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[8] Our correction uses the theoretical estimate for the $\pi^+\pi^-\gamma$ rate calculated by M. Bég, R. Friedberg, and J. Schultz as quoted in Ref. 5. Events which fit $\pi^+\pi^-\gamma$ with a γ momentum, in the K^0 rest frame, of less than 50 MeV/c have been removed from the sample. This cut results in a 2% loss of leptonic decays.

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[11] Experiments are in progress to measure the charge asymmetry in $K_L \rightarrow \pi e \nu$ (J. Steinberger et al. at Brookhaven National Laboratory) and in $K_L \rightarrow \pi\mu\nu$ (M. Schwartz et al. at Stanford Linear Accelerator Center) in order to resolve the ambiguity in the Wu-Yang description of the neutral K system. One solution predicts an asymmetry which would be observed in these experiments, while the other does not, but the effects could, in principle, be suppressed by $\Delta S = -\Delta Q$ amplitudes. Our experiment rules out a suppression from these amplitudes of more than 10 to 20%.

[12] If we ignore the charge of the lepton in the likelihood fit, we still obtain a two-standard-deviation violation. A χ^2 test to the total lepton time distribution yields for no violation $P(\chi^2) = 1.5\%$ and for best estimates $P(\chi^2) = 34\%$. This also corresponds to a two standard effect.

[13] In a Monte Carlo study of experiments, in which 86 positive leptons and 57 negative leptons were generated with $x = \varphi = 0$, only 6% of the experiments resulted in a violation more significant statistically than our experiment.

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RECOIL-PROTON POLARIZATION IN π^0 PHOTOPRODUCTION*

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In this Letter, we wish to communicate the results of an investigation into the energy dependence of the polarization of the final-state proton in neutral pion photoproduction. The energy region covered extends from 750 to 1450 MeV/c incoming photon momentum, at π^0 c.m. angles around 60°.

The results of this experiment indicate a zero crossing of the 60° polarization in the energy region covered, and a very strong angular dependence. We have attempted to incorporate this information into a unified picture of π^0 photoproduction, making use of all the presently available experimental information.[1]

In the absence of polarization data from π^0 photoproduction above ~900 MeV and outside the 90° region, we choose c.m. angles around 60° for the higher energies. This was done because, in a simple isobar model incorporating a possible elementary vector meson exchange,[2] it promised to yield the most significant information short of a fuller angular distribution (which was excluded by limitations on running and subsequent scanning time); and because our experimental method was best applicable in this region.

In order to obtain a pure sample of protons from π^0 photoproduction, we detected the recoiling proton and both decay photons of the π^0. This procedure sufficiently overdetermines the kinematics so as to give us an event sample which is clean to better than 98%; also, it allows us to determine, within the resolution of our apparatus, the inelasticity of the analyzing scatter of the recoil proton.

The experimental procedure employed is the following: A bremsstrahlung beam from the 1.5-BeV California Institute of Technology electron synchrotron impinged on a liquid-hydrogen target. The recoil proton passed through three scintillation counters and two thin-foil spark chambers; it subsequently entered a modular spark chamber built out of modules of carbon plates of varying thickness and two-gap sparking units, which served as both a range and scattering chamber. The dimensions were chosen such that all protons are stopped in the chamber, whether they undergo a scatter off a carbon nucleus or not. Carbon was chosen as a scatterer, because its analyzing power has been extensively studied over the energy region of interest to us (80 MeV $\leq T_p$

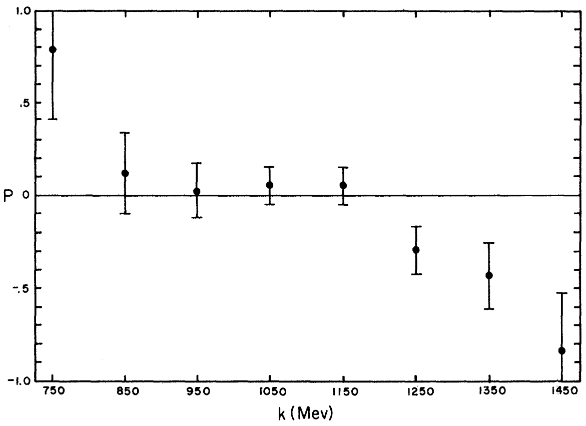

FIG. 1. Proton-polarization values for the full angular bin of $\theta_\pi^* = 60° \pm 10°$, as given in Table I. The errors shown incorporate statistical errors and the (nonsystematic) uncertainty in assigning the proper analyzing powers. Positive polarization is defined in the direction $\vec{k}\times\vec{p}_{\text{proton}}$.

