Angular Distributions of Photoprotons*

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The angular distributions of photoprotons from Cu, Ni, and Co targets irradiated with bremsstrahlung of 23-Mev maximum energy have been measured. Protons from Cu and Co show a large asymmetric component which is described by the expression $(\sin\theta+0.5\sin\theta\cos\theta)^2$. Absorption experiments on the protons are consistent with the assignment of the asymmetric component to transitions involving discrete levels in the vicinity of the ground state of the residual nucleus. The angular distributions observed are interpreted as resulting from interference between electric dipole and quadrupole absorption of the initial photons with the relative quadrupole intensity equal to 5 percent.

I. INTRODUCTION

RECENT measurements[1–4] of the angular distributions of protons from targets irradiated with bremsstrahlung of maximum energy in the vicinity of 25 Mev have indicated that (1) from certain targets (Cu, Rh, and Ag) roughly 10 percent of the protons are emitted preferentially at 90 degrees and (2) the protons comprising the nonisotropic component of the distributions are those of highest energy. From other targets (Mg and Al) the photoproton angular distributions were observed to be spherically symmetric. The details of such angular distributions might be expected to provide information concerning the mechanism of the nuclear photoeffect. Indeed, the experimental results mentioned above have been interpreted[5] in part as confirming the existence of direct photodisintegration processes in middle weight nuclei in the energy region about 25 Mev.

However, all of the previous measurements utilized photographic emulsions for the detection of the emitted protons, which has limited the statistical precision of these measurements. In order to improve the precision we have used scintillation counter techniques to measure the angular distributions of protons from γ, p reactions in Co, Ni, and Cu. The remainder of this paper will be devoted to a description of these measurements and to a discussion of the conclusions to be drawn from them.

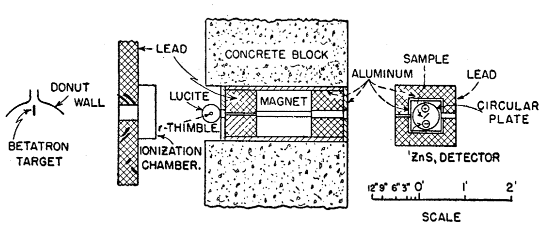

FIG. 1. The general arrangement of apparatus showing shielding, collimator, and scattering chamber.

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[1] M. E. Toms and W. E. Stephens, Phys. Rev. 82, 709 (1951).
[2] B. C. Diven and G. M. Almy, Phys. Rev. 80, 407 (1950).
[3] P. R. Byerly and W. E. Stephens, Phys. Rev. 83, 54 (1951).
[4] Curtis, Hornbostel, Lee, and Salant, Phys. Rev. 77, 290 (1950).
[5] E. D. Courant, Phys. Rev. 82, 703 (1951).

II. EXPERIMENTAL PROCEDURE

The apparatus employed in the present experiment has been described in detail previously.[6] Briefly, a strongly collimated bremsstrahlung beam of maximum energy 23 Mev strikes a target placed at a given angle (60 degrees) with respect to the detectors, as shown in Fig. 1. The detectors which consist of ZnS scintillators subtend an angle of 10 degrees at the target. The target and detectors rotate as a unit about the incident beam direction, the relative orientation of target and detectors remaining fixed throughout the experiment. This procedure eliminates the effect of differential proton absorption in the target but requires that data obtained at various angles be normalized to the same effective target thickness presented to the incident beam. To satisfy the latter requirement with the degree of precision necessary in the present experiment the target is initially aligned at a known angle with the x-ray beam by optical and photographic means, which are also used to assure that the center of the x-ray beam passes through the axis of rotation of the rotating unit. A calibrated scale attached to the rotating target-detector assembly then measures the absolute angle between the target and incident beam at any detector position. The absolute orientation of the target and detectors is not measured with the same accuracy as that of target and beam. Consequently, in the data to be presented the absolute values of the proton angles, i.e., detector positions, may be in error by as much as ± 3 degrees, although the relative angles are known to approximately ± 0.5 degree.

In addition to misalignment there are two other geometric factors which might influence the detector solid angle as the detector position varies. The first of these factors arises from the fact that as the angle between the target and incident beam is varied, the source of photoprotons changes shape. When the target surface is perpendicular to the incident beam direction, the proton source is a circle of diameter 7 mm; when the target is in the most oblique position (the angle between target surface and x-ray beam 30 degrees), the proton source is an ellipse of eccentricity two. This

[6] A. K. Mann and J. Halpern, Phys. Rev. 82, 733 (1951).

effect produces only second-order changes in the solid angle, which within the accuracy of our experiment can be neglected. Similarly, the second factor, the transformation from center of mass to laboratory angle and solid angle, is negligible for these nuclei at these energies.

