ELASTIC SCATTERING OF 247-Mev GAMMA RAYS ON HYDROGEN

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The angular distribution of 247 ± 10 Mev gamma rays produced in the synchrotron of the Lebedev Physics Institute, which were scattered elastically on hydrogen, has been investigated. Differential cross sections were obtained for c.m. scattering angles of 148, 132, 108, 93, 70, and 55°. The experimental results are compared with calculations based on one-dimensional dispersion relations with an additional contribution from a single-meson intermediate state taken into account.

1. INTRODUCTION

THE elastic scattering of a γ quantum by a proton (the Compton effect) is an elementary process whose investigation can in principle supply information regarding the structure of the proton. At the present time we unfortunately have no satisfactory meson theory of the proton Compton effect at γ-ray energies above the meson photoproduction threshold. Some endeavors to construct a theory of the Compton effect based on different variants of meson theory or even using a phenomenological approach have produced no positive results.

The attempts to develop a theory of the Compton effect on the basis of dispersion relations are more promising.[1-4] However, difficulties are encountered when the contribution of the high-energy region and the effect of the nonphysical region are taken into account.[5]

It has been noted[6] that when constructing a theory of the Compton effect one must take into account the relation between γ-ray scattering and the two-photon decay of the π^0 meson. It is then possible in principle to determine from experimental data the mean life of the π^0 meson (a fundamental property).[7]

At the present time very meager experimental information is available regarding the elastic scattering of γ rays on hydrogen at energies above the meson photoproduction threshold. In the only experimental investigation[8] the dependence of the differential cross section on γ-ray energy was measured in the 120 — 280 Mev range for 90° and 130° c.m. scattering angles. The present work is a detailed investigation of the angular distribution of elastically scattered γ rays of about 250 Mev.

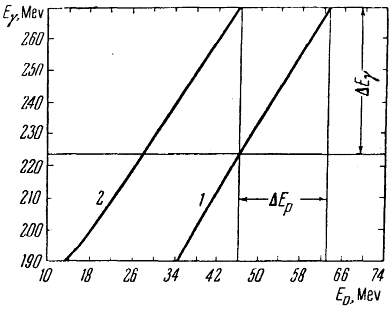

FIG. 1. Kinematic relation between proton energy and γ-ray energy at a fixed angle of proton recoil ($\theta_p = 36°$). 1 — for Compton effect; 2 — for π^0 photoproduction.

2. FORMULATION OF THE EXPERIMENT

Method of identifying the process. The principal difficulty encountered in the experimental investigation of the proton Compton effect,

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

is its extremely small cross section ($\sigma_{tot} \sim 2 \times 10^{-31}$ cm^2). At energies below the meson photoproduction threshold we can confine ourselves to registering only the scattered γ ray, without observing the recoil proton.[9]

Above the meson photoproduction threshold the difficulties are augmented considerably by the photoproduction of neutral mesons and their subsequent decay to two γ quanta:

$$\begin{array}{c}\gamma + p \rightarrow p' + \pi^0, \\ \downarrow \\ \gamma_1 + \gamma_2\end{array} \tag{2}$$

with a cross section that is two orders of magnitude larger than the cross section for process (1). For these reasons, the experimental investigation

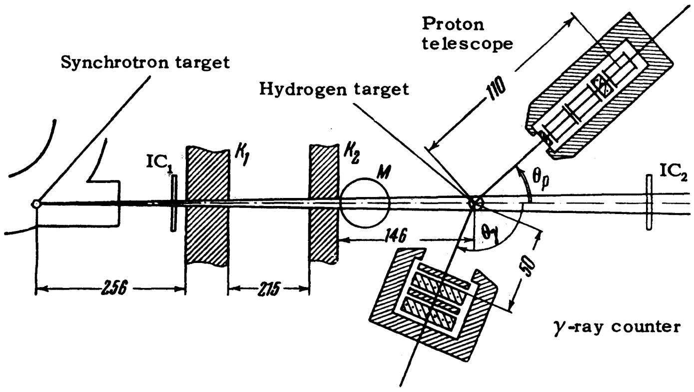

FIG. 2. Experimental geometry (with notation explained in the text).

of elastic γ-ray scattering on hydrogen in the given energy region depends primarily on identifying process (1) against the background of process (2).

