Scattering of 25–87 Mev Photons by Protons*†

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Scattering of 87-Mev bremsstrahlung by liquid hydrogen has been measured with a lead converter-telescope arrangement at angles from 70–150 degrees. The weighting function of the cross-section peaks at 60 Mev, has a full width of 55 Mev, and is approximately symmetrical. In this angular range contributions from processes other than elastic scattering from protons are believed to be small. The observed cross sections are somewhat smaller and flatter in angular distribution than those given by Powell's formula for scattering by a point proton with the static anomalous moment.

INTRODUCTION

THE scattering of gamma rays by protons has been noticed as being of interest in probing the mesonic structure of the proton. Sachs and Foldy[1] showed some of the general features as calculated on the basis of weak-coupling meson theory. Capps and Holladay[2] have continued this work using an extended-source model. More recently, dispersion relations have been applied which relate the scattering to the photoproduction of pions.[3]

In the low-energy limit under quite general assumptions it has been shown that the scattering contains the frequency-independent Thomson amplitude[4] plus a term linear in the frequency which is determined by the static magnetic moment.[5] In the higher energy region the scattering is expected to decrease due to interference with the Rayleigh scattering of the meson cloud, and above photomeson threshold to increase quite rapidly.

Since the expected (and observed) cross sections are of the order of 10^{-32} cm^2/steradian, which is very small compared to electronic cross sections, positive identification of elastic gamma scattering by coincidence observation of the recoil proton is desirable. However, Fig. 1 shows the recoil energies available and their ranges in liquid hydrogen. With the fluxes from the "100-Mev" betatron, we have used targets 12.5 cm thick in order to reach a counting rate of one gamma ray per minute scattered into 2.5×10^{-2} steradian. It can be seen that under these conditions it is difficult to use targets thin enough to permit detection of the protons. This would be particularly unfeasible for scattering of gammas toward the forward direction where the background from other processes becomes most bothersome.

We have undertaken, as a first step, the measurement with the 87-Mev bremsstrahlung beam of the scattering from liquid hydrogen as detected by a gamma-sensitive counter telescope with a low-energy cutoff. We confine ourselves to scattering at angles large enough to avoid sizable contributions from other processes which produce counts in the telescope.

APPARATUS

The experimental layout is shown in Fig. 2. Figure 3 shows the final version of the liquid-hydrogen target. It is of the usual Styrofoam type but with windowed beam holes through the walls. A dead gas space between window membranes affords sufficient insulation so that the loss rate is not appreciably larger than for solid Styrofoam walls. Liquid hydrogen vaporizes due to heat leakage into the target at about 1.5 liters per hour.

The counter telescope is shown in Fig. 4. Counters are all made of plastic scintillator. A total of 5.2 g/cm^2 of aluminum between the counters sets an energy threshold for detection. The radiator is 7.4 g/cm^2 of lead. In front of the anticoincidence counter is placed

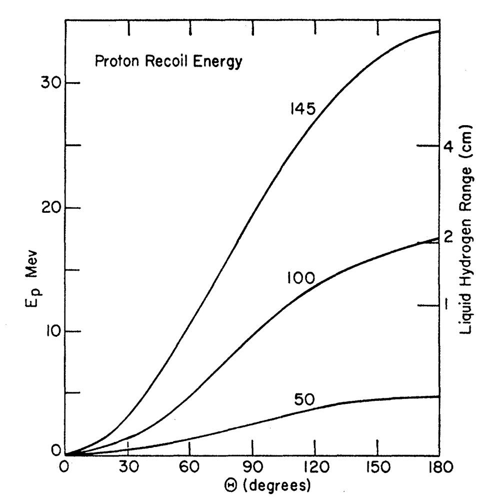

FIG. 1. Recoil-proton energy *versus* gamma-ray scattering angle for three incident gamma-ray energies in Mev.