≤ 280 MeV).

The decay photons of the π^0's were detected in a plane perpendicular to the production plane, at the symmetric decay angles.[3] The localization of the decay photon showers by means of hodoscopes led to a resolution of π^0 production angles of about 1°.

A coincidence between the proton telescope and the two gamma signatures formed the master trigger and fired the spark-chamber telescope on the proton side. The use of 90° stereoscopy and of a field lens in conjunction with the large scattering chamber insured that the proton trajectory would be fully reconstructed.

The polarization values were calculated using a maximum-likelihood method. A careful study was made of all the available data on the analyzing power of carbon over the energy range covered in this experiment, including its decrease with increasing inelasticity of the scatter.[4]

Figure 1 shows the results from all events, from a 20°-wide angular window, centered at 60° in the c.m. The error, as determined by the maximum-likelihood calculation, incorporates statistical errors and the uncertainties in assigning the proper analyzing power. The point at $k = 750$ MeV is shown for consistency with previous experiments only. It lies on the tail of our efficiency curve and is based on very few events. The 60° polarization is seen to pass from positive to large negative values, and is small in the region of the third πN resonance. (The sign convention is such that $\vec{k}\times\vec{p}_{\text{proton}}$ defines the positive direction.)

Table I. Polarization data for $\theta_\pi^* = 60 \pm 10°$, $\Delta k = \pm 50$ MeV.

$\langle k\rangle^{a}$	$\langle \bar{k}\rangle^{b}$	$\langle\theta_\pi^*\rangle_{\text{geom}}^{a}$	$\langle\theta_\pi^*\rangle_{\text{ev av}}^{b}$	P	$\pm\Delta P$
750	765	60	63.5	0.79	0.38
850	852	60	62.5	0.12	0.22
950	955	60	60.5	0.02	0.12
1050	1051	60	59.8	0.05	0.1
1150	1145	60	59.7	0.05	0.1
1250	1246	60	59.5	−0.3	0.13
1350	1343	60	59.0	−0.44	0.18
1450	1435	60	59.5	−0.84	0.32

[a] Geometrical center of bin.

[b] Center of bin as determined from weighted average over events.

Recently, a large number of states have been identified in πN phase-shift analysis, in the upper isobar region, indicating the possibility of a much more complicated angular structure of the polarization. After completion of the experiment and the analysis leading to the results displayed in Fig. 1 and Table I, we therefore divided the data for the central-energy points into two angular bins each (changing the π^0 c.m. angles from $60 \pm 10°$ to $55 \pm 5°$ and $65 \pm 5°$). Although the statistics on our data do not fully justify this procedure, we display in Fig. 2 the results of this angular separation. There is evidence for a dramatic angular gradient, indicating an angular zero crossing for the polarization values around 60° throughout the energy region covered. Because of the statistical uncertainties, we do not wish to take this as quantitative evidence. However, we take this dependence as a prominent feature which will have to be satisfied by any model attempting to describe π^0 photoproduction in this region.[5]

In an attempt to incorporate the data obtained in this experiment in a somewhat unified picture of the π^0 photoproduction process, we used the following fitting program:

The isobars [up to N_{17}(1920 MeV)] are put in as Breit-Wigner forms in the s channel, including a phase-space factor, as in the isobar model developed by Walker.[6] As in this model, we include the electric Born approximation (s- and u-channel nucleon poles) without anomalous magnetic coupling. In addition, we add the exchange of an ω_0 trajectory in the

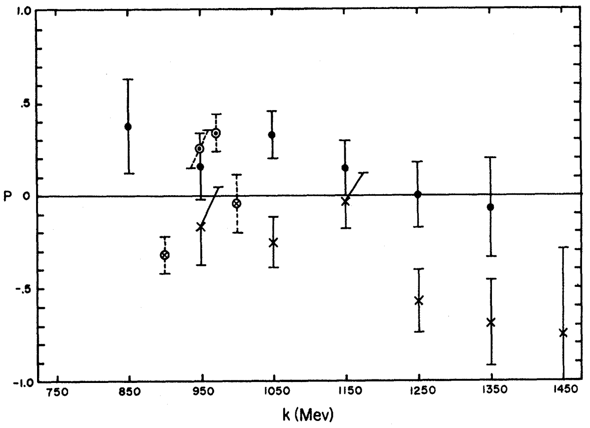

FIG. 2. Polarization data broken up into two angular bins. This was done, in spite of unsatisfactory statistics, in order to demonstrate a persistently strong angular gradient over the energy region covered. Full circles: geometrical bin $\theta_\pi^* = 65 \pm 5°$; crosses: geometrical bin $\theta_\pi^* = 55 \pm 5°$. The bin centers as determined from weighted averages over all events are roughly $\theta_\pi^* = 62$-$63°$ and $57°$. For comparison, dashed data points are shown at comparable angles from unpublished Stanford work (Ref. 5). The error bars in the Stanford points are statistical only.

