Phys. Rev. Lett. 20, 1265 (1968)], between the Haystack-Millstone observations and those obtained at Arecibo have now been resolved and will be discussed in a joint publication with R. B. Dyce and R. F. Jurgens.

[12]A further contribution will come from the Mariner Venus-Mercury Flyby Mission scheduled for 1973-1974, which will allow in addition a reduction by about three orders of magnitude in the uncertainty of the estimate of Mercury's mass—the parameter at present most highly correlated (0.5) with the estimate of $\dot{G}/G$. Even for the current radar data set, an independent knowledge of Mercury's mass would reduce the formal standard error in $\dot{G}/G$ by 25%.

[13]See, for example, C. O. Alley *et al.*, Science 167, 458 (1970).

π^0 Photoproduction from Hydrogen with Linearly Polarized Photons*

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The asymmetry in the process $\gamma+p\rightarrow\pi^0+p$ with polarized photons has been measured at 6 GeV for momentum transfers from $t=-0.4$ $(\text{GeV}/c)^2$ to $t=-1.1$ $(\text{GeV}/c)^2$, using coherent bremsstrahlung from a diamond crystal. A coincidence was made between the recoil proton in a 1.6-GeV/c spectrometer and one of the π^0 decay photons in a Lucite shower counter. The measured asymmetry $(\sigma_\perp-\sigma_\parallel)/(\sigma_\perp+\sigma_\parallel)$ is consistent with strongly dominant natural parity exchange in the t channel.

In a strict Regge-pole model, π^0 photoproduction at small t values and high energies should proceed by Reggized ω, ρ, and B exchange.[1] However, measurements[2,3] of the differential cross section show that if the commonly accepted trajectories for the ω and the ρ are used, cuts or absorption must be included to account for the data. The cross-section data alone cannot differentiate between a wide variety of models[4-7]; in particular, they cannot exclude B exchange. Measurements with linearly polarized photons allow the separation of[8] the natural- and unnatural-parity exchanges to leading orders of t/s. The asymmetry is defined as $A=(\sigma_\perp-\sigma_\parallel)/(\sigma_\perp+\sigma_\parallel)$, where $\sigma_\perp$ $(\sigma_\parallel)$ is the cross section with photons polarized normal (parallel) to the reaction plane. Trajectories with a natural-parity sequence (ω,ρ) will contribute only to $\sigma_\perp$, whereas trajectories with unnatural parities (B) will contribute only to $\sigma_\parallel$. Absorption or cuts are expected to make contributions to both.

Previous to this experiment, asymmetry data[9] were available at 3 GeV. The data clearly demonstrated that π^0 photoproduction is dominated by natural-parity exchange even in the region of $t=-0.5$ $(\text{GeV}/c)^2$; however, they still allowed an appreciable amount of B exchange.[4] Furthermore, it was argued that at 3 GeV resonances might still be playing an important role. We report here preliminary results of an experiment at 6 GeV and values of the four-momentum transfer t between -0.4 $(\text{GeV}/c)^2$ and -1.1 $(\text{GeV}/c)^2$.

The layout of the experiment is shown in Fig. 1. A well-prepared electron beam with a phase space $(\Delta x\,\Delta\theta)^2=(8\times10^{-6})^2$ (cm rad)^2 is focused onto a suitably oriented diamond 0.1 cm thick. After the radiator the electrons are deflected into a beam dump, and the photon beam, as defined by several collimators, is passed through a liquid hydrogen target and stopped in a secondary emission quantameter (SEQ) which was our primary beam monitor. The beam was also monitored by a Cherenkov cell placed just upstream of the target. The process was determined by a coincidence between the recoil proton detected in the 1.6-GeV/c spectrometer, and one of the γ's from the π^0 decay observed by one of two lead-Lucite shower counters.