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† A preliminary account of this work has been published: Phys. Rev. **100**, 435 (1955).
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[1] R. G. Sachs and L. L. Foldy, Phys. Rev. **80**, 824 (1950).
[2] R. H. Capps and W. G. Holladay, Phys. Rev. **99**, 931 (1955).
[3] Gell-Mann, Goldberger, and Thirring, Phys. Rev. **95**, 1612 (1954).
[4] W. E. Thirring, Phil. Mag. **41**, 1193 (1950); N. Kroll and M. Ruderman, Phys. Rev. **93**, 233 (1954); Deser, Thirring, and Goldberger, Phys. Rev. **94**, 711 (1954).
[5] F. E. Low, Phys. Rev. **96**, 1428 (1955); M. Gell-Mann and M. L. Goldberger, Phys. Rev. **96**, 1433 (1955).

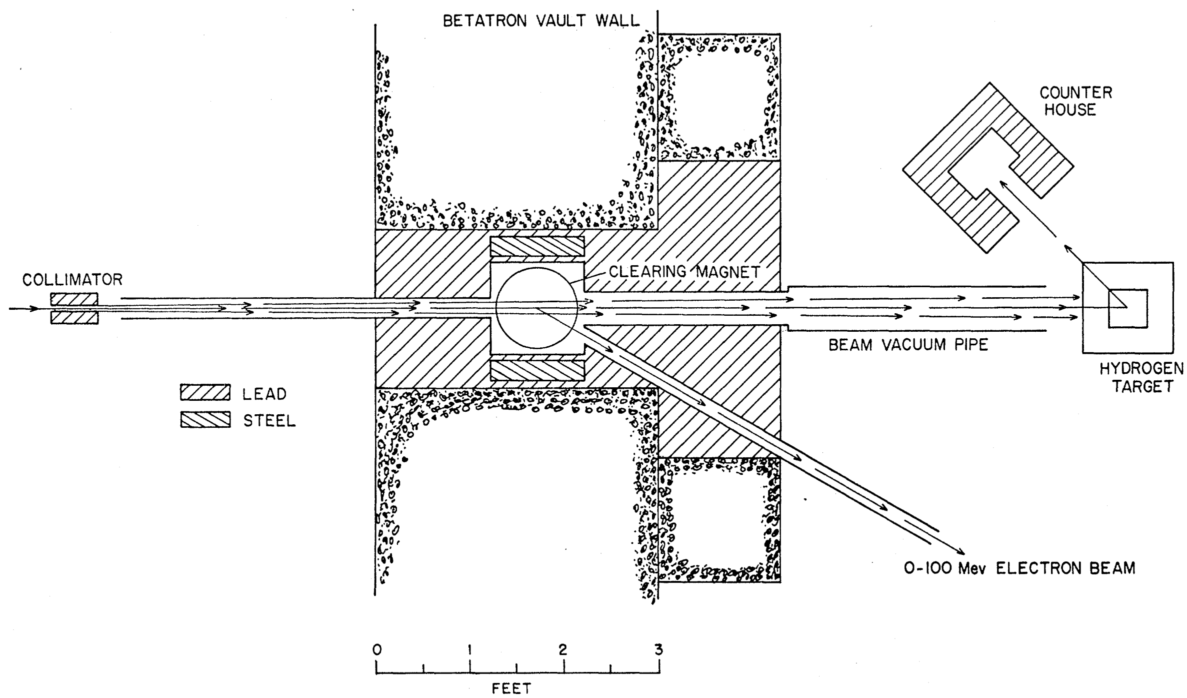

FIG. 2. Plan view of experimental layout.

a plug of low-Z material to reduce the slow electrons and soft gammas entering the anticoincidence counter. This plug has been on occasion $\frac{1}{2}$ or 1 inch of carbon or 2 inches of beryllium. Corrections independent of gamma-ray energy and amounting to less than 10% have been required for the absorption in the plug.

The counter photomultiplier pulses are sent through wide-band amplifiers to a coincidence-anticoincidence circuit described as by Garwin.[6] With clipped pulses a resolution of time 10^{-8} second is attained. The anticoincidence input pulses include many small pulses caused by slow electrons which tend to load the coincidence circuit. These have been suppressed by a biased diode between two amplifiers. All input pulses are adjusted to give amplitude plateaus in the coincidence circuit when an electron beam penetrates the telescope with all absorbers and radiators removed. Two coincidence circuits are used in parallel, one of which records triples without anticoincidence, thus counting electrons and gammas; the other, with anticoincidence, counts gammas alone.