Measurements were made simultaneously with two identical detectors fixed at 180 degrees with respect to each other and with each detector covering the region from 30 to 330 degrees. The absolute counting rate was, within the statistical errors, the same for each detector at a given angular position. In all instances the measured angular distributions were symmetric about the incident beam direction. In treating the data we have combined the results from the two detectors and for the same positions on opposite sides of the incident beam. Data could not be taken in the intervals from 150 to 210 and from 330 to 30 degrees because in these regions the beam would strike the detector assembly.

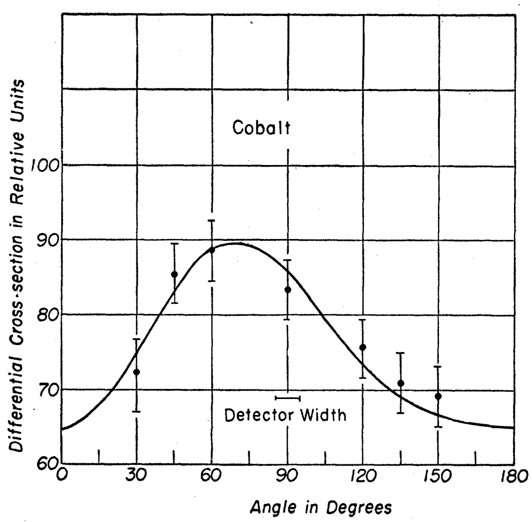

FIG. 2. The angular distribution of photoparticles from cobalt including both photoprotons and photodeuterons. The curve drawn through the experimental points has the form $(\sin\theta+0.5\sin\theta\cos\theta)^2$.

The targets were foils of natural isotopic composition and of the following thicknesses in mg/cm^2: Co, 113; Ni, 104; Cu, 92.

RESULTS

The angular distributions from each of the targets are shown in Figs. 2–4. Each of the points shown in the figures represent a total of at least 2500 counts. The errors indicated are approximately twice the statistical errors and correspond to the internal consistency of the measurements. The numerical values of the ordinates in the figures are the observed counting rates in counts per 100 roentgen at the target position. The background counting rate was found to be independent of angle and was about 10 percent of the counting rate measured with the cobalt target.

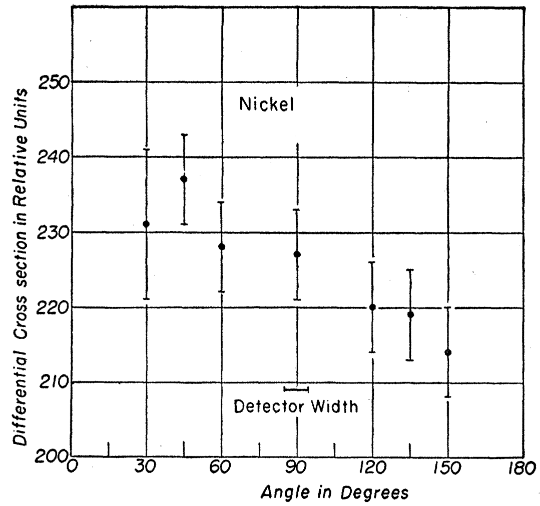

FIG. 3. The angular distribution of photoparticles from nickel including both photoprotons and photodeuterons.

The differential cross section curves for Co and Cu consist of symmetric and forwardly peaked asymmetric components. For Co and Cu the asymmetric components are identical in shape, and both can be fitted by a single curve of the form $(\sin\theta+0.5\sin\theta\cos\theta)^2$, which is drawn through the experimental points in Figs. 2 and 4. Because the total photoproton yield from Ni is about three times greater than that from Co and Cu, it would require considerably improved precision to detect an asymmetric component of the same magnitude as that found for Co and Cu.

