[4]G. C. Ball and J. Cerny, Phys. Rev. 177, 1466 (1969).
[5]S. M. Austin, P. J. Locard, W. Benenson, and G. M. Crawley, Phys. Rev. 176, 1227 (1968); P. J. Locard, S. M. Austin, and W. Benenson, Phys. Rev. Letters 19, 1141 (1967).
[6]A. S. Clough, C. J. Batty, B. E. Bonner, C. Tschalär, L. E. Williams, and E. Friedman, Nucl. Phys. A137, 222 (1969).
[7]B. D. Walker, J. D. Anderson, J. W. McClure, and C. Wong, Nucl. Instr. Methods 29, 333 (1964).
[8]R. R. Borchers and C. H. Poppe, Nucl. Phys. 129, 2679 (1963).
[9]J. D. Anderson and C. Wong, unpublished.
[10]N. K. Glendenning, Phys. Rev. 144, 829 (1966).
[11]G. R. Satchler, Nucl. Phys. 77, 481 (1966).
[12]V. A. Madsen, Nucl. Phys. 80, 177 (1966).
[13]F. A. Schmittroth, thesis, Oregon State University, 1968 (unpublished).
[14]C. Wong, J. D. Anderson, J. McClure, B. Pohl, V. A. Madsen, and F. Schmittroth, Phys. Rev. 160, 769 (1967), and J. D. Anderson, V. A. Madsen, F. A. Schmittroth, and C. Wong, to be published.
[15]E. Rost and P. D. Kunz, Bull. Am. Phys. Soc. 14, 71 (1969), and to be published.
[16]J. Atkinson and V. A. Madsen, Phys. Rev. 1, 1377 (1970).
[17]S. D. Bloom, *Isobaric Spin in Nuclear Physics*, edited by J. D. Fox and D. Robson (Academic, New York, 1966), p. 895.
[18]E. J. Konopinski, *Theory of Beta Radioactivity* (Oxford Univ., Oxford, England, 1966), p. 403.
[19]T. Lauritsen and F. Ajzenberg-Selove, Nucl Phys. 78, 1 (1966).
[20]H. A. Jahn and H. van Wieringer, Proc. Roy. Soc. (London), Ser. A 209, 502 (1951).
[21]F. Petrovich, private communication.

PRODUCTION OF SINGLE NEGATIVE PIONS FROM DEUTERIUM WITH POLARIZED PHOTONS*†

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The asymmetry $A=(d\sigma_\perp - d\sigma_\parallel)/(d\sigma_\perp + d\sigma_\parallel)$ of the differential cross section for the reaction $\gamma d \rightarrow \pi^- pp$ has been studied with linearly polarized photons of 3.0 GeV at squared four-momentum-transfers between 0.15 and 2.0 $(\text{GeV}/c)^2$. The asymmetry was found to be positive at $-t$ values below 0.3 $(\text{GeV}/c)^2$, dipping to negative values between 0.4 and 0.6 $(\text{GeV}/c)^2$, and then rising again to positive values above 0.7 $(\text{GeV}/c)^2$.

Experiments on single $\pi^\pm$ production from nucleons with unpolarized photons[1] have shown that over a large range of energy and momentum transfer the π^-/π^+ cross-section ratio $R = d\sigma(\gamma n \rightarrow \pi^- p)/d\sigma(\gamma p \rightarrow \pi^+ n)$ is appreciably smaller than one, indicating a strong interference between the isovector and isoscalar photon amplitudes. In a t-channel exchange picture, this implies the interference between exchange amplitudes of opposite G parity. The interference can occur only between exchanges of the same spin and parity, for instance between exchange amplitudes of ρ $(G=+1)$ and A_2 $(G=-1)$, which have natural spin and parity, $P(-1)^J=+1$, or between B $(G=+1)$ and π $(G=-1)$, which have unnatural spin and parity, $P(-1)^J=-1$.