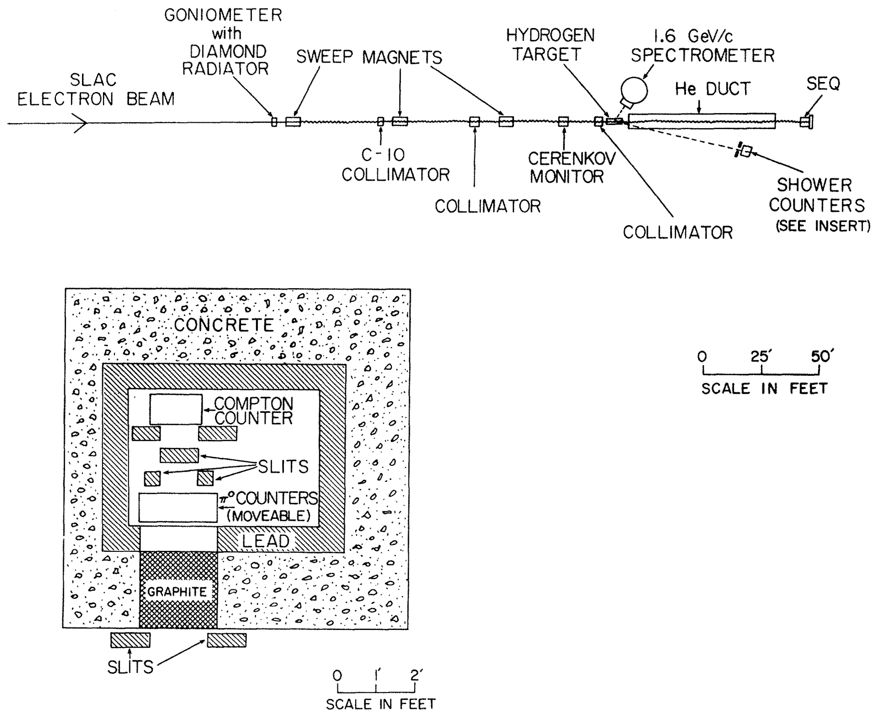

FIG. 1. Experimental layout.

The goniometer for the diamond was constructed and installed at the Stanford Linear Accelerator Center (SLAC) by L. Osborne, D. Luckey, and R. Schwitters. It permits rotations around two perpendicular axes in well-defined steps of 2.32×10^{-5} rad. To align the diamond with respect to the electron beam we used the method proposed by Luckey and Schwitters.[10] This method is based upon the fact that the ratio of the number of photons in the beam to the total power in the beam increases rapidly as the energy of the leading edge of a major spike in the spectrum approaches zero. In our case, this ratio was determined by the ratio of the Cherenkov monitor to the SEQ. Hence, by measuring this ratio we efficiently determined the whole lattice map of the diamond. From the lattice map we can uniquely predict the position of the goniometer to obtain a required spectrum. To check the bremsstrahlung spectrum and our positioning of the diamond we measured the spectrum using the 022 plane as well as the 02$\bar{2}$ plane with the polarized spike set at $x=k/E_0=0.5$ according to the lattice map. The measurement was done using the SLAC pair spectrometer[11] at 0° with the energy of the incident electron beam 12 GeV. The measured spectra for the 022 plane and the 02$\bar{2}$ plane were the same within statistics and they were in good agreement with the computed spectrum.[12] Because of the poor duty cycle at SLAC, the pair spectrometer can only be used at 0° for extremely low beam intensities. However, the phase space and the direction of the electron beam do not depend upon the beam intensity but are completely defined by collimators. During the experiment the peak current was limited to about 1 mA. At this beam level no changes in the lattice map due to heating of the crystal or its holder were observed. We therefore assume that the measured spectrum represents the true spectrum under data-taking conditions. To minimize systematic errors the polarization was switched approximately each half hour and the positions of the 022 and the 02$\bar{2}$ ridges determined. The reproducibility was excellent and the observed changes in the position of the polarized spike at $k=6$ GeV were generally consistent with $\Delta k/k=0$ and never larger than 2%.

The properties of the 1.6-GeV/c spectrometer and the counter system have been described in detail in earlier publications.[3] The spectrometer is a 90° bend, $n=0$ magnet that focuses production angles θ and momentum p of a charged particle into a single focal plane normal to the flight path. Protons were identified by pulse height and range, with pions vetoed by a Lucite Cherenkov counter. The eight hodoscope elements were rotated about the central flight path to align with

(p, θ) lines of constant missing mass.

