Elastic Scattering of Photons by Protons. I*

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The results of some preliminary measurements on the elastic scattering of photons by protons are reported. In the region of the (3,3) resonance and immediately above, our measurements join smoothly with those previously reported at lower energies. The scattering cross section shows a peak in the vicinity of 300 Mev. There is indication of a $\cos^2\theta$ term in the center-of-mass angular distribution.

WE report the results of some observations on the proton Compton effect, i.e., the elastic scattering of photons by protons:

$$\gamma+p\rightarrow p'+\gamma'. \tag{1}$$

This reaction appears to be adequately described by a modified Klein-Nishina formula[1] below the threshold for meson production; above this threshold, however, mesonic processes dominate the scattering. By making measurements in this region, it can be hoped that important information about the meson-nucleon system can be obtained.[2,3]

Observation of reaction (1) above the meson threshold is made more difficult by the presence of neutral photopions,

$$\gamma+p\rightarrow p'+\pi^0\rightarrow p'+\gamma'+\gamma'', \tag{2}$$

whose production kinematics resemble those of reaction (1), and whose decay photons can have energies as high as that of the elastically scattered quantum. Reaction (2) has a cross section about two orders higher than that of (1).

EXPERIMENTAL METHOD

The photons to be scattered were obtained in the form of a beam of bremsstrahlung from the Cornell 1.2-Bev electron synchrotron. The machine energy was adjusted so as to produce a photon spectrum with a selected upper limit W_0 for each run. Discrimination in favor of reaction (1) relied on two factors: First, measurements were carried out at such angles that the recoil protons from (1) were of longer range than any that could be produced by (2), given the maximum incident energy W_0; second, the angular correlation between the scattered photon and the recoil proton was studied. This correlation is exact (determined by experimental geometric factors) for reaction (1), but is smeared out by the decay kinematics of the neutral pions from reaction (2).

Our apparatus is shown in Fig. 1. A beam of bremsstrahlung, suitably collimated, passed through a cylindrical liquid hydrogen target[4] 5.7 cm in diameter; the total flux was monitored by a Quantameter.[5] Photons and protons emerging from the target were detected in time coincidence by counter telescopes as shown.

The photon detector consisted of a lead glass Čerenkov counter C [6] viewing the target through a rectangular aperture in a 15-cm lead wall. Behind the aperture, and covering its edges, was a scintillation counter A whose function was to veto counts due to charged particles, including conversion electrons from the edges of the lead aperture and the polyethylene absorber (inserted to help shield A from soft electrons). The pulse height from C was proportional to the energy of the photon totally absorbed in the lead glass; pulse-height spectra were monitored continuously and served as a corroborative check.

The protons were counted in a telescope of scintillation counters ($P1$–$P4$) interspersed with absorbers. Two range thresholds were simultaneously defined by counting coincidences $P1+P2$ as well as $P1+P2+P3$. With the addition of tapered absorbers $R1$ and $R2$, these

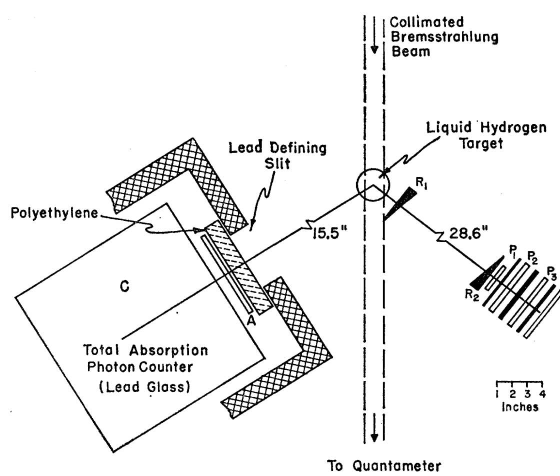

FIG. 1. Experimental arrangement.

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[6] Similar to a counter described by I. Filosofo and T. Yamagata, *Proceedings of the CERN Symposium on High-Energy Accelerators and Pion Physics, Geneva, 1956* (European Organization of Nuclear Research, Geneva, 1956), Vol. 2, p. 89, but using four 5-in. photomultiplier tubes. See also J. M. Brabant, B. J. Moyer, and R. Wallace, Rev. Sci. Instr. 28, 421 (1957).

