Angular and Energy Distributions of Photoprotons from Aluminum and Tantalum*†

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Foils of aluminum and tantalum were irradiated at energies from 25 to 65 Mev in the x-ray beam of the Iowa State College synchroton. Photoprotons produced at various angles were recorded in nuclear emulsions. Those emitted with low energies appear isotropically distributed and have energy distributions characteristic of statistical evaporation processes. The higher-energy protons from aluminum have an angular distribution of the form $(\sin\theta+p\sin\theta\cos\theta)^2$ with $p\approx0.7$, whereas those from tantalum have a nearly pure $\sin^2\theta$ distribution. Their energy distributions can be represented in the form E_p^{-n}, where E_p is the proton energy. For aluminum, sharp increases in the exponent n occur at a value of E_p slightly greater than half the maximum photon energy of the irradiation. The increases are considerably less in the case of tantalum. The aluminum results are qualitatively consistent with Levinger's quasi-deuteron model of the nucleus. None of the proposed photon interaction models gives a good explanation of the tantalum results.

I. INTRODUCTION

SOME investigations of the angular distributions of photoprotons have recently been carried out using bremsstrahlung energies in the neighborhoods of 25 and 300 Mev. Earlier irradiations[1] with 22-Mev bremsstrahlung had indicated a slight excess of photoprotons emitted from rhodium and silver at 90° to the beam direction as compared to the numbers in the forward and backward directions. In recent more accurate measurements with 25-Mev bremsstrahlung, it has been found[2] that the lighter elements tend to give photoproton distributions peaked near 60°. This was taken as evidence for an interference between electric dipole and electric quadrupole photon absorption processes according to a quasi-deuteron model of the nucleus developed by Levinger.[3]

Investigations[4] with bremsstrahlung energies in the neighborhood of 300 Mev have indicated that very high-energy photoprotons prefer to be emitted nearly into the forward direction. This behavior is also qualitatively but not quantitatively consistent with Levinger's model. The energy distributions of these high-energy photoprotons can be roughly represented in the form $I(E)=\text{const}E^{-n}$, where n is of the order of 2 for proton energies lower than half the maximum photon energy, and n is of the order of 4 for the more energetic protons.

In the present investigation aluminum and tantalum have been irradiated in the x-ray beam of the Iowa State College synchrotron at bremsstrahlung energies of 25, approximately 40, and 65 Mev. The energy and angular distributions of the ejected photoprotons have been studied. In the irradiations at 40 and 65 Mev, attention was concentrated on those photoprotons with energies greater than one would expect to obtain from statistical evaporation processes.[5] However, their energies were not sufficiently large to require corrections to convert angular distributions from the center-of-mass system to that of the laboratory. It was hoped that the results would exhibit a behavior characteristic of the direct interaction of photons with nuclei.

II. EXPERIMENTAL PROCEDURE

The photoprotons were detected in Ilford *C2* nuclear research emulsions of 500 microns thickness. The emulsions were exposed in an evacuated camera (Fig. 1) provided with a thin window in each end through which passed the x-ray beam. The camera was divided into two parts, each containing a thin target of the material under investigation. In the forward half the target was set at an angle of 45° to the beam direction, and protons were recorded at angles of 25°, 60°, and 90°. The backward half of the camera was a mirror image of this arrangement: the target was set at an angle of 135° to the beam direction and protons were recorded at angles of 90°, 120°, and 155°. Thus the observed protons left the targets at angles making not more than 45° with the normal to the planes of the targets, and the corrections for proton energy losses in the targets were small. Since each half of the camera contained an emulsion recording protons ejected at 90° to the beam direction, it was possible to check to be sure that there were no differences in proton yields attributable to differing geometry of the two halves of the camera.

Approximately 40 cm of lead was placed between the

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[1] Curtis, Hornbostel, Lee, and Salant, Phys. Rev. **77**, 290 (1950); B. C. Diven and G. M. Almy, Phys. Rev. **80**, 407 (1950).