The photons from the π^0 decay were detected in two shower counters, one above, the other below the reaction plane. The arrangement of the counters is shown in detail in the insert of Fig. 1. Each was 60 cm long, 30 cm high, and about 13 radiation lengths thick. The counters were placed inside a well-shielded cave, which could be moved remotely in angle and height. The distance from the target was approximately 18 m. The θ aperture was defined by remotely movable slits and $\Delta\theta/\theta \sim \Delta k/k$ was kept constant during the experiment. To reduce the pileup from low-energy photons, 2 radiation lengths of carbon was put in front of the counters. To avoid counting Compton events, the counters were placed a distance above and below the reaction plane defined by the incoming photon and the recoil proton. In Compton scattering the scattered photon is in this plane, whereas the π^0 decays into two photons with a typical opening angle of m_π/E_π. The required distance between the π^0 counters is then given by the $\Delta\varphi$ acceptance of the proton spectrometer including multiple scattering. The geometry of the counters was such that only one of the photons could be detected; hence, the outputs from the two counters were simply added linearly. To record simultaneously the Compton events,[13] we had a third shower counter placed in back of the π^0 counters, as indicated in the insert. A coincidence between this counter and the recoil proton defined a Compton event with some residual π^0 events.[14] The aperture of the counter was defined by two pairs of remotely movable slits in front of the counter. To check the alignment as well as to calibrate the counters, we measured e-p scattering at 12 and 6 GeV for $t = -0.5$ (GeV/c)^2. For this measurement the counters were placed in the reaction plane.

In the π^0 measurement the t value as well as the photon energy k were defined by the recoil proton, with the shower counter acting as an approximately $\frac{2}{3}$-efficient device. To make sure that the background was negligible we moved the shower counters down below the π^0 decay cone. After subtraction of the accidentals, the coincidence rate out of the "plane" was (-9 ± 11)% of the coincidence rate in the plane. We therefore subtracted only the accidental counts and no background from the coincident events. Since the background events are presumably less asymmetric than π^0 production, this procedure would lead to a lower limit for the resulting asymmetry. The ratio of accidentals to reals was typically less than 0.2.

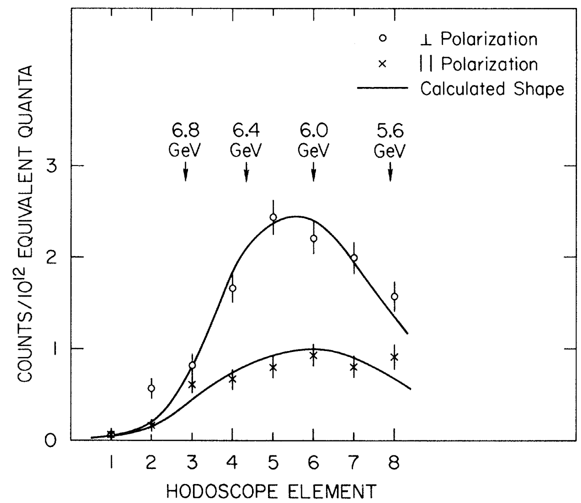

FIG. 2. Coincidence yields in the eight hodoscope elements at $t = -0.8$ (GeV/c)^2 with photons polarized perpendicular and parallel to the production plane. Photon energy increases to the left, as indicated above the points. The edge of the spike was set at 6.74 GeV.

In Fig. 2 the true coincidence rate between the π^0 shower counter and the proton is plotted for the photon polarized normal to the plane and in the plane. Plotted is the result for $t = -0.8$ (GeV/c)^2. The results at other t values are very similar. The photon energy as defined by the recoil proton is indicated on the drawing. For the measurement the leading edge of the 022 ($02\bar{2}$) spike was set at 6.74 GeV. The shape of the solid curve was computed using the measured photon spectrum, folding in the multiple scattering of the proton and the acceptance of the shower counter. The height was then adjusted to give agreement with the data. To determine the asymmetry only the last five ladder elements were used. The part of the photon spectrum corresponding to these elements had an average polarization of 46%. The asymmetries extracted from these data are plotted versus t in Fig. 3, together with the earlier results[9] from the Cambridge Electron Accelerator and a theoretical prediction by Frøyland.[6] Only the statistical error is plotted. In addition we have an estimated systematic error of about 5% resulting from uncertainties in determining the photon energy as well as errors in computing the polarization of the photon beam.