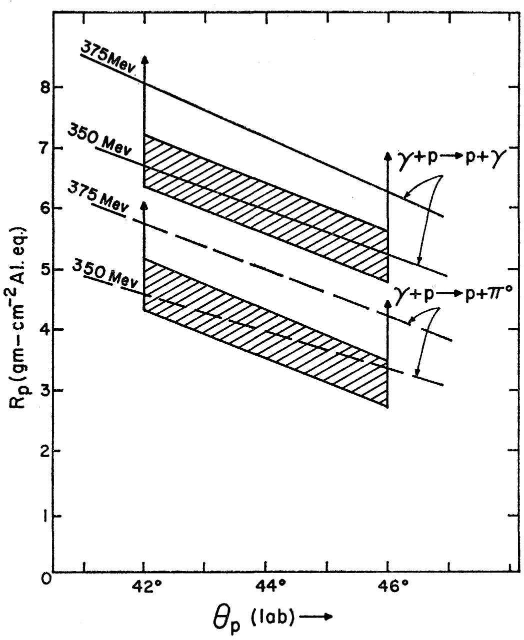

FIG. 2. The reaction kinematics for both reactions are shown over a narrow sample angular interval. The proton range is plotted as a function of its laboratory angle. The parameters on the curves are the incident photon energies. The upper shaded box represents the range threshold for the Compton channel; it is smeared out by the effect of target thickness. Its variation as a function of angle is obtained with suitably tapered absorbers. The lower shaded box is the smeared-out range threshold for the pion channel. If the bremsstrahlung cutoff energy W_0 is set at 375 Mev in this example, no recoil protons from reaction (2) should be detected in the Compton channel. The angular limits of detection are defined by the width of the first proton counter $P1$.

thresholds were made a function of the proton angle; Fig. 2 illustrates how they then serve to define two counting channels, of which one is sensitive, in principle, only to protons from reaction (1), while the other detects those from both (1) and (2). The two channels (each taken in coincidence with the photon counter C) will be called Compton and pion channel, respectively.

The reason for the inclusion of a pion channel is illustrated by Fig. 3. It is seen that the Compton channel is sensitive to only a narrow interval of incident photon energies, defined on the lower side by the range threshold for recoil protons, and on the upper by the end-point of the bremsstrahlung spectrum. Because this interval is narrow, errors in the locations of its boundaries have severe effects. For example, a 1-Mev error in the end-point energy will change the number of selected quanta in the bremsstrahlung typically by 5%; similarly, an error of 0.1° in the setting of the proton telescope angle will change this number by 4%, since the proton angle enters, via the reaction kinematics, very sensitively into the determination of the lower boundary. Now the pion channel is subject to almost precisely the same errors since its parameters are tied to those of the Compton channel. Hence we can use the known pion cross sections[7] as a means of calibration. This calibration did, in fact, reveal significant (−10% to +40%) systematic errors due to deviations in the definition of the bremsstrahlung boundaries; the detailed source of these errors has not, however, been traced.

For each run, the angular correlation between photon and proton was explored. At the lower energies, this was

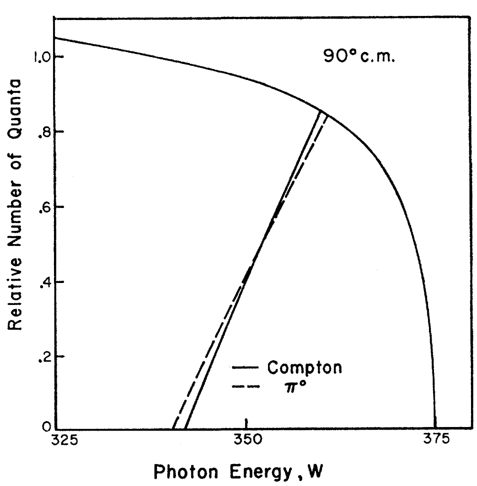

FIG. 3. The upper end of the bremsstrahlung distribution is shown for $W_0=375$ Mev, corresponding to the conditions of Fig. 2. The shaded range thresholds for the two channels are reflected as the slanted lines in this diagram. The number of quanta contributing to the reactions being observed is given by the area under the curve lying to the right of the line.

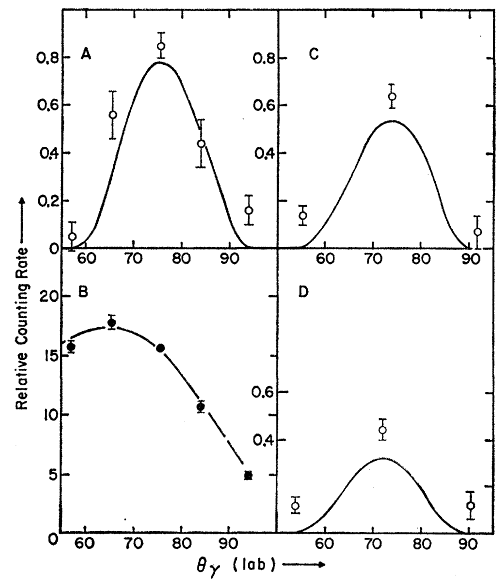

FIG. 4. Sample angular correlations between proton and photon. All curves apply to θ_p(lab)=44°. A: Distribution in Compton channel, W=300–325 Mev. B: Distribution in pion channel, 300–325 Mev. C: Compton channel, 350–375 Mev. D: Compton channel, 400–425 Mev. The expected angular distributions are indicated in each case.