t channel, with a modified energy dependence (cf. below). The low-lying partial waves are regarded as adjustable parameters throughout, with the condition that they exhibit a smooth behavior with energy.

For the inclusion of the Reggeized ω exchange, we use a modified version of the formalism developed by Kramer and Stichel.[7] We obtain, for the amplitudes A, B, C, and D introduced by Chew et al.,[8]

$$A = \frac{\pi t}{\sin \pi\alpha(t)}\left(1 - e^{-i\pi\alpha(t)}\right)\left(\frac{s}{s_0}\right)^{\alpha(t)-1}\gamma_2(t), \tag{1}$$

$$B = A/t, \tag{2}$$

$$C = 0, \tag{3}$$

$$D = \frac{\pi}{\sin \pi\alpha(t)}\left(1 - e^{i\pi\alpha(t)}\right)\left(\frac{s}{s_0}\right)^{\alpha(t)-1}\gamma_1(t), \tag{4}$$

with the following expressions[9] for γ_1, γ_2:

$$\gamma_1(t) \approx [\alpha(t)+1][\alpha^2(t)\beta_1 t/2M^2 + 2M\alpha(t)\beta_2], \tag{5}$$

$$\gamma_2(t) \approx [\alpha(t)+1][\alpha^2(t)\beta_1/M + \alpha(t)\beta_2]. \tag{6}$$

The residues[10] β_1, β_2 are assumed to be constant along the trajectory $\alpha(t)$. We take $s_0 = 1$ BeV^2. We furthermore choose the ω trajectory roughly parallel to the ρ trajectory, in accordance with experimental evidence.[11] $\alpha_\omega(t)$ is given by

$$\alpha_\omega(t) \approx 0.9t + 0.45. \tag{7}$$

Using these inputs, our best fits to all cross section and polarization data presently available[12] can be summarized as follows:

(1) The region $k \leq 1$ BeV can be understood in terms of an isobar model as developed by Walker.[6]

(2) Inclusion of all isobar states[13] up to $N^*(1924)$ can qualitatively fit the strong angular gradients of the polarization in the energy region above $k = 1$ BeV, as observed in our experiment.

(3) Simultaneous fitting of the forward hemisphere in the cross section necessitates the inclusion of vector-meson exchange terms. Since ρ and φ couple more weakly to $\gamma\pi$ than the ω,[14] we neglect the latter two in our fit. Elementary ω exchange cannot fit the data even if the lower partial waves are absorbed out (see Fig. 3). The angular dependence favors trajectory exchange.

(4) The energy dependence of the single Regge-pole approximation, i.e.,

$$(d\sigma/d\Omega)(t) \sim s^{2\alpha(t)-1}, \tag{8}$$

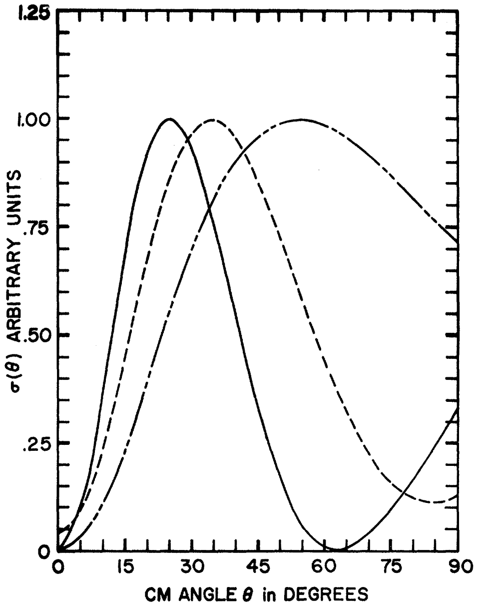

FIG. 3. Comparison of influence of various ω-exchange models in forward-π^0-photoproduction cross section at $k = 1350$ MeV. Full curve: Reggeized ω exchange. Dashed curve: elementary ω exchange with s and p waves absorbed out completely. Dash-dotted curve: elementary ω exchange without absorption. The steep rise at forward angles of the Reggeized exchange is needed to fit the data.

cannot be expected to hold in the intermediate energy region because of the small value of s and the possible presence of lower lying trajectories associated with presently unidentified particles which might be exchanged in π^0 photoproduction.