In the present work process (1) was identified by registering coincidences between scattered γ rays and recoil protons. The registration of a recoil proton and the determination of its energy for a fixed γ-ray energy provide the basis for distinguishing between processes (1) and (2).

Figure 1 shows the kinematic relation between the recoil-proton energy in reactions (1) and (2) and the incident γ-ray energy for a fixed proton-recoil angle. It is apparent that in a certain γ-ray energy range, $\Delta E_\gamma = E_1 - E_2$, the energy of protons from reaction (1) exceeds that from (2). Since the bremsstrahlung spectrum is continuous, the described method of discrimination can be used only at the end of the spectrum, where $E_1 = E_{\gamma\,max}$. The scattered γ ray must be registered in addition to the proton in order to distinguish process (1) from the reaction

$$\gamma + p \rightarrow n + \pi^+, \quad (3)$$

since the proton telescope sometimes registers charged mesons. The distinction of reaction (1) from reaction (3) is based on the difference between the neutron and γ-ray directions associated with a given angle of charged-particle flight. This difference in the correlated angles is used to exclude the background reaction

$$\gamma + d \rightarrow n + p, \quad (4)$$

which can occur in the 0.02% natural admixture of deuterium contained in liquid hydrogen.

An upper estimate of the background process associated with electron production in the hydrogen target, and with the subsequent electron-proton scattering, has shown that this process contributes $\lesssim$ 0.2% and can be neglected for all the registration angles used in our work.

The background from the walls of the hydrogen target was also sharply reduced by registering proton-γ coincidences.

Experimental geometry (Fig. 2). The bremsstrahlung beam from the synchrotron of the Physics Institute, operated at 260 Mev maximum energy, passed through two lead collimators K_1 and K_2 before entering the liquid hydrogen target. The γ-ray pulse duration was ~ 3000 μsec, corresponding to variation of the maximum bremsstrahlung energy from 244 to 260 Mev. The beam was monitored by two thin-walled ionization chambers IC_1 and IC_2, one placed ahead of collimator K_1, and the other positioned behind the hydrogen target.

Proton telescope. Protons were registered by a telescope consisting of three proportional counters and one scintillation counter placed ahead of either the first or last proportional counter. The proportional counters were glass cylinders of 60-mm diameter and 200-mm length, each with its axial wire parallel to the flight paths of the registered particles. Pieces of 250-micron aluminum foil were cemented to the ends of the counters. The counters were filled with argon and 1% CO_2 at 500 mm Hg. A collimated Po^{210} α-particle source was placed within each proportional counter for the purposes of energy calibration of the counter and a sensitivity check of the setup during operation. The proportional counters in the proton telescope served to determine the energy range of registered protons and to distinguish protons from charged particles of smaller mass ($e^\pm$, $\pi^\pm$). The minimum proton energy was fixed by the total amount of matter ahead of the third telescope counter, while the maximum proton energy was set by the electronic threshold in the amplifying circuit connected to the third counter.

The scintillation counter in the proton telescope consisted of a plastic scintillator (p-terphenyl in polystyrene) 60 mm in diameter and 5.5 mm thick for measurements at 16, 24, 36, and 44°, or 0.3 mm thick for measurements at 56° and 64°, a Plexiglas light pipe, and a FÉU-33 photomultiplier. In the work involving coincidences with γ-ray counter pulses the use of a scintillation counter in the proton telescope resulted in a sharp reduction of the random correlation background, and provided for supplementary discrimination of process (1) from the background process (3) based on the time of flight of particles in these reactions. The angle resolution of the proton telescope was ± 1.5°.

