1.5–2.0 smaller than those previously measured in the 10–30 GeV/c momentum band.[6]

To summarize our findings, we have measured with excellent mass and t resolution the dependence of the slope of the t distribution on mass for neutron dissociation into the two-body $p\pi^-$ final state. At small t we observe a variation of the slope parameter with the mass of the $p\pi^-$ system similar to that found at lower energies. Fine structure is observed in the $p\pi^-$ mass distribution, particularly at large t values. These general features of the data have been interpreted previously in terms of the dominance of low-spin s-channel helicity-nonflip production amplitudes at small $(p\pi^-)$ mass, and the emergence of higher-spin helicity-flip terms for larger mass values.[7] The pertinence of such arguments will be discussed in the following Letter.

We thank J. P. DeBrion, C. Bromberg, D. Chaney, J. Keren, R. Lipton, P. Mühlemann, D. Spelbring, and H. Scott for assistance in the running of the experiment. We also acknowledge the excellent support of P. Koehler and the staff at the Meson Detector Laboratory during the execution of this experiment.

---

*Research supported by the U. S. Energy and Research and Development Administration.

[1] The properties of the neutral beam have been discussed previously by M. Longo *et al.*, University of Michigan Report No. UM HE 74-18, 1974 (unpublished). The neutron spectrum has an average momentum of ~200 GeV/c, with a peak value at ~240 GeV/c.

[2] A report describing the design and performance of the target assembly is in preparation.

[3] We believe that the main source of background is from neutron dissociation into $p\pi^-\pi^0$ systems. We expect this background to be at a level of ~10% for the $p\pi^-$ signal. It is worth noting that the signal-to-background ratio observed in Fig. 1(c) is essentially independent of the dynamic variables to be presented in this paper.

[4] See the summary of J. Rushbrooke, in *Proceedings of the Third International Colloquium on Multiparticle Dynamics, Zakopane, Poland, 1972,* edited by A. Bialas, O. Czyzewski, and L. Michejda (Nuclear Energy Information Center of the Polish Government Commissioner, Warsaw, Poland, 1972).

[5] See T. Ferbel, in Proceedings of the International School of Subnuclear Physics, "Ettore Majorana," Erice, 1975, edited by A. Zichichi (Academic, New York, to be published). The neutron momentum spectrum extracted from our Pb data is consistent with the results given in Ref. 1.

[6] E. Nagy *et al.*, in Proceedings of the Seventeenth International Conference on High Energy Physics, London, 1974 (unpublished). The relevant information from the CERN intersecting storage ring is contained in the report of A. Diddens which appears in the *Proceedings of the Seventeenth International Conference on High Energy Physics, London, England, 1974,* edited by J. R. Smith (Rutherford High Energy Laboratory, Didcot, Berkshire, England, 1975). For data at low energies see J. Hanlon *et al.*, Vanderbilt University Report No. VAND-HEP 74(2), 1974 (unpublished).

[7] For a discussion of this class of models see G. Kane, Acta Phys. Pol. B3, 845 (1972).

Decay Properties of $p\pi^-$ Systems Produced in Neutron Dissociation at 50–300 GeV/c*

J. Biel, E. J. Bleser, D. Duke, T. Ferbel, D. Freytag, B. Gobbi, L. Kenah, J. Rosen,
R. Ruchti, P. Slattery, and D. Underwood
University of Rochester, Rochester, New York 14627, and Fermi National Accelerator Laboratory,
Batavia, Illinois 60510, and Stanford Linear Accelerator Center, Stanford, California 94305, and
Northwestern University, Evanston, Illinois 60201

(Received 29 September 1975)

We have examined the decay angular distributions of $(p\pi^-)$ systems produced in the reaction $n+p\rightarrow(p\pi^-)+p$ for neutron momenta between 50 and 300 GeV/c. The production process appears to be dominated by comparable contributions from both the pion-exchange Deck mechanism and the proton-exchange Deck mechanism.