(5) In an attempt to blend the isobar model and a description in terms of a single-pole exchange in the intermediate energy region, we disregard isobars with masses higher than $N^*(1924)$ and empirically add an ω-trajectory-exchange term. By gradually "turning on" the coupling of this trajectory, we are able to fit the available data quite well.

(6) In the higher energy region, predominance of the ω-trajectory exchange is suggested by the limited data available[12] at ~3 BeV. If we approximate these data in the forward hemisphere with ω exchange alone, our best fits yield the residues β_1 and β_2 of Eqs. (5) and (6) with values 5-8 times those calculated from considerations of elementary exchange at the pole.[10] The numerical input values for the couplings (from Abarbanel, Callan, and Sharp[10]) are reliable at best to a factor of ≈ 2; similar procedures frequently involve an over-all scale factor taken from experiment.[15] We therefore take this discrepancy as nothing more than a cautioning with respect to the assumptions of a fixed residue along the ω trajectory.

These conclusions based on the very suggestive, but somewhat scant experimental evidence presented above ought to be made more quantitatively compelling by means of an extension of the polarization data in the crucial intermediate region to different angles and higher energies. The data-handling problems will be so severe that we hope to accomplish this after installation of a digitized spark-chamber system.

We wish to acknowledge stimulating conversations with Professor Steven Frautschi and Professor Robert Walker. Miss Lorella Jones offered some very helpful criticism. Walter Nilsson was of great help in the setting up of the experimental equipment. Steven Cheng, William McNeely, and Bruce Winstein contributed to the data analysis.

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[2] D. S. Beder, Nuovo Cimento 33, 94 (1964).

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[5] Equally strong dependence of polarization on the scattering angle has been observed in πN scattering: R. D. Eandi, University of California Radiation Laboratory Report No. UCRL-10629, 1963 (unpublished). Some similar evidence in photoproduction at energies up to ~950 MeV is being reported by D. Lundquist and D. Ritson, private communication.

[6] R. L. Walker, to be published. This work, although more complete and refined, is basically similar in approach to such isobar models as those put forward by P. Salin, Nuovo Cimento 28, 1294 (1963), and D. Beder, Ref. 2. It includes all isospin amplitudes occurring in simple π photoproduction. It fits all available cross section, recoil-proton polarization, and polarized-photon asymmetry data in terms of Born terms, isobars, and adjustable nonresonant lower partial waves. We thank Professor Walker for making these fits available to us prior to publication.

[7] G. Kramer and P. Stichel, Z. Physik 178, 519 (1964). We simplify Eqs. (72)-(76) of this paper on the principle that only physically required t variations should be included. E.g., the nonsense zero in the spin-flip amplitude at $\alpha_\omega = 0$ should be present, in addition to the kinematical zero in the total amplitude at $\alpha_\omega = 0$, etc. We also require that the explicit t dependence of the elementary ω^0 exchange be reproduced by the Reggeized exchange near the pole.

[8] G. Chew, M. L. Goldberger, F. E. Low, and Y. Nambu, Phys. Rev. 106, 1347 (1957).

[9] This choice for the functions γ_1, γ_2 yields the amplitudes A, B, C, and D such that they satisfy the conditions dictated by crossing, $2MA - D \propto \beta_1$ and $A - 2MD \propto \beta_2$. We wish to thank Miss Lorella Jones for bringing this point to our attention.

[10] The values of the residues β_1, β_2 were obtained by going to the pole and using the elementary exchange formulas there. Applying normal Feynman rules, the amplitudes corresponding to Eqs. (1) through (4) are then, for the elementary exchange,

$$A^E = \frac{t f_{\omega\pi\gamma} F_{2\omega NN}}{(t - m_\omega)^2 + i\Gamma_\omega m_\omega}, \tag{1'}$$

$$B^E = -A^E / t, \tag{2'}$$

$$C^E = 0, \tag{3'}$$

$$D^E = \frac{f_{\omega\pi\gamma} F_{1\omega NN}}{(t - m_\omega)^2 + i\Gamma_\omega m_\omega} \tag{4'}$$