Gamma-ray counter. The γ-ray counter consisted of two liquid scintillators (p-terphenyl in phenylcyclohexane) in Plexiglas containers of 150-mm diameter and 30-mm thickness, used in conjunction with FÉU-33 photomultipliers. A lead converter 8 mm thick was placed before each scintillator. Pulses from the two photomultipliers were summed and sent into coincidences with pulses from the scintillation counter in the proton telescope. The angle resolution of the γ-ray counter was ± 9°; its efficiency was found experimentally to be ~ 80% by comparing the proton-γ coincidence count from reaction (2) with the count of protons alone. Details of the technique and the energy dependence found for γ-ray registration efficiency are described in [10].

Hydrogen target. Our liquid hydrogen target has been described in [11]. The irradiated target volume was a thin-walled brass cylinder of 15-mg/cm^2 wall thickness, 50-mm diameter and 100-mm length. The γ-ray beam had the same diameter as the cylinder. Vacuum pipes were used for γ-ray beam entrance and exit. The first section of the entrance vacuum pipe was located between the poles of a 2000-gauss electromagnet M 20 cm long (Fig. 2). In order to reduce the amount of matter in the proton path, the target vacuum cylinder was equipped with windows covered by 250-micron aluminum foil. The construction and thermal regime of the hydrogen target insured continuity of the measurements during a prolonged period, with liquid hydrogen added at intervals of ~ 50 hours.

Electronics. Figure 3 is a block diagram of the electronic circuit. Pulses from the proportional counters P_1, P_2, and P_3 were amplified and fed through threshold circuits and gates to slow coincidence circuits I, II, and III having the resolving time $\tau = 2 \times 10^{-6}$ sec. Proton-γ coincidences were registered by a fast coincidence circuit with 4×10^{-9} sec resolving time (gated by the scintillation counters), from which pulses were fed to the coincidence circuit III.

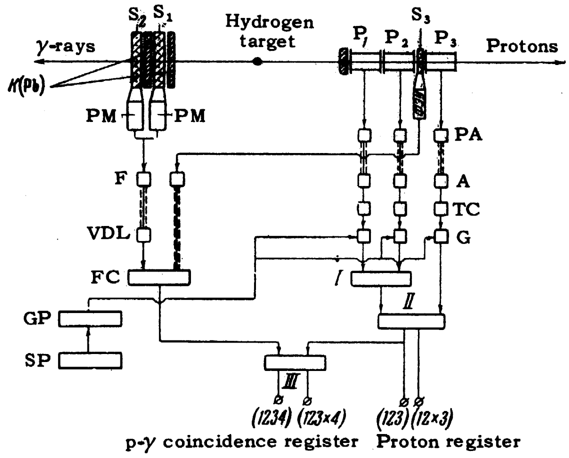

FIG. 3. Block diagram of electronic circuit. P – proportional counters; S – scintillation counters; I, II, III – "slow" coincidence circuits; PA – preamplifiers; A – amplifiers; TC – threshold circuits; G – gates; K – lead converters; F – pulse former; VDL – variable delay line; FC – "fast" coincidence circuit; GP – gating pulse; SP – master pulse from synchrotron.

The entire apparatus was adjusted by registering the photoproduction of π^0 mesons on protons [reaction (2)]. The operation of all electronic units was charted, the dependence of the p-γ coincidences on delay time in one of the fast-coincidence channels was determined, and the resolution times of all coincidence circuits were selected.

In adjusting for the registration of process (1) we took into account the different proton flight times in reactions (1) and (2).

Formulation of experiment and measurement procedure. Our experiments were designed to determine the angular distribution of γ rays, with a given energy, scattered elastically on protons. The kinematic conditions for distinguishing reactions (1) and (2) permitted measurements over a γ-ray range $\Delta E_\gamma \sim 20$ Mev for the maximum bremsstrahlung energy $E_{\gamma max} = 260$ Mev.