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done by moving the photon telescope in azimuth. At the highest energy, it is advantageous to move the counters in the *polar* direction instead since this results in a sharper angular definition for a given solid angle of detection.[8]

RESULTS

Illustrative correlation functions for the proton and photon angles are shown in Fig. 4. These show that the Compton channel counts predominantly protons from process (1), but that some "leakage" from reaction (2) does persist. This can probably be explained by the scattering of some recoil protons from (2) into a more backward angle. The expected correlation functions for the two processes are shown on the figure; if we assume that these correlations will also hold for counts from (2) leaking into the Compton channel, then the contributions in this channel can be clearly resolved.[9]

The coincidence resolving time was 15 nsec; random coincidences were monitored and corrected for ($<2\%$).

TABLE I. Angles, energy intervals, and differential cross sections observed.

Scattering angle (c.m.)	W (Mev)	θ_p (lab)	θ_γ (lab)	$d\sigma/d\Omega$ (c.m.) (10^{-31} cm^2)
75°	300–325	51.5°	60.5°	1.80±0.16
	300–350	51.5°	60.5°	1.95±0.26
90°	275–300	43.5°	76.5°	1.58±0.11
	300–325	44.0°	75.6°	1.43±0.09
	350–375	44.0°	73.8°	1.33±0.13
	400–425	44.0°	72.2°	1.20±0.17
120°	300–315	29.2°	106.6°	2.06±0.21
60°	725–775	57.5°	39.0°	0.3±0.3

Empty-target counting rates were measured and subtracted ($<10\%$). As a check, some excitation functions for the two counting channels were observed by varying the bremsstrahlung end-point energy in small steps. Although the statistical accuracy obtained in this check was not high, the results were consistent with the interpretation that reactions (1) and (2) were responsible for the observed counting rates. Finally, the pulse-height spectra in photon counter C were monitored; within the energy resolution of this counter, agreement with the expected spectra was observed.

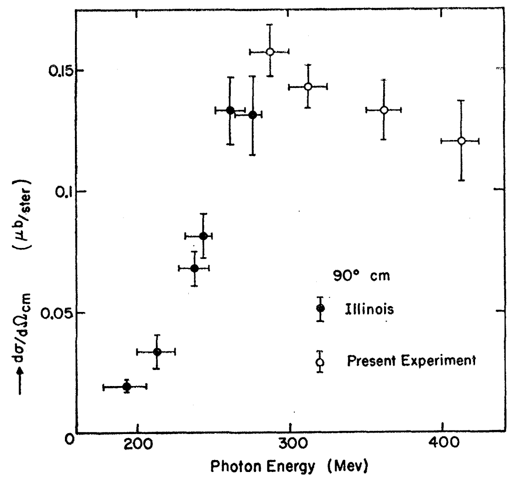

FIG. 5. 90° c.m. differential scattering cross section as a function of incident photon energy.

Differential cross sections for elastic scattering measured by this technique are summarized in Table I and Figs. 5 and 6. The stated errors are computed from statistics and the uncertainty in the π^0 cross section[7] used for calibration. No systematic errors are included, but these are believed to be comparatively smaller. Figure 5 shows the cross sections at 90° in the center-of-mass as a function of incident photon energy. Some lower-energy data obtained by Bernadini *et al.*[3] are included on the plot. Although the errors are too large to permit a detailed interpretation, it is seen that the scattering cross section follows the general course of the photopion production cross sections in the region of the (3,3) resonance. Figure 6 shows the variation of the 312-Mev cross section with angle over the limited

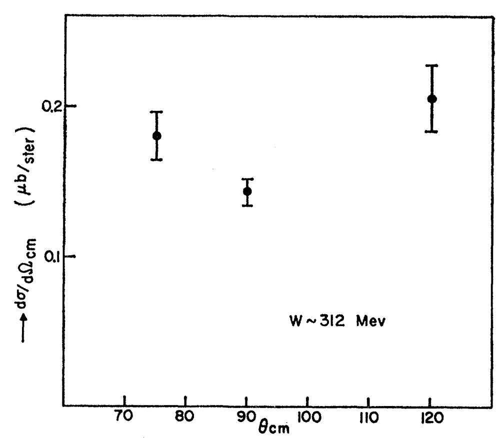

FIG. 6. Variation of scattering cross section with angle at about 312 Mev. For detailed parameters relevant to each point, see Table I.