[2] Halpern, Mann, and Rothman, Phys. Rev. **87**, 146, 164 (1952).

[3] J. S. Levinger, Phys. Rev. **84**, 43 (1951).

[4] D. Walker, Phys. Rev. **81**, 634 (1951); C. Levinthal and A. Silverman, Phys. Rev. **82**, 822 (1951); J. C. Keck, Phys. Rev. **85**, 410 (1952); J. W. Rosengren and J. M. Dudley, Phys. Rev. **89**, 603 (1953); Wattenberg, Feld, and Godbole, Phys. Rev. **90**, 380 (1953); J. W. Weil and B. D. McDaniel, Phys. Rev. **90**, 380 (1953).

[5] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952), Chap. VIII.

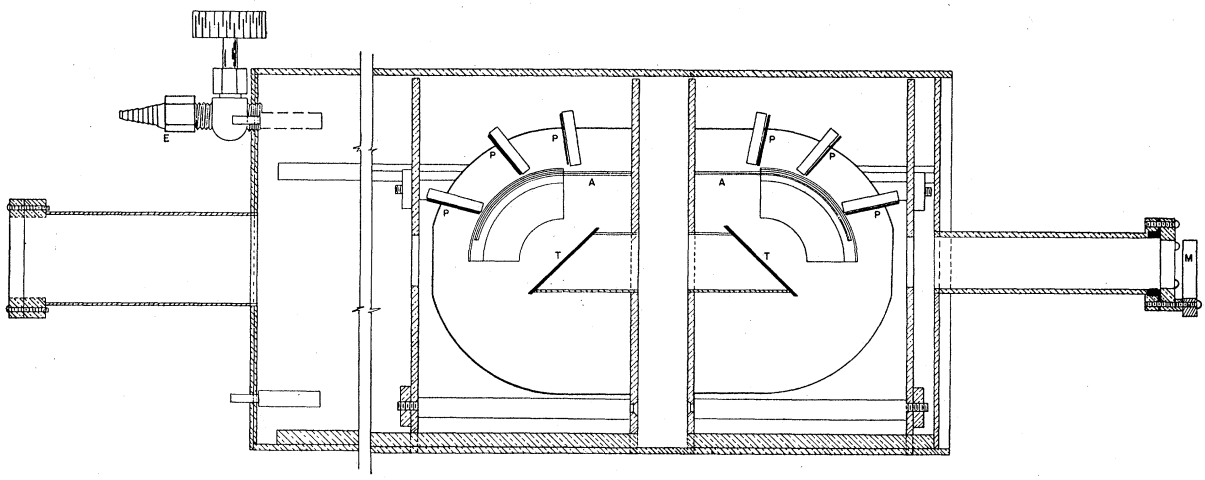

FIG. 1. Sectional view of the nuclear emulsion camera. P=nuclear emulsions; T=target foil; A=absorber; E=exhaust valve; M=monitor holder.

camera and the synchrotron to shield against scattered radiation. The x-ray beam passed through two circular apertures in the lead and had a diameter of 1.12 cm at the position of the targets. A magnetic field of about 4000 gauss immediately preceding the camera served to deflect electrons away from the emulsions.

Photoprotons ejected from the illuminated area of the targets entered the emulsion surfaces at an angle near grazing incidence. Under these conditions protons with energies up to 20 Mev would have been stopped before traversing the thickness of the emulsions. Copper absorbers were placed between the targets and the emulsions in order to reduce the energies of the incident protons by suitable amounts.

In all exposures the irradiation time was adjusted in an attempt to obtain the best possible track density without excessive electronic blackening of the emulsions. The plates were processed by the low-temperature method[6] with 22-percent extra amidol in the developer. For the scanning and measurements a Cooke binocular microscope with 21× objective was used. Tracks were measured only if they satisfied a set of selection criteria which insured that the protons came from the direction of the illuminated areas of the target foils.