The measuring procedure consisted in the alternate registration of yields from reaction (1) at the angles θ_p = 16, 24, 36, 44, 56, and 64°, and of the yield from reaction (2) at θ_p = 16°. The transition to registration of process (2) was accomplished by changing both the energy adjustment of the proton telescope and the angle of the γ-ray counter. For the sake of reliability and convenience in treating the data, the yield of reaction (2) was measured as far as possible in the same γ-ray energy range as for reaction (1).

The measuring procedure gave the yield ratio of processes (1) and (2) for a given γ-ray energy, so that the cross section for (1) could be calculated

θ_p, deg	θ_γ, deg	θ^*_γ, deg	$\bar\theta_p$ (l. s.) deg	$\Delta\bar\theta_p$ (l. s.), deg	$\bar\theta_\gamma$ (c.m.s.) deg	$\bar E_\gamma$, Mev	$\Delta\bar E_\gamma$, Mev	Yield ratio ($\times10^4$) of reactions (1) and (2)	$\frac{d\sigma}{d\Omega}/\left(\frac{e^2}{Mc^2}\right)^2$, cm²/sr (c.m.s.)
16	140	104	15.5	±1.65	148.0	247.7	± 5	140±12	4.17±0,35
24	121	94	23,5	±1,70	132,2	247,8	± 5	110±9,0	3.33±0,28
36	94	140	35,0	±1.70	108,8	247.2	± 5	74±8.0	3.09±0.33
44	78	—	42,5	±1.70	93.1	245.2	± 6	25,7±2.7	2.08±0,24
56	56	94	54.5	±2.0	70,3	237.0	±15	9.43±1.37	1,60±0.20
64	42	76	62.0	±2.0	54.8	232.6	±15	8.07±1.07	1,34±0.18

dependence of differential cross sections given in [8]. Figure 4 shows the resulting angular distribution.

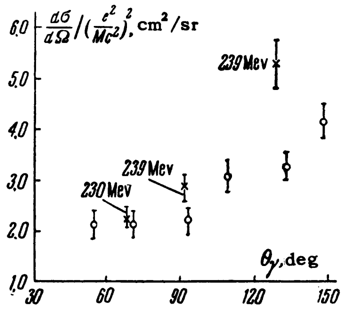

FIG. 4. Angular distribution (c.m.) of γ rays scattered elastically on hydrogen, converted to 247 Mev (lab. system). o – present work; x – from [8].

Comparison with other experimental results. The literature contains only one experimental investigation[8] of the Compton effect at energies above the photomeson threshold. In that work the energy dependence of the cross section at c.m. γ-ray angles 90° and 129° was measured for E_γ = 239 Mev. The differential cross section for the Compton effect is also given at θ_γ = 70° (c.m.) for E_γ = 230 Mev. Our angular distribution can thus be compared with only three points in [8]. Figure 4 shows that both experiments reveal the same tendency toward growth of the cross section for $\theta_\gamma > 90°$, with greater increases in [8].

Comparison with theory. Among the theoretical studies of the Compton effect at energies above the photomeson threshold the work based on dispersion relations is of current interest. Dispersion relations for the proton Compton effect were first derived by Bogolyubov and Shirkov.[1] Numerical results have been given by several investigators.[2,3,7] Our results can be compared directly with those of Akiba and Sato (abbreviated hereafter as AS)[3] and of Jacob and Mathews (abbreviated as JM).[7] The results given in [2] pertain to lower γ-ray energies.*

*Note added in proof (November 17, 1961). After the present article had been sent to press L. I. Lapidus and Chou Kuang-chao published (Preprint D-740 of the Joint Institute for Nuclear Research) numerical calculations for the Compton effect, extended to 300-Mev rays. These results are not compared with ours in the present article.