The data at 6 GeV show a very high positive asymmetry, consistent with strongly dominant natural-parity exchange in the t channel. There might be some indication of a dip around $t = -0.5$

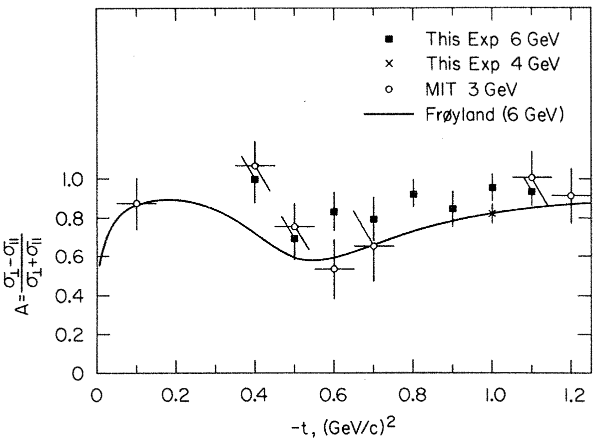

FIG. 3. The measured asymmetry is plotted versus $|t|$ at 6 GeV with one point at 4 GeV. Points at 3 GeV from a previous experiment by the Massachusetts Institute of Technology group are included for comparison. The solid line is a theoretical prediction by Frøyland.

$(\text{GeV}/c)^2$. A comparison with the data at 3 GeV reveals no striking energy dependence within the rather large combined errors.

Theoretical models[4] that rely on B exchange to explain the old data seem to be ruled out by this experiment. These models used a rather flat B trajectory which would dominate in the dip region at higher energies. Hence, with increasing energies the unnatural-parity exchanges become increasingly important in these models, in contradiction to the results of this experiment. A model[5] by Bajpai and Donnachie which explains the differential cross-section data by assuming rather different values for the ρ and ω trajectories also seems to be in disagreement with the results for this experiment.

Models based on ω and ρ exchange as well as cuts can fit all the data.[6,7] Using s-channel helicity amplitudes $f_{\lambda\mu}$, where λ denotes the final and μ the initial proton helicity and the photon helicity is always set equal to 1, the asymmetry A can be written as

$$A=\frac{2\operatorname{Re}(f_{-1/2,-1/2}f_{1/2,1/2}{}^*-f_{-1/2,1/2}f_{1/2,-1/2}{}^*)}{|f_{1/2,1/2}|^2+|f_{-1/2,-1/2}|^2+|f_{-1/2,1/2}|^2+|f_{1/2,-1/2}|^2}.$$

In terms of t-channel exchanges, these amplitudes $f_{\lambda\mu}$ contain natural- as well as unnatural-parity exchanges. However, in a simple Regge model with only natural-parity exchange, the amplitudes are related with $f_{-1/2,-1/2}=f_{1/2,1/2}$ and $f_{-1/2,1/2}=-f_{1/2,-1/2}$, thus $A=1$. The π^0 photoproduction data cannot be fitted by pole exchange alone. Cuts or absorption must be present. In such an absorptive model the relation $f_{1/2,1/2}=f_{-1/2,-1/2}$ still remains valid, but $f_{-1/2,1/2}$ is no longer equal to $-f_{1/2,-1/2}$. Hence, in general we would expect A to be different from 1. Since A is very close to 1 at large t values where absorption dominates, we interpret the results of this experiment to show that $f_{1/2,1/2}$ must be approximately equal to $f_{-1/2,-1/2}$, and $f_{1/2,-1/2}$ and $f_{-1/2,1/2}$ must both be small. The exchange particle must then predominantly couple to the helicity-nonflip amplitude. This is expected to be the case for ω exchange.[7]

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[10]D. Luckey and R. F. Schwitters, Nucl. Instr. Methods 81, 164 (1970).

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[13]In this experiment we collected only preliminary data at 6 GeV and $t=-0.4$ and $-0.5(\text{GeV}/c)^2$, where we measured $A=-0.2\pm0.1$ and 0.04 ± 0.1, respectively. An experiment is in progress to measure the asymmetry in the proton Compton effect with polarized photons over a wide range of t values.