It was assumed that all tracks satisfying these criteria were produced by protons. However, it is possible that an appreciable number of the tracks were produced by deuterons.[2,7] Grain counts were made on selected groups of short- and long-range tracks in some of the 25-Mev plates, but no significant differences were observed which might be attributed to deuterons. It is possible that the developing conditions might minimize such differences; hence it is not possible to set any limits on the numbers of deuterons present.

[6] Stiller, Shapiro, and O'Dell, Phys. Rev. **85**, 712 (1952).
[7] P. R. Byerly and W. E. Stephens, Phys. Rev. **83**, 54 (1951); W. H. Smith and L. J. Laslett, Phys. Rev. **86**, 523 (1952).

Details of the various exposures are given in Table I. At the time of the exposures the synchrotron energies were uncertain by about 2 Mev. Measurements were made on a total of over 2500 tracks in the various plates.

The minimum proton energies observable with any given absorber thickness were calculated using the range-energy-loss relationship of Lindhard and Scharff.[8] This relation was also used to calculate the energy loss in targets and absorbers for protons with varying residual ranges in the emulsions. The energy distributions of such protons were further corrected for the energy interval distortion introduced by the absorption process.

Unfortunately, the plates exposed in the backward half of the camera to aluminum targets in the 25- and 40-Mev irradiations were spoiled. Also, in all the irradiations with tantalum targets, the 25° emulsions were found to be too darkened for measurement. Fortunately the nature of the results appears to minimize the importance of the lost information.

III. RESULTS

A. Angular Distributions

The relative numbers of protons observed at various angles from the aluminum and tantalum foils irradiated at the various bremsstrahlung energies are plotted

TABLE I. Data for the exposures.

Target Material	Target Thickness (mg/cm²)	Synchrotron energy (Mev)	Proton energies observed (Mev)	Absorber thickness (mg/cm² of Cu)
Al	29	25	0 to 17	none
Al	76	40	16 to 28.5	520
Al	150	65	27 to 43	1253
Ta	264	25	0 to 19	none
Ta	420	38	18.6 to 28	670
Ta	840	65	27 to 40	1253

[8] J. Lindhard and M. Scharff, Phys. Rev. **85**, 1058 (1952).

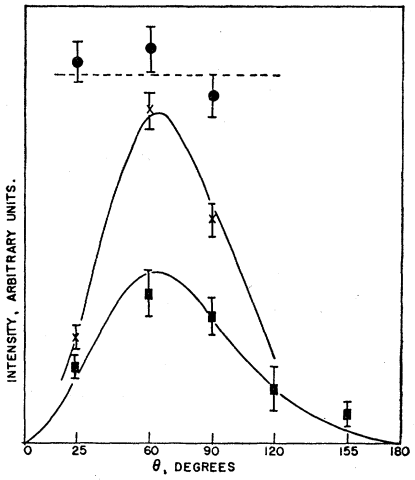

FIG. 2. Angular distributions of the photoprotons from aluminum. The separate irradiations are indicated as follows: ● 25 Mev, × 40 Mev, ■ 65 Mev. These data have been arbitrarily normalized so that the errors on the points do not overlap. The two lower curves are fitted by Eq. (1).

in Figs. 2 and 3. The numbers of tracks in the different plates have been normalized to equal solid angles and to equal minimum proton energies.

Figure 2 gives the results for aluminum irradiated at the various energies. The angular distribution of the photoprotons from the 25-Mev irradiation appears isotropic within statistical errors. Such a distribution is consistent with a statistical evaporation of the protons at the low energies observed here. A rough calculation based on the optical model[9] of the nucleus indicates that if the incoming photon transfers its energy to a proton in the nucleus, that proton will share such energy with the rest of the nucleus (through collisions) in more than 90 percent of the cases for the energies involved in this irradiation. Such compound nuclei may be expected to decay according to the theory given by Blatt and Weisskopf.[5]

In the case of aluminum irradiated at 40 Mev, there is a definite asymmetry with the greatest number of protons being emitted at approximately 60° to the direction of the x-ray beam. This asymmetry cannot arise from the decay of a compound nucleus (which would have to give reaction products emitted symmetrically about 90°),[10] but evidently indicates the effects of some direct interaction between the photons and the nucleus. The energies of these protons vary from 16 to 28.5 Mev, so that in any case not many of them are likely to arise from statistical evaporation.