Experiments with linearly polarized photons can separate the natural from the unnatural spin and parity exchanges, since at high energy and small momentum transfers photons that are linearly polarized perpendicular (parallel) to the pion production plane contribute only to the natural (unnatural) spin and parity exchange mode.[2] Data from such experiments provide a stringent test of various theoretical models for the photoproduction of pions.[3] Combined π^+ and π^- data, where available,[4,5] permit one to determine the magnitude of the $G=\pm1$ interference term separately in each of the spin and parity exchange modes and may aid in the identification of the contributing amplitudes.[6] Previous polarized-beam experiments on π^- production covered small $-t$ values up to 0.6 $(\text{GeV}/c)^2$; this experiment extends the range of four-momentum transfers in π^- production up to $-t=2.0$ $(\text{GeV}/c)^2$.

We have studied the reaction $\gamma d \rightarrow \pi^- pp$ with linearly polarized photons of energy 3.0 GeV at squared four-momentum-transfers, $-t$, between 0.15 and 2.0 $(\text{GeV}/c)^2$. Coincidence yields were measured between the pion and one of the recoil protons using photons polarized both perpendicular ($\perp$) and parallel ($\parallel$) to the pion production plane. From these measurements, differential cross-section ratios $(d\sigma_\perp/d\sigma_\parallel)_{\gamma d \rightarrow \pi^- pp}$, and asymmetries $A^- = [(d\sigma_\perp - d\sigma_\parallel)/(d\sigma_\perp + d\sigma_\parallel)]_{\gamma d \rightarrow \pi^- pp}$, were determined.

Electrons of 6.0 GeV from the Cambridge Electron Accelerator (CEA) incident on a suitably oriented diamond monocrystal produced a bremsstrahlung beam with the characteristic polarized-photon spikes.[7,8] The orientation of the diamond was chosen so that the principal spike was produced for the perpendicular and the parallel polarization direction from single equivalent reciprocal lattice points with Miller indices (220) and (2$\bar{2}$0), respectively. As a result of this symmetry, the coherent photon spectra for the two polarization states have the same shape and degree of polarization (~50%), so that systematic errors in the cross-section ratios due to differences in the photon spectra are effectively minimized. For each polarization direction, the energy of the principal spike, E_c, was chosen to lie typically at 3.1 and at 2.85 GeV, respectively. By subtracting the normalized photon yields from two runs with the same polarization direction but different E_c, we determine the energy of the polarized photons producing the pions to within $\Delta E_c \cong 250$ MeV [see Fig. 1(a)].

The collimated photon beam traversed, in order, a liquid-deuterium target at the pivot point of the pion-proton detection system, a thin converter in a pair spectrometer used to monitor the photon spectrum, and a thin ionization chamber, before being absorbed in a gas-filled quantameter.

The pions produced in the deuterium target were detected and their momentum and production angle measured using scintillation trigger counters and wire spark chambers mounted on a magnetic spectrometer.[9] The recoil proton was detected in coincidence with the pion by a scintillation-counter telescope. The solid angle subtended by this telescope at the deuterium target was large enough to allow for Fermi-momentum and direction smear in the recoil proton. The other proton, assumed to be a spectator, was not detected.

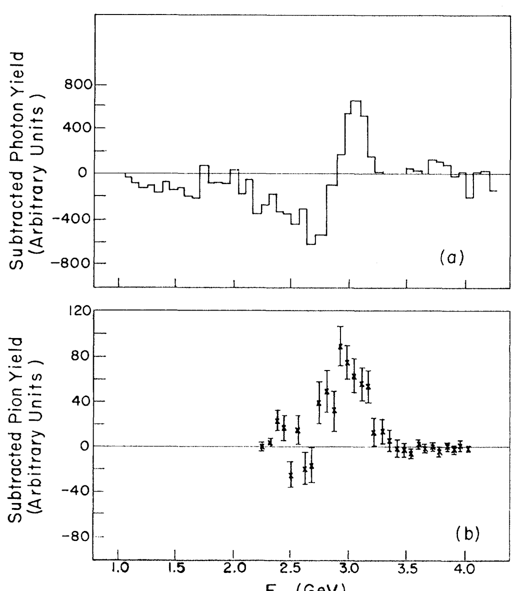

FIG. 1. (a) Typical photon-yield spectrum, obtained by subtracting normalized photon yields of two runs with spike energy $E_C = 3.10$ and 2.85 GeV, respectively, and (b) corresponding subtracted pion-yield spectrum.

