7) falls too rapidly to fit the data. Droplet-model fits to exchange data generally deviate from the data in this direction for $-t\gtrsim 0.5$. For momentum transfers in this range, amplitudes are sensitive to details which the model, at present, is too crude to supply.

If our model is correct, (5) should fit the small-momentum-transfer data for

$$\gamma+p\rightarrow K^+ +\Lambda. \tag{9}$$

Here $\pi$ exchange is forbidden. Of course, $K$ exchange is possible. However, the range of $K$ exchange [$\sim 2$ (GeV/$c$)$^{-1}$] is "small" compared with the "droplet radius" [$\sim 4.5$ (GeV/$c$)$^{-1}$].[12] In our view, therefore, it is included in the droplet amplitudes. The preliminary data[11] indicate that (5) can account for $K^+$ photoproduction with $-t<0.3$ [as in the $\pi^+$ case, (5) falls much faster than the data for $-t\geq 0.3$]. The dip in the forward direction occurs because of a maximum near $-t=0.1$ due to strong contributions from helicity-flip amplitudes. (An analogous effect occurs in $\pi p$ charge exchange.[6]) Large $\Lambda$ polarization and/or large right-left asymmetry in production with polarized target in the region of the maximum would support our explanation of the dip.[13]

The data of Braunschweig et al.[14] on

$$\gamma+p\rightarrow\pi^0+p \tag{12}$$

can be fitted using (5). At very small $-t$, the Primakoff effect [Figure 1(c)] is important. Its contribution is appreciable only in the region $-t<0.001$; one has (interference terms are negligible)[15]

$$\left(\frac{d\sigma}{dt}\right)_{\pi^0}=\frac{e^2}{4\pi}\left(\frac{8\pi}{m_\pi^{\ 3}\tau_{\pi^0}}\right)\frac{p^2\sin^2\theta}{t^2}+\left(\frac{d\sigma}{dt}\right)_{\mathrm{droplet}}. \tag{13}$$

A fit to the data is shown in Fig. 3. For this fit

$$A_0=0.0315s^{-1},\quad A_1=0.05a^2s^{-1},\quad A_2=0, \tag{14}$$

and $(d\sigma/dt)_{\mathrm{droplet}}$ behaves for $-t<0.1$ similarly to the data for $K^+$ production; i.e., it has a dip in the forward direction.

Our conclusions are that the coherent-drop-

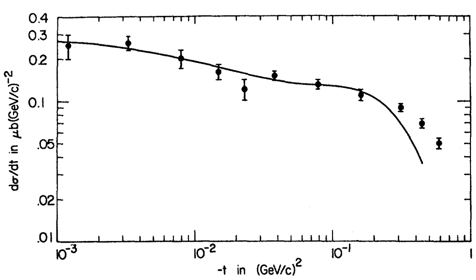


FIG. 2. $d\sigma/dt$ vs $-t$ for $\gamma+p\rightarrow\pi^++n$ with $E_\gamma=16$ GeV. Points with error flags are the data of Boyarski et al. (Ref. 1). Smooth curve is Eq. (7).

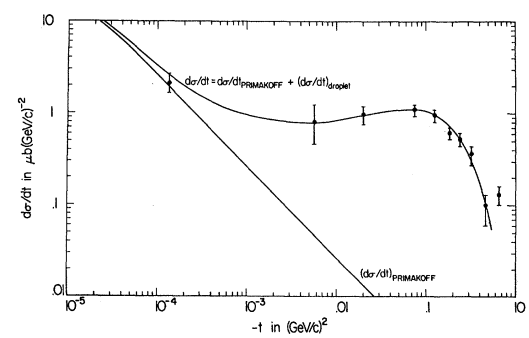


FIG. 3. $d\sigma/dt$ vs $-t$ for $\gamma+p\rightarrow\pi^0+p$ with $E_\gamma=5.8$ GeV. The (nearly) straight line is the contribution of the Primakoff effect (see Ref. 15). The points with error flags are the data of Braunschweig et al. (Ref. 14) as reported by Richter (Ref. 11). The smooth curve is Eq. (13).

let model with long-range $\pi$ exchange and the Primakoff effect included can fit the $\pi^+$, $\pi^0$, and $K^+$ photoproduction data for $-t<0.3$. The $\pi^0$ data are fitted out to $-t\approx 0.5$. Those data indicate a minimum in $(d\sigma/dt)_{\pi^0}$ near $-t=0.5$; a corresponding minimum is not indicated by the $\pi^+$ or $K^+$ data.[1,16] Our model does not account for the relative flatness of the $\pi^+$ and $K^+$ differential cross sections ($\sim e^{3t}$) for $0.2 < -t \lesssim 1$. At these larger $-t$ values, the differential cross section becomes much more sensitive to the detailed behavior with $b$ of its partial-wave components. Our estimates for the partial-wave amplitudes are crude and not expected to give good agreement with the data at the larger $-t$ values. The model is an incomplete theory. In particular, it does not explain the energy dependence of the cross sections. Experimental curves for $s^2 d\sigma/dt$ with $0<t\lesssim 1$ seem to be approximately energy independent for both $\pi^+$ and $K^+$ photoproduction.[11] From the point of view expressed here, this is remarkable.