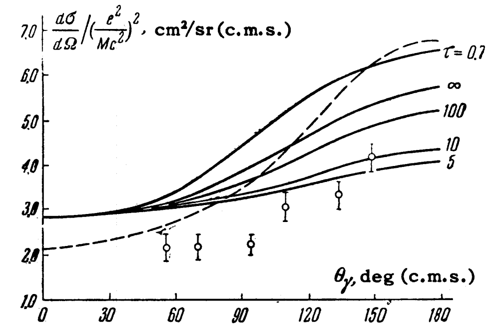

FIG. 5. Comparison of our results, converted to E_γ = 247 Mev (lab. system), with theoretical results of Akiba and Sato [3] (dashed curve) and of Jacob and Mathews [7] (continuous curves). The numerals at the ends of the curves are values of τ in the unit 10^{-18} sec.

Figure 5 shows the data of AS interpolated by us for 247-Mev γ rays, and the data of JM converted by us to the same energy for different values of the mean π^0 life. Both investigations suffer from some uncertainty in the calculation of the dispersion integrals, associated with the existence of a nonphysical region and with the high-energy contribution (5). At 247 Mev the inaccuracy associated with the nonphysical region can appear at c.m. angles $\theta_\gamma > 70°$.[1] In addition to the basic diagrams of the process the JM article takes into account the Low diagram[6] relating γ-ray scattering to two-photon π^0 decay. The Low amplitude makes no contribution to the differential cross section at θ_γ = 0° and increases monotonically with the angle.

The JM result corresponding to zero contribution from the Low amplitude (the curve for $\tau = \infty$) should be close to the AS result. Figure 5 shows large disagreement between the two theoretical studies, and thus indicates the incompleteness of the existing theory.

The comparison of the AS and JM results with our experimental findings in Fig. 5 shows that our absolute values lie somewhat closer to the AS curve at small angles, but fall considerably below that curve at large angles. We could expect that an additional contribution from the Low amplitude when a cross section for (2) was known.

The measurements at each angle θ_p for reaction (1) were checked by varying the γ-ray counter angle.

Measurements were also obtained with an empty target for a few thicknesses of the absorbers ahead of the proton telescope, in order to determine the compensating effect of hydrogen in the target. The p-γ coincidence count in the checking measurements and in the empty target run practically agreed and comprised about 10% of the count from reaction (1). Since the yield from (1) was very small, amounting to from 10 to 3 pulses per hour, a long period was required for the accumulation of sufficient data. In order to obviate all types of errors associated with variation of the synchrotron operating mode the measurements were performed in a number of runs, each of which included several angles θ_p. The sensitivity of the proton telescope was measured regularly at the beginning and end of each run. All measurements were monitored by thin-walled ionization chambers, whose absolute sensitivity was determined with a thin-walled graphite chamber.

Special attention was devoted to the stability of the energy limit $E_{\gamma max}$ and to the shape of the lengthened γ-ray pulse. Continuous visual monitoring was employed for this purpose.

3. RESULTS

Treatment of experimental data. The data obtained in each run of measurements on reaction (1) were subjected to separate statistical analysis, and the average yield per unit radiation dose was computed. This yield was then converted for 100% γ-ray counter efficiency, taking the energy dependence of the efficiency into account.[10] All experimental runs were also combined statistically for each angle, with weighting according to the total radiation dose in each run.

The measurements for the "background" process (the yield at the varied angle θ^*_γ) were treated similarly, and were subtracted from the corresponding values for reaction (1). The measured yields were used to compute the ratio between the differential cross sections for reactions (1) and (2), averaged over the registered energy and angle intervals. In our calculations we used Schiff's bremsstrahlung spectrum, averaged over the energies of the electrons impinging on the synchrotron target.