The quasi-deuteron model of the nucleus proposed by Levinger[3] predicts an asymmetry of the type observed. In this model the photon is absorbed by a pair of nucleons, considered to constitute a quasi-deuteron, and a neutron and a proton are excited each with approximately half of the photon energy. Levinger has adapted the theories of the photodisintegration of the deuteron of Schiff[11] and of Marshall and Guth[12] to this situation. This leads to an interference between electric dipole and electric quadrupole absorption of photons, with an angular asymmetry produced approximately in the form

$$I(\theta)=(\sin\theta+p\sin\theta\cos\theta)^2, \quad (1)$$

where θ is the angle between the x-ray beam and the direction of emission of the proton $p=(5\sigma_q/\sigma_d)^{\frac{1}{2}}$, and σ_q and σ_d are, respectively, the cross sections for electric quadrupole and electric dipole absorption. Levinger expected this model to be valid only for photon energies greater than about 200 Mev; hence it would be surprising to find it valid for the low energies which are involved here.

For this experiment p may be considered as a parameter to be adjusted. If the Levinger model with the existence of deuteron sub-units should be quantitatively valid, then one would expect σ_q to be of the order of 5 percent of σ_d, leading to $p\approx 0.5$. This is indeed the order of magnitude for p found by Halpern *et al.*,[2] for the angular distribution of the non-isotropic fraction of the photoprotons emitted from the lighter elements irradiated with 25-Mev bremsstrahlung.

Since it was expected that the angular distribution of these protons might be partly isotropic, resulting from the presence of evaporation protons and of non-evaporation protons which had made nuclear collisions before escaping, it was at first attempted to fit the points by the equation

$$I(\theta)=a+b(\sin\theta+p\sin\theta\cos\theta)^2, \quad (2)$$

where a and b are constants to be adjusted. However it

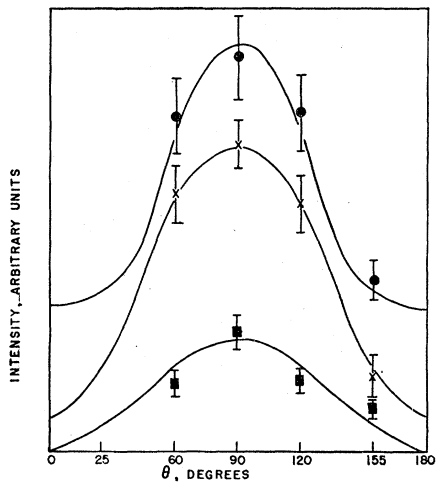

FIG. 3. Angular distributions of the photoprotons from tantalum. The separate irradiations are indicated as follows: ● 25 Mev, × 38 Mev, ■ 65 Mev. These data have been arbitrarily normalized so that the errors on the points do not overlap. The curves are fitted by Eq. (3).

[9] D. C. Peaslee, Phys. Rev. **86**, 269 (1952).
[10] Reference 5, Chap. X.
[11] L. I. Schiff, Phys. Rev. **78**, 733 (1950).
[12] J. F. Marshall and E. Guth, Phys. Rev. **78**, 738 (1950).

was found that $a/b \leq 0.1 (E_p > 18.5$ Mev), indicating that the isotropic component must be small compared to the "interference" component. The curve in the middle of Fig. 2 is therefore that of equation (1), with the constant found to be $p = 0.7 \pm 0.1$. Hence $\sigma_q/\sigma_d = 0.10 \pm 0.03$, if this interpretation of the theory can be trusted.