The beam pulse from the betatron has been lengthened to 100 microseconds with roughly square shape by slow beam expansion.[7] A gate opened about 1% of the time by ejection pulses reduces the cosmic-ray background from an appreciable to a nearly negligible amount.

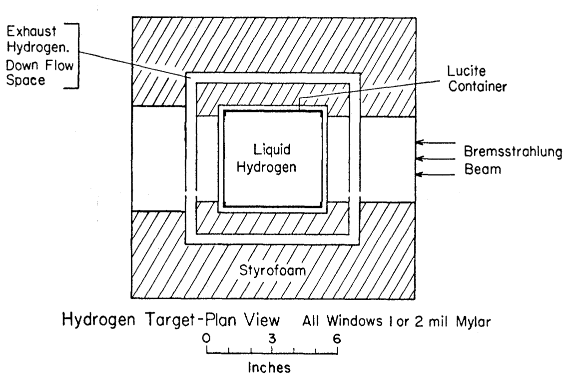

FIG. 3. Liquid-hydrogen target.

BEAM CALIBRATION AND COUNTER EFFICIENCY DETERMINATION

The counter efficiency has been determined by first measuring the efficiency for electrons of known energy incident axially on the telescope with several fractional thicknesses of lead converter in place. From these measured electron efficiences and the electron production as tabulated by Grodstein[8] we have calculated the efficiency for gamma rays centrally incident on the counter. The efficiency thus determined is shown in Fig. 5. Edge effects were measured by comparing the counting rates in the 87-Mev bremsstrahlung beam for central and over-all illumination of the counters, giving an 11% reduction in the average as compared to the central efficiency.

The gamma flux was monitored by off-beam or in-

[6] R. L. Garwin, Rev. Sci. Instr. 24, 618 (1953).

[7] T. J. Keagan, Rev. Sci. Instr. 24, 472 (1953).

[8] G. W. Grodstein, National Bureau of Standards Circular 583 (U. S. Government Printing Office, Washington, D. C., 1957).

beam ion chambers, using the measurement of C^{11} activity in a polyethylene foil as counted in a standard counter for working checks of ion chambers and their intercomparison.

The activation measurements were put on an absolute scale by use of the absolute $C^{12}(\gamma,n)C^{11}$ cross section as determined by Barber, George, and Reagan[9] with Faraday-cup monitored electron beams. For better accuracy we also used a thick-walled ion chamber of the type described by Edwards and Kerst[10] and kindly calibrated by J. S. Pruitt at the National Bureau of Standards against a similar chamber which had been calorimetrically[11] calibrated in bremsstrahlung beams and in addition had also been calibrated with a total absorption counter.[12] The ion chamber and activity calibrations agreed within 4.5%.

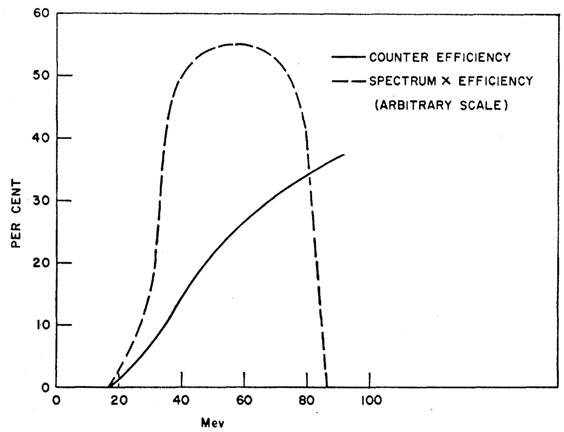

FIG. 5. Telescope efficiency and cross section weighting *versus* gamma-ray energy.