In an accompanying Letter[1] we presented the main production features of the dissociation reaction

$$n+p\rightarrow(p\pi^-)+p\,. \tag{1}$$

Here we turn our attention to the decay angular distribution of the $(p\pi^-)$ system for $M<1.55$ GeV. The qualitative characteristics of the data are displayed in Fig. 1 in a scatter plot of the decay angular variables $\cos\theta$ and φ of the proton in the Gottfried-Jackson (GJ) frame (t channel). (The data are for $1.2<M<1.375$ GeV and $0.02<-t<0.2$ GeV^2. Because no asymmetry about $\varphi=0$ is observed, nor expected for unpolarized neu-

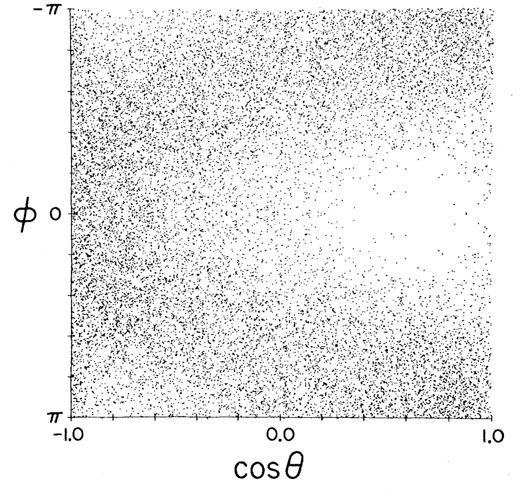

FIG. 1. Scatter plot of the $\cos\theta$ of the produced proton versus the φ of the proton in the Gottfried-Jackson frame of the $p\pi^-$ system in Reaction (1). The data are for $1.2 < M < 1.375$ GeV and $0.02 < -t < 0.20$ GeV^2.

trons, we have symmetrized the scatter plot about $\varphi = 0$.) The gross structure of the scatter plot, namely, the peaking near $\varphi \approx \pi$ for $\cos\theta > 0$, and near $\varphi \approx 0$ for $\cos\theta < 0$, and the corresponding depletion of events outside of each φ peak, is a common feature of the data for $M \lesssim 1.55$ GeV that does not depend strongly on the specific values of the mass M of the $(p\pi^-)$ system or the square of the four-momentum transferred to that system (t).[2] Projections on the φ axis of the data shown in Fig. 1 are presented in Figs. 2(a) and 2(b) for $\cos\theta > 0.8$ and for $\cos\theta < -0.8$, respectively. It is tempting to conclude from these qualitative features of the data that two separate production mechanisms contribute to Reaction (1).

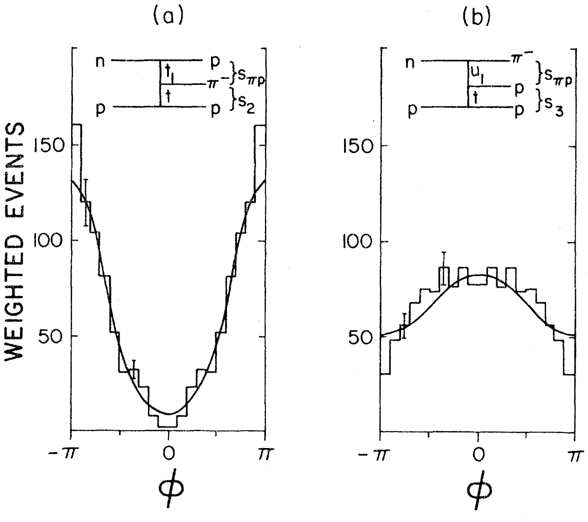

FIG. 2. Projected φ distributions from data in Fig. 1 for (a) $\cos\theta > 0.8$ and (b) $\cos\theta < -0.8$. The Deck diagrams expected to dominate in these regions of $\cos\theta$ are shown above the data. The curves are calculations of Deck contributions described in the text.