For each coincidence between the two detection arms the energy of the incident photon E_γ was calculated from the measured momentum and angle of the pion assuming two-body ($\gamma n \rightarrow \pi p$) kinematics. The subtracted normalized pion yields from two runs with $\Delta E_c = (3.1-2.85)$ GeV, but the same polarization direction, plotted as a function of E_γ, shows a peak centered around 3.0 GeV with a full width at half-maximum of typically 350 MeV. This peak [see Fig. 1(b)] corresponds to the photon subtraction interval of $\Delta E_c = 250$ MeV smeared by the energy resolution of our detection system and by the Fermi momentum of the recoil nucleon.

Single-pion-production events in the subtracted pion yield spectra were identified with events under this peak, typically between $E_\gamma = 2.9$ and 3.1 GeV. We checked for multiple-pion contamination of our data by varying the width of this interval (up to $\Delta E_\gamma \cong 300$ MeV). Within the statistical accuracy of the experiment, no multiple-pion contamination was found in the cross-section ratios.

The calculation of E_γ from the pion's momentum and angle, using two-body kinematics, treats the undetected nucleon as a spectator particle. In addition, spectator-model assumptions are needed if one identifies the ratio measured from deuterium $(d\sigma_\perp/d\sigma_\parallel)_{\gamma d \rightarrow \pi^- pp}$ with the free-neutron ratio $(d\sigma_\perp/d\sigma_\parallel)_{\gamma n \rightarrow \pi^- p}$. In earlier experiments[1] in which measurements of the hydrogen/deuterium π^+ ratio, $d\sigma(\gamma p \rightarrow \pi^+ n)/d\sigma(\gamma d \rightarrow \pi^+ nn)$, were made with unpolarized photons, similar assumptions had been tested and found to be valid in the region of s and t covered by this experiment. As a further check of the validity of the spectator model for calculating asymmetries in this polarized-photon experiment, cross-section ratios $d\sigma_\perp/d\sigma_\parallel$ have been measured recently by our group[4] for the reactions $\gamma d \rightarrow \pi^+ nn$ and $\gamma p \rightarrow \pi^+ n$ at $-t = 0.3$ and 0.9 $(\mathrm{GeV}/c)^2$. The data support the validity of the model.

Our results for the asymmetry A^- are presented in Fig. 2. At $-t$ values below 0.6 $(\mathrm{GeV}/c)^2$, we observe a steep drop in the asymmetry from positive values to a minimum at $-t \cong 0.5$ $(\mathrm{GeV}/c)^2$

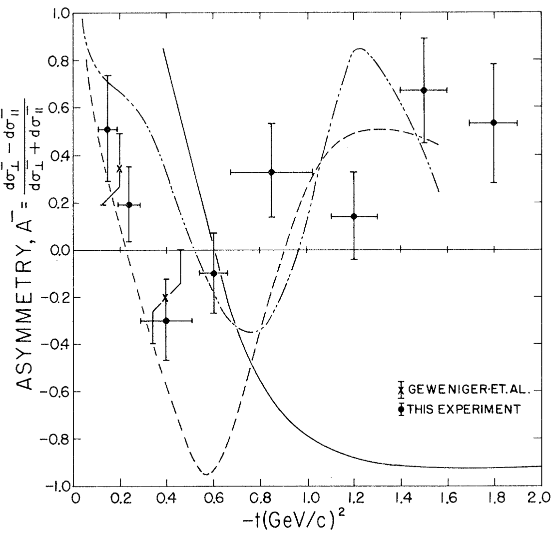

FIG. 2. Asymmetry for the process $\gamma d \rightarrow \pi^- pp$ at 3.0 GeV incident photon energy as a function of $-t$. The vertical error bars include statistical errors, the uncertainty in the number of photons in the subtracted photon-yield spectrum (10%), and the error in the degree of photon polarization (5%). Horizontal bars indicate the $-t$ range included in each data point. The two DESY points are from Geweniger *et al.* of Ref. 5. The dashed curves are from two different models due to Korth; the solid curve is the prediction of Frøyland and Gordon, Ref. 3.

in good agreement with the DESY data. At $-t$ values above 0.6 $(\mathrm{GeV}/c)^2$, the asymmetry seems to rise again, though more slowly, and reaches positive values above 1.2 $(\mathrm{GeV}/c)^2$. Thus, natural parity exchange dominates both at small $-t$ $[\lesssim 0.2\ (\mathrm{GeV}/c)^2]$ and at large $-t$ $[\sim 1.5\ (\mathrm{GeV}/c)^2]$, whereas natural and unnatural parity exchanges seem to contribute about equally in the intermediate $-t$ region.[10]