BACKGROUND EVENTS

Since we are unable to use proton recoils to identify the elastic scattering, we must consider in some detail the magnitude and angular distributions of processes

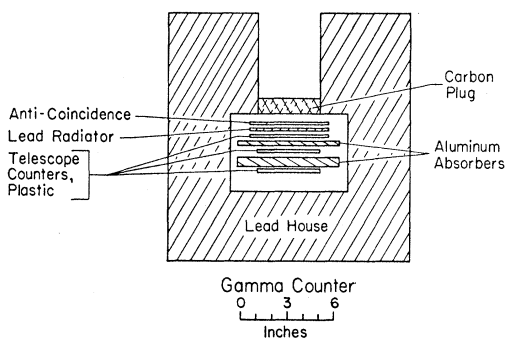

FIG. 4. Counter telescope and shield.

which lead to high-energy gamma rays, or electrons in numbers in excess of those which can be reliably rejected by an anticoincidence counter. These will be produced both by direct processes involving incident gammas and by secondary processes due to (pair) electrons. We discuss these sources of background in turn comparing them in each case to the order of magnitude of the elastic scattering, $1-2\times10^{-32}$ cm^2/steradian.

Processes involving electrons as targets are unimportant, since on kinematic grounds emission at large angles is much degraded in energy: for example the Compton scattering, although large in cross section, yields only 1.2-Mev quanta at 45 degrees from incident 100-Mev photons. Soft quanta and electrons are rejected by the telescope although they lead to high singles rates in the individual counters.

Primary processes involving gammas on protons include pair production, Delbrück scattering, and radiative pair production. Pairs at large angles have been considered by Hough[13] and convenient integrations over bremsstrahlung spectra have been published by Miller.[14] Table I shows the differential cross sections for emission of a pair member with $E>25$ Mev, averaged over all incident gammas above 25 Mev in a 100-Mev bremsstrahlung spectrum. Inner screening is neglected. Although this process is almost two orders of magnitude larger than the Thomson scattering at 45°, the electrons fall off rapidly with increasing energy ($\sim E^{-3.5}$) and angle ($\sim 1/\theta^4$). Owing to the falling sensitivity of the telescope toward threshold, actual counts from electrons are reduced to a level where they can be rejected reliably by the anticoincidence counter. In the measurements at angles $>70°$, electron counts were observed which were of the same order of magnitude as the gamma counts.

Delbrück scattering[15] is the scattering in the Coulomb field of the nucleus which is associated with real or virtual pair formation. It is strongly peaked in the forward direction and is in addition small enough that it is completely negligible at angles of $>45°$ in hydrogen.

A more serious background, pointed out by Pugh, Gomez, Frisch, and Janes,[16] is radiative pair production

TABLE I. Large-angle pair production.

θ	$d\sigma/d\omega$ (cm^2/sterad)
45°	8.0×10^{-31}
60°	2.5×10^{-31}
90°	4.6×10^{-32}

[9] Barber, George, and Reagan, Phys. Rev. **98**, 73 (1955).
[10] P. D. Edwards and D. W. Kerst, Rev. Sci. Instr. **24**, 490 (1953).
[11] J. S. Pruitt and S. R. Domen, Bull. Am. Phys. Soc. Ser. II, **1**, 199 (1956).
[12] Koch, Leiss, and Pruitt, Bull. Am. Phys. Soc. Ser. II, **1**, 199 (1956).
[13] P. V. C. Hough, Phys. Rev. **74**, 80 (1948).
[14] R. C. Miller, Phys. Rev. **95**, 796 (1954).
[15] F. Rohrlich and R. L. Gluckstern, Phys. Rev. **86**, 1 (1952); H. A. Bethe and F. Rohrlich, Phys. Rev. **86**, 10 (1952).
[16] Pugh, Gomez, Frisch, and Janes, Phys. Rev. **105**, 982 (1957).

TABLE II. Large-angle bremsstrahlung.

Primary gamma energy (Mev)	Effective differential cross sections (cm^2/sterad) following 10^{-2} radiation length, $\theta=70°$
100	1.1×10^{-34}
75	1.3×10^{-34}
50	1.0×10^{-34}

in which a gamma ray is emitted at large angles. The magnitude is indicated by rough theoretical estimates to be potentially troublesome. Complete theoretical calculations of the effect are not available, but the data of Pugh *et al.* with several elements provide an indication of the size of the effect, since it is evidently visible in the lower-energy gamma rays scattered from several elements in a 140-Mev bremsstrahlung beam. On the basis of their results, with a $1/\theta^4$ dependence one would estimate that this scattering might amount to as much as 15% of the elastic scattering at 70°, the smallest angle at which we believe our data are reliable.§

Important secondary effects involve the interaction of the pair electrons. In estimating their size which depends quadratically on the target thickness, we speak in terms of an effective cross section as seen following a nominal radiator of 10^{-2} radiation length of hydrogen. This allows a more direct comparison with the scattering cross sections. Our target is 1.3×10^{-2} radiation length, the thin windows used recently are less than 10^{-3} radiation length and the Styrofoam walls present in older large-angle work at 0.09 radiation length.