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[3]See, e.g., R. R. Wilson, The Nucleon-Nucleon Interaction (Interscience Publishers, Inc., New York, 1963), Fig. 6.3. Also, G. Manning, A. G. Parham, J. D. Jafar, H. B. van der Raay, D. H. Reading, D. G. Ryan, B. D. Jones, J. Malos, and N. H. Lipman, Nuovo Cimento 41A, 167 (1966).

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[8]For Fig. 1(b), one has (2) with $e$ replaced by $g$. We take $\hbar=c=1$ and unless specified otherwise momenta in GeV/$c$; $e^2/4\pi\cong 1/137$, $g^2/4\pi\cong 14$, $\sqrt{s}$ = total energy in c.m. system, $p$ = c.m. momentum, $m_\pi$ = pion mass. Throughout this paper we assume $p\gg m_\pi$ and neglect terms of order $m_\pi/p$.

[9]Because absorption effects are not very strong, the $\Delta\lambda=0$ droplet amplitude is, to a good approximation, proportional to the $\pi p$ elastic scattering amplitude. (As in Ref. 6, for elastic scattering we neglect spin dependence and the real part of the amplitude.) For the $|\Delta\lambda|=1$ and $\Delta\lambda=2$ amplitudes, introducing the minimum power of $b$ consistent with the assumption of no central singularities, one obtains a similar result with additional factors $\sqrt{-t}$ and $t$, respectively.

[10]The $\Delta\lambda=2$ amplitude $F_4$ is zero at $t=0$ and maximum at $-t\approx m_\pi^2$; its maximum contribution is small compared with the data in this region. [The interpolation used in I for the $\Delta\lambda=2$ amplitude involved an additional assumption—a factor $b^2/(b^2+m_\pi^{-2})$; perhaps $b^2/(b^2+a^2)$ would be a better estimate. This choice increases $F_4^2$ near its maximum by a factor of about 1.5.] If $C_2$ is nearly real, the interference of $F_4$ with the droplet contribution may not be negligible; however, in the region where it is appreciable, this term behaves like the single-flip contribution $te^{10t}$.

[11]B. Richter, report to 1967 International Symposium on Electron and Photon Interactions at High Energies, Stanford University (to be published). We wish to thank Dr. Richter for making data available to us in advance of publication.

[12]The contribution of the $K$-exchange exponential (2) with $m_\pi$ replaced by $m_K$ and $g$ by $g_{Kp\Lambda}$ may be estimated using (6) and the recent result $g_{Kp\Lambda}^2/4\pi\approx 16$ [J. K. Kim, Phys. Rev. Letters 19, 1079 (1967)]. One finds that at $t=0$, $F_K(0)^2/F_\pi(0)^2\approx 0.06^2$. This is much smaller than the ratio of the corresponding cross sections (see Ref. 11).

[13]Measurement of $\Lambda$ polarization (unpolarized target and beam) yields information different from that given by the right-left asymmetry in production with transversely polarized target because there are two single-flip amplitudes $f_{1/2,-1/2}$ and $f_{1/2,3/2}$. The $\Lambda$ polarization is given by

$$\hat{n}\cdot\vec{P}_\Lambda(d\sigma/d\Omega)_{\text{c.m.}}=\tfrac{1}{2}\,\text{Im}(f_{\frac12,-\frac12}f_{\frac12,\frac12}{}^*+f_{\frac12,-\frac32}f_{\frac12,-\frac12}{}^*),$$

whereas one has for the right-left asymmetry ($P_T$ = target polarization)

$$\left(\frac{N_R-N_L}{N_R+N_L}\right)\left(\frac{d\sigma}{d\Omega}\right)_{\text{c.m}}=\frac{2}{\pi}P_T\,\text{Im}(f_{\frac12,\frac12}f_{\frac12,\frac32}{}^*+f_{\frac12,-\frac32}f_{\frac12,-\frac12}{}^*).$$

Measurement of the above for $\pi^+$ photoproduction is also of interest; if our theory is correct and if the parameters $B$ and $\text{Im}C_{-1}$ are large, the asymmetry would be large at very small angles. Owing to $\pi$ exchange, it would increase from zero very rapidly for $0<-t\lesssim 0.02$.

[14]M. Braunschweig, W. Braunschweig, D. Husman, K. Lübelsmeyer, and D. Schmitz, contributed paper to 1967 International Symposium on Electron and Photon

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 $\pi^0$ 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 $\omega$ 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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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/$c$ $\pi^-$. 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 $\pi$'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 $\pi^-$.

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 $\rho$ 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 $1/p_{\rm lab}^2$.

That $\rho^0$ 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 $\rho^0$ and $f^0$ bands. However, in the 25-BeV/$c$ data the production of $\rho$ and $f^0$ while present is less important than the process giving rise to the low-mass $\pi$-nucleon combination.

In Fig. 2, we show the projections from the Dalitz plot on the $\pi^+$-$n$ and $\pi^0$-$p$ axes. At both the energies the $\pi$-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 $\pi^+$-$n$ and $\pi^0$-$p$ 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 $\pi$-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 $\pi$-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 $\pi^+$-$n$ mass is less than 1.4 BeV/$c^2$. The cross section is found to fall by a factor of $1.4 \pm 0.3$ 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