For a detailed interpretation of the results it is desirable to determine the variation of these angular distributions with energy of the emitted particles. With the ZnS detector it is only possible to separate the distributions in terms of particle energy by the use of

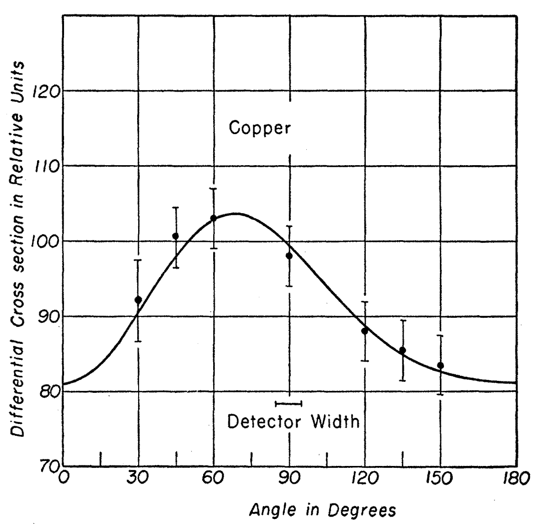

FIG. 4. The angular distribution of photoparticles from copper including both photoprotons and photodeuterons. The experimental points are fitted with the expression $(\sin\theta+0.5\sin\theta\cos\theta)^2$.

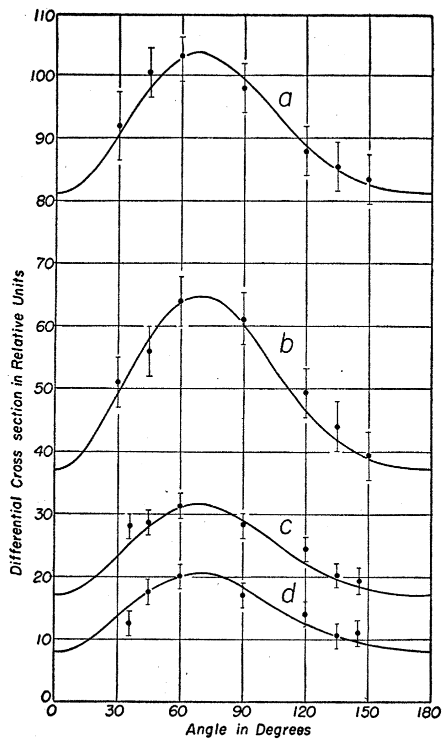

FIG. 5. The angular distribution of photoparticles from copper with different thicknesses of aluminum absorber between target and detector. The distribution in (a) contains both protons and deuterons. The distributions (b), (c), and (d) contain only protons. All of the distributions have been fitted with the expression $(\sin\theta+0.5\sin\theta\cos\theta)^2$.

differential absorption techniques. Figure 5 shows the measured angular distributions in copper with several different thicknesses of aluminum absorbers placed between target and detector. In the geometry used the effect of absorber scattering could not modify the angular distributions. The absorber thicknesses shown in Fig. 5 include the aluminum equivalent of the air in the scattering chamber, which was 11 mg/cm^2. The asymmetric component of each of the distributions is described by the expression $(\sin\theta+0.5\sin\theta\cos\theta)^2$, which is plotted through the experimental points in Fig. 5.

The particles detected with an absorber thickness of 11 mg/cm^2 [Fig. 5(a)] could be either protons of minimum energy 2 Mev, determined by the absorber thickness, and maximum energy 16 Mev, determined by the reaction threshold or deuterons with energies between 2.8 and 8 Mev. The absorber thickness used in obtaining the data in Fig. 5(b) corresponds to the range of a 4-Mev proton and a 5.6-Mev deuteron. The distribution shown in Fig. 5(b) is that for protons only because the number of deuterons with energies between 5.6 and 8 Mev has been observed[3] to be about 5 percent of the total deuteron yield. Within the experimental errors the shapes and magnitudes of the asymmetric components of the distributions in Figs. 5(a) and 5(b) are identical. The symmetric component has been reduced by 55 percent. From the measured proton energy distribution[3] the increased absorber thickness could only remove 10 percent of the protons. We therefore attribute approximately 45 percent of the total yield in Fig. 5(a) to deuterons which are spherically symmetric in their angular distribution. This large photodeuteron yield is in agreement with previous measurements[3] and of better accuracy. The parameters of the curves in Figs. 5(b), (c), and (d) are tabulated in Table I.

In order to interpret the results in Table I it is necessary first to consider the energy distribution of protons emitted by nuclei absorbing monoenergetic x-rays. Most of the emitted protons are the products of transitions which involve relatively highly excited states of the residual nucleus with level widths greater than the level separations. On the basis of the statistical theory the angular distribution of these protons is expected to be spherically symmetric although other distributions are possible.[7] The protons arising from transitions to the ground state (or very close) of the residual nucleus are those in the high energy "tail" of the energy distribution, and their angular distribution can be influenced by both the initial x-ray absorption process and by the properties of the initial and final states of the transition. If it is assumed that only those protons of highest energy can be emitted asymmetrically, then measurements of the proton angular distribution with various thicknesses of absorber between the proton source and detector should show a large symmetric component which decreases rapidly and steadily with increasing absorber thickness and possibly a smaller asymmetric component which is independent of absorber thickness until a certain critical value is attained.