The electrons yield gamma rays into our angular range by large-angle bremsstrahlung and scattered electrons by Coulomb scattering. The large-angle bremsstrahlung from the pair spectrum may be calculated from the treatment of Hough,[14] with the results shown in Table II for the composite process. These effective cross sections contain counter efficiency weighting for the degraded gammas.

Pair electrons scattered directly into the counters will become troublesome at small enough angles. Only single scatterings need be considered in our angular range. Their magnitude is estimated in Table III. When

TABLE III. Scattered pair electrons.

Electron energy range (Mev)	Effective differential cross section (cm^2) following 10^{-2} radiation length, $\theta=60°$
30–40	3.3×10^{-32}
40–50	1.3×10^{-32}
50–60	5.5×10^{-33}
60–70	2.5×10^{-33}
70–80	1.2×10^{-33}
80–90	4.8×10^{-34}

§ *Note added in proof.*—In a private communication R. Gomez has indicated that an improved theoretical estimate of the radiative pair production gives a cross section at least an order of magnitude smaller than previous ones and that a re-examination of the experimental arrangement indicates that the effects ascribed to this process[16] are probably due to converted electrons in the beryllium absorber in front of the counter. This effect is thus of negligible magnitude in our 70° observation.

weighted with the electron telescope response, the low-energy part is reduced. This secondary source of electrons is then smaller for our targets than the primary source of large-angle pairs, which accounts for most of the electrons in our experiment. These do, as remarked above, yield counts in about the same numbers as do gamma rays.

PROCEDURE AND DATA

Typically, after checking the counters with their associated circuits, runs were taken with target empty, that is, filled with helium gas. The target was then filled with liquid hydrogen and data were taken at one or two angles for a period of 12–24 hours, then empty-target data were taken again. The beam integrator was checked every few hours by activating a polyethylene disk. The length of the beam pulse was monitored by visual and photographic oscilloscope observation, particularly during the small-angle runs where some accidental coincidences were encountered. The 70° data required delay-line evaluation of chance coincidences during the full- and empty-target runs.

TABLE IV. Experimental cross sections.

Laboratory angle	Differential cross sections ($cm^2\times10^{-33}$) Individual runs	Combined results	Background total counts %
70°	10.6±0.8	10.6±0.8	20
90°	10.6±0.6 10.8±0.9 10.7±0.8	10.8±0.4	19
120°	11.3±0.7 13.4±1.2	11.8±0.5	32
150°	14.8±0.8 14.5±1.2	14.7±0.6	67

The data from several series of runs are presented in Table IV. Cross sections as finally corrected are given along with the empty-target background.

In addition to background subtraction the cross section has been corrected for the change in counter efficiency due to the loss of gamma-ray energy to the recoiling protons. This correction turns out to be substantially independent of gamma-ray energy for a fixed angle of scatter and so depends little on the energy dependence of the scattering. The correction ranges from 4.5% at 70° to 14% at 150°. Because of the energy independence of this correction, the energy weighting of the cross section is reliably given by the product of the bremsstrahlung spectrum with the telescope efficiency as shown in Fig. 5. The weighting function peaks at 60 Mev is 55 Mev wide, and is nearly symmetrical.

The differential cross sections are also given graphically in Fig. 6. The uncertainties indicated are root-mean-square statistical errors only. Additional errors which effect the angular distribution are believed to be small in the 90–150° region. The cross sections measured do however have no experimental guarantee against contributions from unwanted processes, and may in this sense be considered upper limits on the desired cross sections. In the section on backgrounds, however, estimates of other processes have been made. Considering the energy sensitivity of the counters, the responses to these processes are found to be small compared with the observed cross sections, with the exception of the contribution of radiative pair production to the 70° data which may amount to 15%.