Processes such as Reaction (1) have been discussed in the past in the framework of Deck-like models.[3] In this paper we will also compare our data with the Deck production models indicated by the Feynman graphs at the top of Fig. 2. The square of a simple Deck-type matrix element for the pion-exchange contribution to Reaction (1) can be written as

$$|M|_\pi^2 \approx \frac{[\frac{1}{2}(s_{\pi p} - u_1)]^{2\alpha_\pi}}{\alpha_\pi^2} s_2^2 e^{8t}, \tag{2}$$

where $\alpha_\pi = 0.9(t_1 - \mu^2)$ is the pion Regge trajectory, μ is the pion mass, and t_1 and t are squares of the four-momentum transfers; $s_{\pi p}$ and s_2 are squares of the πp invariant masses as indicated in Fig. 2(a), and u_1 is the square of the four-momentum transferred to the pion from the incident neutron. The $\pi^- p$ elastic differential cross section is taken proportional to $\exp(8t)$. An analogous expression can be written for the proton-exchange Deck calculation [Fig. 2(b)], with the substitution of α_p for α_π, where $\alpha_p = -0.35 + 0.9u_1$ is the proton Regge trajectory, and with the substitution of $\exp(10t)$ for $\exp(8t)$ to account for the difference between πp and pp elastic scattering:

$$|M|_p^2 \approx \frac{\exp(4u_1)[\frac{1}{2}(s_{\pi p} - t_1)]^{2\alpha_p}}{(\alpha_p - \frac{1}{2})^2} s_3^2 e^{10t}. \tag{3}$$

Expression (2) is dominant for $\cos\theta > 0$ while expression (3) is important for $\cos\theta < 0$. [We have introduced a multiplicative form factor $\exp(4u_1)$ in expression (3) in order to diminish the contribution from proton exchange for $\cos\theta > 0$. We will show subsequently that, with this additional form factor, expressions (2) and (3) provide a surprisingly good understanding of the structure in the data observed in Fig. 1.]

In the GJ frame, expressions (2) and (3) depend on φ through the terms s_2^2 and s_3^2, respectively. This dependence, which is indicative of the πp and pp off-shell elastic scattering, is an essential aspect of the Deck model, and consequently the φ distribution in the data is a clear indicator of the contribution of Deck-like processes. The curves superposed on the projected φ distributions in Figs. 2(a) and 2(b) have been obtained by using expression (2) for $\cos\theta > 0.8$ and expression (3) for $\cos\theta < -0.8$, and normalizing each to the data. The model curves are in good agreement

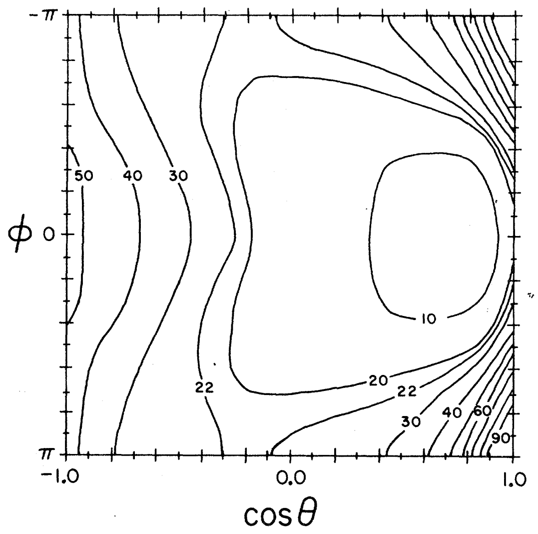

FIG. 3. Contour plot of $\cos\theta$ versus φ of the proton in the GJ frame calculated using equal amounts of Deck expressions (2) and (3).

with the data in the separate regions of $\cos\theta$ and imply the presence of both the pion-exchange as well as the proton-exchange Deck contributions to Reaction (1). [The shape of the pion-exchange contribution for $\cos\theta < -0.8$ is similar to that for $\cos\theta > 0.8$, and therefore cannot explain the data in Fig. 2(b).]

In Fig. 3 we display the contours of equal cross section in the $(\cos\theta, \varphi)$ space obtained from an addition of equal amounts of expressions (2) and (3). It is clear that the main features of Fig. 1 are reproduced rather well by the superposition of contributions from the two Deck diagrams.