[8] For reasons of convenience, we decided to move the *proton* telescope, and to move it straight up and down instead of in an arc about the target. The resulting variation of the effective azimuthal angle (by 0.25°) implies a rather severe error in the measurement of the angular correlation. This unfortunately turns out to have invalidated the results from the Compton channel at that energy; what meager data remain are taken from the pion channel only, where [because reaction (1) is not being observed at the end point of the bremsstrahlung spectrum] the variation of azimuthal angle has a much less pronounced effect.

[9] This assumption is unlikely to be strictly correct, since the chief process of leakage presumably comes from recoil protons more forward, and hence pions more backward, than the selected angles. However, errors introduced by this effect are likely to be small. We have in all cases simply *averaged* the forward and backward off-angle counts to obtain the best estimate of the pion contribution.

range accessible to us. It must be emphasized that the 75° point has not been normalized to the neutral photopion cross section, since the short range of recoil protons from that reaction at this angle prevented them from being observed in our telescope. The observed angular distribution suggests the presence of a $\cos^2\theta$ term, as expected on theoretical grounds.[2]

CONCLUSION

The results presented here are, evidently, to be regarded only as preliminary. The calibration procedure involving the photopion cross section reveals, in particular, that the technique of discriminating between scattering and pion production events by working close to the bremsstrahlung end point is subject to systematic errors whose influence cannot be considered as eliminated until their origin is better understood. At present it appears that a more promising technique would be to discriminate entirely on the basis of the angular correlation peculiar to the scattering; this involves observations in much better geometry, requiring higher beam intensities to maintain an acceptable counting rate.

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Elastic Scattering of Photons by Protons. II*

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The differential cross section for Compton scattering on protons is calculated at various energies in the region of and above the peak corresponding to the 3–3 pion-nucleon resonance. For this, the unitarity of the S matrix and a set of approximate dispersion relations for the scattering amplitudes is used. Small admixtures of electric quadrupole in the radiation that produces the first photopion resonance are shown to affect the angular distribution significantly. In the region of the second photopion peak the resonant behavior is found to be clearly reflected on the proton Compton effect.

I. INTRODUCTION

One of the first and most successful applications of dispersion relations and unitarity of the S matrix is on the scattering of photons by protons.[1–5] It has been shown that the basic characteristics of the process in the low-energy region can be explained by assuming that the main contribution to the absorptive part of the process comes from single pion photoproduction in the s state (for π^+) and in the state of the first resonance. Finally, inclusion of the Low amplitude[6] gives very good agreement with the experimental data below 270 Mev.[7,8]

Recently, the experimental group at Cornell[9] has extended the existing data well above the energy of the first peak. The purpose of the present paper is to show that these results can be well accounted for by the basic contributions to single pion photoproduction including that of the second resonance, the contribution of two-pion production estimated with the help of the 3-3 isobar model, and the Low amplitude. Moreover, apart from magnetic dipole, small admixtures of electric quadrupole radiation are considered to be responsible for the photoproduction at the first resonance. Their effect is discussed at the end, where also the results of the calculation are compared with the existing experimental data.

II. APPLICATION OF UNITARITY

Provided that we treat the problem to the lowest order in the fine-structure constant, the amplitude for scattering of photons by particles with spin $\frac{1}{2}$ can be written

$$
\begin{aligned}
A_{\gamma\to\gamma}=&f_1(\hat{e},\hat{e}')+f_2(\hat{k}\times\hat{e},\,\hat{k}'\times\hat{e}')\\
&+if_3(\boldsymbol{\sigma},\,\hat{e}\times\hat{e}')+if_4(\boldsymbol{\sigma},\,[\hat{k}'\times\hat{e}']\times[\hat{k}\times\hat{e}])\\
&+if_5\{(\boldsymbol{\sigma},\hat{k})(\hat{k}',\,\hat{e}'\times\hat{e})-(\boldsymbol{\sigma},\hat{k}')(\hat{k},\,\hat{e}\times\hat{e}')\}\\
&+if_6\{(\boldsymbol{\sigma},\hat{k}')(\hat{k}',\,\hat{e}'\times\hat{e})-(\boldsymbol{\sigma}\hat{k})(\hat{k},\,\hat{e}\times\hat{e}')\},
\end{aligned}
\tag{1}
$$

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