A comparison of the results with the vector-dominance model (VDM) free of the $\rho^0-\omega$ interference term requires asymmetry data on both π^- and π^+ production.[11] This comparison has been made for $-t$ values up to 0.6 $(\mathrm{GeV}/c)^2$ by two groups at the Stanford Linear Accelerator Center,[12,13] and at DESY.[14] Completion of the analysis of CEA data on the π^+ photoproduction[4] up to 1.2 $(\mathrm{GeV}/c)^2$ will permit a further check of VDM at higher momentum transfers. Deibold and Poirier,[12] using the helicity and also the Donohue-Högaasen frame, find strong disagreement with VDM for both the asymmetry and the cross-section sum $(d\sigma_\perp^+ + d\sigma_\perp^-)$ at 0.2 and 0.4 $(\mathrm{GeV}/c)^2$, but reasonable agreement at 0.6 $(\mathrm{GeV}/c)^2$. Guiragossián and Levy,[13] using the Donohue-Högaasen frame, find agreement with VDM at all $-t$ values for the asymmetry, but their VDM relation on the cross-section sum shows discrepancies between the photoproduction and the vector-meson data.

The Regge model of Frøyland and Gordon[3] successfully fitted the π^-/π^+ ratio from unpolarized photons at 3.4 GeV. It also was successful in predicting the π^-/π^+ ratio at energies up to 16 GeV and the asymmetry A^+ for π^+ production with polarized photons measured at DESY. However, large discrepancies between the model and our A^- data are evident from Fig. 2 in the region between $-t = 1.0$ and 2.0 $(\mathrm{GeV}/c)^2$. Fits based on other multiparameter models have been attempted with varying success[3]; see Fig. 2.

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[1]Z. Bar-Yam, J. de Pagter, M. M. Hoenig, W. Kern, D. Luckey, and L. S. Osborne, Phys. Rev. Letters 19, 40 (1967); P. Heide, U. Kötz, R. A. Lewis, P. Schmüser, H. J. Skronn, and H. Wahl, Phys. Rev. Letters 21, 248 (1968); A. M. Boyarski, R. Diebold, S. D. Ecklund, G. E. Fischer, Y. Murata, B. Richter, and W. S. C. Williams, Phys. Rev. Letters 21, 1767 (1968).

[2]P. Stichel, Z. Physik 180, 170 (1964).

[3]See, for instance, J. Frøyland and D. Gordon, Phys. Rev. 177, 2500 (1969); K. H. Mütter and E. Tränkle, Phys. Rev. 184, 1555 (1969); W. Korth, to be published, cited in the report by K. Lübelsmeyer, in *Proceedings of the Fourth International Symposium on Electron and Photon Interactions at High Energies, Liverpool, England, September 1969,* edited by D. W. Braben (Daresbury Nuclear Physics Laboratory, Daresbury, Lancashire, England, 1970); F. Henyey, G. Kane, D. Richards, and M. Ross, *ibid.,* Abstract No. 10. Many other models deal with the small $-t$ region only; a summary of recent results is contained in the report by K. Lübelsmeyer cited above in the review article by R. Diebold, Stanford Linear Accelerator Center Report No. SLAC-PUB-673, 1969 (unpublished).

[4]π^+ production with polarized photons was measured at DESY up to $-t = 0.6$ $(\mathrm{GeV}/c)^2$ by C. Geweniger, P. Heide, U. Kötz, R. A. Lewis, P. Schmüser, H. J.

Skronn, H. Wahl, and K. Wegener, Phys. Letters 29B, 41 (1969), and at CEA up to $-t = 1.2$ (GeV/c)^2 by Z. Bar-Yam, J. de Pagter, J. Dowd, W. Kern, P. D. Luckey, and L. S. Osborne. Preliminary results of the CEA group and additional preliminary DESY data were included in the report by K. Lübelsmeyer, Ref. 3.