We have not attempted in this note to compare the M and t characteristics of the data with those provided by expressions (2) and (3). In the past, such comparisons have established that there is, in fact, qualitative agreement in t and M between processes such as Reaction (1) and Reggeized Deck models.[3] Our preliminary studies also support this general conclusion[4]; in addition, we find that the sort of detailed M-t correlation observed for small M values[1] cannot be reproduced using expressions (2) and (3).[5] More sophisticated Deck models involving rescattering corrections (absorption) have recently been proposed to account for the details of the M-t interdependence.[6]

The origin of the strong correlation between the mass M of an inelastic system produced in diffraction dissociation and the square of the four-momentum transferred to that system has been the object of extensive investigation.[7] One class of models suggested for understanding the t-M interdependence in these highly peripheral reactions is based on the assumption that s-channel helicity amplitudes for small masses ($M \lesssim 1.3$ GeV) are dominantly helicity nonflip.[8] These models would predict a steep differential cross section for small t and a dip or sharp break near $-t \sim 0.2$–0.3 if the helicity nonflip system is produced peripherally (i.e., near an impact parameter $b \sim 1$ fm). The contributions from the helicity-flip amplitudes are hypothesized to become more important as the mass and spin of the diffractively produced system increases, thus leading to a substantial broadening of the t distributions with increasing M values. A particularly simple approach of this kind,[9] one in which the diffractive amplitudes are taken to be imaginary, contains specific predictions for the t dependence of the moments of the angular distributions which will be discussed below.

In Table I we show preliminary results for the normalized low-order moments $\langle Y_{lm}\rangle$ versus t for fixed mass M (1.300–1.375 GeV) in the helicity frame. (No background subtractions have been made in the data; however, the moments in the background sample are similar to those characterizing the signal. See Fig. 1 of Ref. 1.) The $\langle Y_{11}\rangle$ moment in the helicity frame consists of interference terms proportional to a helicity-nonflip amplitude and a helicity-flip amplitude. In

TABLE I. Low-order $\langle Y_{lm}\rangle$ in helicity frame for $1.300 < M < 1.375$ GeV.

$-t$ (GeV^2)	$\langle Y_{10}\rangle$	$\langle Y_{11}\rangle$	$\langle Y_{20}\rangle$	$\langle Y_{21}\rangle$	$\langle Y_{22}\rangle$
0.02–0.05	-0.096 ± 0.006	0.015 ± 0.005	-0.065 ± 0.006	0.017 ± 0.005	0.012 ± 0.005
0.05–0.08	-0.081 ± 0.008	0.026 ± 0.007	-0.079 ± 0.008	0.042 ± 0.007	0.041 ± 0.007
0.08–0.12	-0.085 ± 0.009	0.030 ± 0.008	-0.084 ± 0.009	0.051 ± 0.007	0.059 ± 0.007
0.12–0.20	-0.044 ± 0.010	0.065 ± 0.009	-0.112 ± 0.009	0.068 ± 0.008	0.102 ± 0.008
0.20–0.40	-0.062 ± 0.011	0.130 ± 0.009	-0.120 ± 0.011	0.026 ± 0.011	0.132 ± 0.008
0.40–0.60	-0.123 ± 0.014	0.102 ± 0.012	-0.067 ± 0.015	-0.040 ± 0.014	0.064 ± 0.012

terms of the simple s-channel peripheral model discussed above,[9] one therefore expects $\langle Y_{11}\rangle$ in the helicity frame to pass through zero at the t value where the break is observed in the differential cross section. Although this prediction may not be true in the general case when absorption corrections are important or when the phases of the individual s-channel helicity amplitudes differ, two specific models which we have examined[10] indicate that the zero in $\langle Y_{11}\rangle$ near $-t \sim 0.25$ GeV^2 is preserved when such complications are taken into account. The observed absence of this predicted zero in $\langle Y_{11}\rangle$ implies that, at the very least, the simple s-channel peripheral model cannot be the dominant production process. (Similar behavior is observed for $\langle Y_{11}\rangle$ for all $M < 1.5$ GeV.)