(with $F_{1\omega NN}$, $F_{2\omega NN}$ the electric and anomalous magnetic couplings, respectively, and $|f_{\omega\pi\gamma}|^2$ proportional to the decay rate $\omega\to\pi\gamma$). A comparison with Eqs. (1) through (4) near the pole then yields the following for the fixed residues β_1 and β_2:

$$\beta_1 \approx \frac{\frac{1}{2}F_{1\omega NN}f_{\omega\pi\gamma}}{4-m_\omega^2/M^2} \approx -0.155\ \mathrm{BeV}^{-3}, \qquad (9)$$

$$\beta_2 \approx \beta_1/M \approx 1.65\ \mathrm{BeV}^{-4}, \qquad (10)$$

where we have taken the values for the relevant elementary particle couplings from H. Abarbanel, C. Callan, and D. Sharp, Phys. Rev. 143, 1225 (1966); we chose $\epsilon_\omega = \partial\alpha_\omega(t)/\partial t \approx 1$. Since the anomalous magnetic moment couplings are small, we have neglected terms $\propto F_{2\omega NN}$ for this rough calculation.

[11] M. Braunschweig, D. Husmann, K. Lübbelsmeyer, and D. Schmitz, Phys. Letters 22, 705 (1966).

[12] Details about the parameters used in the fitting, and the fits obtained, will be presented in a separate paper. A table of parameters used, and examples of cross-section fits (at $k = 800$, 1175, and 1400 MeV) and polarization fits (at $k = 850$ and 975 MeV), can also be found in E. D. Bloom, thesis, California Institute of Technology, 1967 (unpublished). As input data for the lower and intermediate region, we used the data compiled in Ref. 1 plus the results of this experiment; for the higher energy region, $k \geq 1500$ MeV, see Ref. 11 and G. C. Bolon, D. Garelick, S. Homma, P. D. Luckey, R. Lewis, L. S. Osborne, and J. Uglum, in Proceedings of the Thirteenth International Conference on High Energy Physics, Berkeley, 1966 (University of California Press, Berkeley, California, 1967).

[13] See the rapporteur talk of P. G. Murphy, in Proceedings of the Thirteenth International Conference on High Energy Physics, Berkeley, 1966 (University of California Press, Berkeley, California, 1967), and references there.

[14] H. Harari, Phys. Rev. 155, 1565 (1967).

[15] See, e.g., M. P. Locher and H. Rollnik, Phys. Letters 22, 696 (1966).

FURTHER EVIDENCE FOR BARYON EXCHANGE FROM K^+p BACKWARD ELASTIC SCATTERING*

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We have studied K^+p elastic scattering near the backward direction at a beam momentum of 3.5 GeV/c. In addition to providing evidence for baryon exchange, the experimental results show a possible turnover of the angular distribution for positive values of u which is interpreted in terms of a Reggeized baryon exchange model. We have made a comparison of K^+p, π^+p, and π^-p backward scattering within the framework of SU(3) which leads to predictions concerning other, as yet unmeasured, K^+N processes.

Backward peaks in meson-baryon scattering processes have been observed for several reactions in the past few years.[1] It is well known that such peaks can result from at least two distinct physical mechanisms: (a) the exchange of baryons in the u channel and (b) the excitation of high-spin baryon resonances in the direct or s channel.[2] In general both processes may be expected to contribute thus complicating the analysis. In order to separate these contributions unambiguously it is necessary to study processes in which one or the other mechanism is expected to be absent. For the reasons given below we believe that the process $K^+p\to pK^+$ is relatively free of the effects of direct-channel resonances and, therefore, the study of backward scattering relates directly to the question of baryon exchange. In this note we present evidence for a relatively large cross section for backward K^+p elastic scattering thus indicating the presence of baryon exchange in this process.

K^+p elastic scattering has been studied in the angular region $-0.5 \leq \cos\theta \leq -1$, using film from an exposure of the Brookhaven National Laboratory 80-inch bubble chamber to a 3.53-BeV/c K^+ beam.[3] The exposure yielded 0.196 μb/event. Events of two types were distinguished on the scanning table according to the following criteria:

(1) A two-pronged interaction in which one track made an angle greater than 90° with the beam track. The other track must then have been on the opposite side of the beam at an angle less than the maximum kinematically allowed for backward elastic scattering. In general the kaon could be distinguished from pions by ionization.

(2) A two-pronged interaction in which a minimum ionizing track had a projected angle be-