[5]π^- production with polarized photons was measured at DESY by C. Geweniger, P. Heide, U. Kötz, R. A. Lewis, P. Schmüser, H. J. Skronn, H. Wahl, and K. Wegener, Phys. Letters 28B, 155 (1968), and at CEA by Z. Bar-Yam, J. de Pagter, J. Dowd, and W. Kern, *cf.* the report by B. Richter in the *Proceedings of the Fourteenth International Conference on High Energy Physics, Vienna, Austria, 1968,* edited by J. Prentki and J. Steinberger (CERN Scientific Information Service, Geneva, Switzerland, 1968), and Bull. Am. Phys. Soc. 14, 542 (1969). Recent preliminary results were included in the report by K. Lübelsmeyer, Ref. 3.

[6]R. Diebold, Phys. Rev. Letters 22, 204 (1969), and Stanford Linear Accelerator Center Report No. SLAC-PUB-673, 1969 (unpublished).

[7]H. Überall, Phys. Rev. 103, 1055 (1956); G. Barbiellini, G. Bologna, G. Diambrini, and G. P. Murtas, Phys. Rev. Letters 8, 454 (1962); G. Diambrini Palazzi, Rev. Mod. Phys. 40, 611 (1968).

[8]A description of the precision goniometer for the remotely controlled alignment of the diamond is contained in IEEE Trans. Nucl. Sci. 16, No. 1, 648 (1969).

[9]Z. Bar-Yam, V. Elings, D. Garelick, R. Lewis, W. Lobar, P. D. Luckey, L. Osborne, S. Tazzari, J. Uglum, and R. Fessel, Nucl. Instr. Methods 56, 1 (1967).

[10]Preliminary results of this experiment, as reported in Abstract No. 51 of the *Proceedings of the Fourth International Symposium on Electron and Photon Interactions at High Energies, Liverpool, England, 1969,* edited by D. W. Braben (Daresbury Nuclear Physics Laboratory, Daresbury, Lancashire, England, 1970), and cited in the report by K. Lübelsmeyer, *ibid.*, p. 45, included a point at $-t = 2.4$ (GeV/c)^2 which showed A^- to be -0.86 ± 0.21. Confirmation of this point and additional measurements in its vicinity are needed and are being pursued by our group.

[11]See, for instance, M. Krammer and D. Schildknecht, Nucl. Phys. B7, 583 (1968).

[12]R. Diebold and J. A. Poirier, Phys. Rev. Letters 22, 255, 692(E), 906 (1969).

[13]Z. G. T. Guiragossián and A. Levy, Phys. Letters 30B, 48 (1969).

[14]See, for instance, D. Schildknecht, DESY Report No. 69/41 (unpublished).

POSSIBLE DIFFICULTY WITH THE "EIKONAL PICTURE" OF HIGH-ENERGY INTERACTIONS*

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We present a heuristic argument suggesting that at high energies the effect of multiple scattering off the energy shell becomes important for an understanding of the propagation of one elementary particle through another.

The physical picture of high-energy scattering at small angles as a diffractive effect[1] plays a large role in our present understanding of these processes. Although mathematically this picture has been related to the eikonal approximation in potential scattering, there are some physical differences, having to do with the "adiabatic" or "closure" concept, which may become important at high energy. In particular, when we consider the propagation of strongly interacting particles through a dense medium, the following problem arises. If we know that only interactions occurring along the classical trajectory are important we can understand that on-shell scattering is more important than off-shell. If, on the other hand, we know that on-shell scattering dominates we can understand (by a stationary-phase argument) that interactions occurring along the classical trajectory are the most important ones.[2] Of course these two statements together do not imply that either of the hypotheses (dominance of the classical trajectory or dominance of on-shell effects) is true at high energies. A very simple picture, described below, suggests that in the "closure approximation" they are both false.

The picture we use is a descendant of the algebraic formulation of multiple scattering introduced by Foldy.[3] We isolate three points in the medium, labeled 1, 2, and 3 in Fig. 1, and ask for the coherent wave incident on point 3, due to scatterings at 1 and 2, averaged over all positions of point 2. This averaging represents the "closure approximation." We consider first the wave incident on 2, due to an interaction at point 1. Now, because point 2 may come very close to point 1, we should use not only the outgoing part of the scattered wave, but also the standing wave, or "near zone" parts, which represent the effects of (half) off-energy-shell scattering. We repre-