An additional error of ±8% is assigned to the absolute scale.

DISCUSSION

The results may be compared with theoretical predictions (Fig. 6). The scattering calculated by Powell for a point proton with the static anomalous magnetic moment has the correct amplitude terms independent of and linear in frequency.

With the experimental data is also shown the 0° scattering which is predicted by dispersion theory from the analysis of the photopion production experiments.[3] Several theoretical studies have been made in which the dispersion theory is extended to angles other than 0°.[17] This process contains ambiguities which require the use of a model. Detailed discussions of the problems involved are yet to appear in the literature.

The data may be compared with that of Pugh *et al.*[16] who worked with energy-resolved detection and 135-Mev bremsstrahlung. Their data are in fair agreement with the Powell formula at 90° and 135°, showing a decrease from it at 45° for energies above 100 Mev. Our data show no qualitative disagreement with theirs.

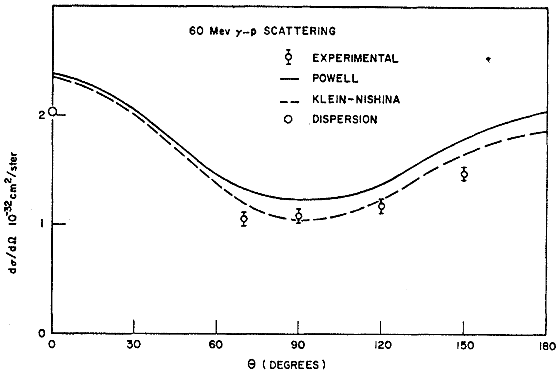

FIG. 6. Experimental and theoretical differential cross sections.

[17] J. Mathews and M. Gell-Mann, Bull. Am. Phys. Soc. Ser. II, 2, 392 (1957); and Watson, Zachariasen, and Karzas, Bull. Am. Phys. Soc. Ser. II, 1, 383 (1956).

ACKNOWLEDGMENTS

Valentine Telegdi shared in this experiment, particularly in the earlier stages. We are indebted to A. S. Penfold and E. Garwin for a calibration of the betatron energy, to R. Gabriel for the construction and maintenance of the electronics, and to the betatron crew for assistance in taking data and operating on an extended schedule.

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Λ-Nucleon Potential from Hyperfragment Data*

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The volume integrals of the Λ-nucleon potentials in the triplet and singlet spin states are deduced from hyperfragment binding-energy data. The effects of tensor forces are neglected in the calculation but are discussed qualitatively. Results are sensitive to the sizes and shapes of the nuclei in which the Λ is bound, but are not very sensitive to Λ binding energies. Results also depend on the range of the Λ-nucleon potential and on the spin configurations of the nuclei. Within the approximations made, the Λ-nucleon potentials are consistent with experiment and agree with theoretical potentials due to pion exchange. A crude determination of the Λ-nucleon potential from the observed lifetime for mesonic decay of hyperfragments is consistent with the binding-energy determination.

I. INTRODUCTION

THE purpose of this work is to interpret hyperfragment data, especially binding energies, in terms of two-body Λ nucleon (hereafter written ΛN) potentials. We assume throughout that the spin of the Λ is $\frac{1}{2}$.

Several analyses of hyperfragment binding energies have appeared recently.[1,2] This new discussion, which is very similar to that of Dalitz,[1] is distinguished by two features:

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† This work was begun while the author was at Indiana University.

[1] R. H. Dalitz, *Proceedings of the Sixth Annual Rochester Conference on High-Energy Physics*, Session V (Interscience Publishers, Inc., New York, 1956), and Midwest Conference on Theoretical Physics, State University of Iowa, 1957 (unpublished); B. W. Downs, Bull. Am. Phys. Soc. Ser. II, 2, 175 (1957); J. T. Jones and J. M. Keller, Nuovo cimento 4, 1329 (1956). G. H. Derrick, Nuovo cimento 4, 565 (1956).

[2] L. Brown and M. Peshkin, Phys. Rev. 107, 272 (1957).