The table gives the weighted mean angles $\bar{\theta}$ and energies E and the corresponding half-widths $\Delta\bar{\theta}_p$ and $\Delta\bar{E}_\gamma$ calculated by means of the angular and energy resolution functions. Specific calculations of the resolution functions were performed by successive numerical integration taking account of the relation between variables. Integration limits were determined by the combined geometry of the proton telescope and target, the registered energy range of the proton telescope, and the kinetics of the process. The geometry of the γ-ray counter did not affect the calculation of the resolution functions.

Corrections for multiple proton scattering in the absorbers were computed for the mean proton energy in the registered interval, using Sternheimer's results.[12]

The last column of the table gives the absolute differential cross sections for reaction (1) in the c.m. system. These were obtained by using the cross section for reaction (2) in the lab. system,

$\frac{d\sigma}{d\Omega}(16°) = (26.6 \pm 2.7) \times 10^{-30}$ cm^2/sr, obtained from the literature.[13]

Our absolute value of the cross section for (2) derived from the bremsstrahlung flux agreed with the foregoing value within statistical error limits.

Accuracy of results. Because of our procedures in the measurements and handling of the data, inaccuracy of the differential cross sections was determined mainly by the statistical inaccuracy (± 10%) of the measured yields. For the differential cross section ratio the inaccuracy of other quantities in the calculation is unimportant because of mutual cancellation. This does not apply to the inaccuracy, not exceeding ± 5%, in determining the solid angle of the γ-ray counter. The accuracy of the absolute cross section for reaction (1) was found to be about ± 15%. This was determined by the indicated errors of the cross section ratio and by the ± 10% inaccuracy of the cross section for reaction (2).

The foregoing inaccuracy estimates are valid for all angles, except in the cases of γ rays scattered at 56° and 74° in the c.m. system. For these two angles a ± 3% error in determining the maximum bremsstrahlung energy can lead to a ± 25% error in the cross section.

4. DISCUSSION

Angular distribution. The table shows that the differential cross sections measured in the present work pertain in most instances to γ-ray energies close to 247 Mev. For the purpose of analyzing the angular distribution all results were converted to the single energy value 247 Mev, using the energy in the AS calculations with the sign given by JM for the interference term would bring about agreement with experiment for all angles.

Figure 5 shows that the JM theoretical results disagree with our experimental absolute values for all the given lifetimes τ.

Lapidus and Chou Kuang-chao[14] have recently pointed out that the relative sign of the pole diagram used by JM is incorrect. A correction of the sign of the pole term should increase the discrepancy between the JM theory and our data. It should be mentioned in this connection that the agreement between the JM theory and experiment concerning the energy dependence of the cross section appears to be accidental.

The theoretical curves given in Fig. 5 were obtained using numerical calculations of the dispersion integrals. As already noted, these results may be incorrect, especially for large angles.

The experimental data can be compared with the theoretical angular distribution in a form unassociated with numerical calculations of dispersion integrals. Following JM, we fitted our data for the angular distribution to the formula

$$\frac{d\sigma}{d\Omega} = A\frac{(1-y)^3}{(y-y_0)^2} + \frac{B+Cy+Dy^2}{y-y_0}, \quad (5)$$

where the parameter A is associated with the π^0 lifetime. The π^0 lifetime derived on the basis of this approximation was four orders of magnitude smaller than that obtained in experiments on K^+-meson decay[15] and from the Primakoff effect.[16] This discrepancy between the values of the π^0 lifetime obtained in [15] and [16], on the one hand, and from the use of Eq. (5) as an approximate equation for our data, on the other, indicates that the JM theoretical treatment is inaccurate.

It should be noted that a theoretical study by Nelipa and Fil'kov,[17] using double dispersion relations, also yields a form of angular distribution different from that of JM.

Further improvement of the theory, especially an improvement of the approximation formula, will apparently permit a more detailed comparison of the theory with our experimental results, and will determine the π^0 lifetime more accurately from the angular distribution of γ rays scattered elastically on hydrogen.

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289