The proton energy distribution from nuclei irradiated with bremsstrahlung is a superposition of the energy distributions resulting from the absorption of monoenergetic photons. The total number of protons in each of the latter distributions is determined by the product of the cross section for the reaction and the bremsstrahlung intensity at each photon energy. Previous measurements[8] of the energy dependence of the cross section of γ, p reactions show a maximum in the vicinity of 20 Mev with a half-width of about 6 Mev. The resultant energy distribution should therefore

TABLE I. Significant parameters of curves in Fig. 5.

Figure	Minimum proton energy, Mev[a]	Relative σ(asym)	Relative σ(symm)	σ(symm)/σ(asym)
b	4	12	37	3.1
c	6.4	6.5	17	2.6
d	7.9	5.5	8	1.5

[a] This column gives the minimum energy of the protons which can reach the detectors. The minimum energy corresponds to the range of a proton equal to the absorber thickness.

[7] L. Wolfenstein, Phys. Rev. 82, 680 (1951).
[8] J. Halpern and A. K. Mann, Phys. Rev. 83, 370 (1951).

contain protons arising from transitions to the ground state of the residual nucleus but with energies differing by at least 6 Mev, because the photons producing these transitions are absorbed with energies differing by a similar amount. Indeed, the decrease of the cross section with decreasing energy below 20 Mev is in part compensated by the increasing bremsstrahlung intensity so that the energy spread of these protons is greater than 6 Mev. Measurements of the bremsstrahlung induced proton angular distributions with various absorber thicknesses should then show a large symmetric component whose dependence on absorber thickness is the same as that described for the symmetric component of the angular distributions produced by monoenergetic x-rays and possibly an asymmetric component which also decreases with increasing absorber thickness but in a different manner than the symmetric component.

A semiquantitative treatment of the data of Table I in the light of the above discussion is shown in Fig. 6. The solid curve represents the energy distribution of the protons from a copper target irradiated with bremsstrahlung of maximum energy 23 Mev as predicted by the statistical theory. To show the consistency of the absorption data of Table I for the symmetric component we have constructed from these data a crude energy distribution represented by the points in Fig. 6. The energy distribution of the asymmetric component as obtained from our data is shown by the dashed curve. It should be emphasized that this curve is only a rough approximation and that the absorption data should be taken only as consistent with but not proving that protons in the high energy "tail" of the energy distribution constitute the asymmetric component of the observed angular distributions.

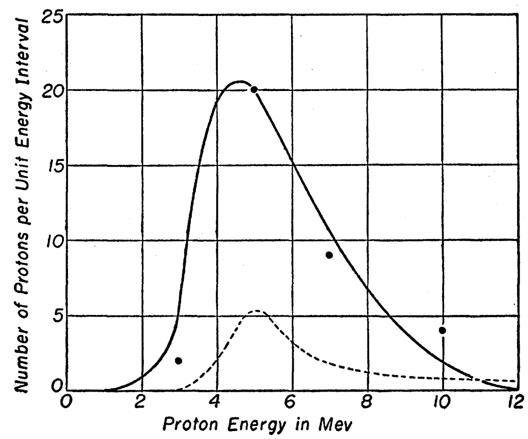

FIG. 6. The energy distributions of the symmetric and asymmetric proton groups from copper. The solid curve is calculated from the statistical theory. The points are obtained from the data for the symmetric component in Table I. The dashed curve indicates the approximate shape of the energy distribution for the asymmetric component as given by the data in Table I.

CONCLUSIONS

Our interpretation of the measurements described here is that the protons produced in transitions to low lying levels of the residual nucleus possess an angular distribution given by $(\sin\theta+0.5\sin\theta\cos\theta)^2$, which represents interference between p and d waves of the emitted protons. If the energy and angular momentum of the incident photons are not randomly redistributed in the nucleus after absorption, then the interference effect observed in the proton angular distribution can be related to interference between electric dipole and electric quadrupole absorption of the incident photons. The observed ratio of d to p wave intensities corresponds to a relative quadrupole absorption intensity of 5 percent in cobalt and copper in the energy region about 20 Mev.