We conclude that the spin structure of diffractively produced, low-mass, $p\pi^-$ systems is in essential agreement with predictions of Deck-like models. It is questionable, however, whether the t-M correlation and the sharp break in the differential cross section near $-t \sim 0.2$–0.3 for small values of M can result purely from elastic rescattering between the final-state particles in Reaction (1), as has been proposed by Tsarev.[6]

We thank E. L. Berger, G. Fox, and H. Miettinen for helpful discussions.

---

*Research supported by the U. S. Energy Research and Development Administration.

[1] J. Biel *et al.*, preceding Letter [Phys. Rev. Lett. 36, 504 (1976)].

[2] Although the scatter plot in Fig. 1 has not been corrected for acceptance of the apparatus, our experimental losses are small and do not materially affect the qualitative features of the data in this mass region. All histograms (e.g., Fig. 2) have been weighted using efficiencies based on a Monte Carlo program.

[3] R. T. Deck, Phys. Rev. Lett. 13, 169 (1964). For a recent comprehensive review see E. L. Berger, in *Proceedings of the Daresbury Conference on Analysis of Three-Particle Decays and Meson Resonance Production, 1975,* edited by J. B. Dainton and A. J. G. Hey (Daresbury Nuclear Physics Laboratory, Daresbury, Warrington, Lancashire, England, 1975).

[4] T. Ferbel, in Proceedings of the International School of Subnuclear Physics "Ettore Majorana, Erice, 1975, edited by A. Zichichi (Academic, New York, to be published).

[5] See a discussion of this question by H. I. Miettinen, in *Proceedings of the Third International Colloquium on Multiparticle Reactions, Zakopane, Poland, 1972,* edited by A. Bialas, O. Czyzewski, and L. Michejda (Nuclear Information Center of the Polish Government Commissioner, Warsaw, 1972).

[6] V. A. Tsarev, Phys. Rev. D 11, 1864 (1975); E. L. Berger and P. Pirilä, Phys. Rev. D 12, 3448 (1975).

[7] See, for example, the following: J. Bartsch *et al.*, Phys. Lett. 27B, 336 (1968); B. Y. Oh and W. D. Walker, Phys. Lett. 28B, 564 (1969); M. S. Farber *et al.*, Phys. Rev. Lett. 22, 1394 (1969); H. I. Miettinen and P. Pirila, Phys. Lett. 40B, 127 (1972); J. Rushbrooke, in *Proceedings of the Third International Colloquium on Multiparticle Reactions, Zakopane, Poland,* 1972, edited by A. Bialas, O. Czyzewski, and L. Michejda (Nuclear Information Center of the Polish Government Commissioner, Warsaw, 1972); H. Lubatti and K. Moriyasu, Lett. Nuovo Cimento 12, 97 (1975).

[8] G. Kane, Acta Phys. Pol. B3, 845 (1972). In these models the nonflip term is proportional to a function, $J_0(b\sqrt{t})$ while single-flip amplitudes contain $J_1(b\sqrt{t})$ terms, etc.

[9] S. Humble, Nucl. Phys. B76, 137 (1974).

[10] We have considered the model suggested by Berger and Pirila (Ref. 5), and the model of B. J. Hartley and G. L. Kane, Nucl. Phys. B57, 157 (1973). We thank G. L. Kane for helpful discussions regarding the more realistic s-channel peripheral models.

Pion-Exchange Contributions to Two-Photon Amplitudes and the Nuclear Magnetic Susceptibility*

J. L. Friar
Los Alamos Scientific Laboratory, Los Alamos, New Mexico 87545, and Department of Physics,†
Brown University, Providence, Rhode Island 02912

(Received 25 September 1975)

The pion-exchange contributions to the two-photon amplitude are derived and gauge invariance of the complete amplitude is shown. A low-energy theorem for a general two-photon process is derived and the pionic contribution to the magnetic susceptibility is calculated. The contribution of this quantity to n-p two-photon radiative capture is shown to be small.

The recent experiment[1] on two-photon decays in thermal n-p capture has rekindled interest in two-photon processes in nuclei. Although the large rate found in this experiment is in disagreement with a more recent experiment,[2] theoretical interest has centered on "exotic" contributions