There is a similar situation in the results for aluminum irradiated at 65 Mev, also shown in Fig. 2. Again an attempted fit with Eq. (2) indicates that the fraction of the distribution which is isotropic is negligibly small. The points are therefore fitted with Eq. (1) with the constant found to be $p = 0.6 \pm 0.2$. This would give $\sigma_q/\sigma_d = 0.07 \pm 0.05$. These errors have been determined by finding the values of p for which the curve fell outside the root-mean-square deviations of more than one of the experimental points.

The angular distributions of the photoprotons from tantalum are shown in Fig. 3. In the case of the protons from the 25-Mev irradiation, there is a pronounced asymmetry at 90°, and there appears to be no appreciable excess of tracks at 60° over the number at 120°. The angular distribution formula used for aluminum thus appears inapplicable for tantalum, unless $p \approx 0$. A combination of an isotropic component and a $\sin^2\theta$ component appears sufficient to fit the uppermost points of Fig. 3. Such a $\sin^2\theta$ component would be characteristic of electric dipole absorption of photons. We may therefore write

$$I(\theta) = A + B \sin^2\theta, \tag{3}$$

where A and B are constants to be adjusted. The points are fitted by Eq. (3) with $B/A = 1.7$.

The two lower sets of points in Fig. 3 show the angular distributions of the higher-energy photoprotons emitted by tantalum irradiated, respectively, by 38- and 65-Mev bremsstrahlung. Again there is no indication in these figures of an excess of protons at 60° as compared with the numbers at 120°. The points in each figure have been fitted by Eq. (3). The best values of B/A were found to be 8 for the 38-Mev irradiation and infinity (i.e., $A = 0$) for the 65-Mev irradiation. The isotropic part of these distributions is therefore insignificant compared to the $\sin^2\theta$ part.

The angular distribution of Eq. (3) was predicted by Courant[13] for "directly ejected" protons. His calculations were based on a single-particle model. The ratio B/A is expected to depend on the orbital angular momenta of the protons which can be excited by the incoming photons. However, the large values of B/A observed for the high-energy photoprotons from tantalum would only be compatible with Courant's calculations if the great majority of the observed protons possessed zero orbital angular momentum in the nucleus before excitation, which seems unlikely. It would be difficult to understand why the photon excitation process should be so selective.

[13] E. D. Courant, Phys. Rev. **82**, 703 (1951).

Courant remarks that a pure $\sin^2\theta$ distribution would be obtained if similar calculations were carried out for an alpha-particle model with the alpha particles at rest. However, the internal motion of the alpha particles would introduce an isotropic component. Thus in principle this would appear not to be a good alternative model. However, quantitative calculations with it have not been carried out, and it might turn out that the isotropic component would be sufficiently small to be compatible with the results found here for tantalum.

Since the observed isotropic component occurs principally for the low-energy protons, it may be that this component chiefly represents statistically evaporated protons, with the directly ejected protons having chiefly the $\sin^2\theta$ distribution.

B. Energy Distributions

The higher-energy protons observed in this experiment may be expected to have been produced for the most part directly in the photon interaction process. The observed protons are those which have managed to avoid losing appreciable amounts of energy in collisions with other nucleons before escaping from the nucleus. The probability of successful escapes can be calculated roughly using an optical model[9] of the nucleus. Such calculations indicate that if 20 to 40 Mev is transferred to a proton in an average nucleus, the entire energy of this proton will go into the formation of a compound nucleus in about 70 percent of the cases. The proton should escape only after suffering some energy loss in a good fraction of the remaining cases. Thus most excitations in the energy range involved here should lead to the formation of a compound nucleus, and high-energy photoprotons should be produced in only a rather small fraction of the excitations. Any other photon interaction mechanism which does not excite a nuclear proton should in part also lead to the formation of a compound nucleus.

Some of these compound nuclei will decay by the emission of a proton of relatively small energy. The energy distribution is expected[5] to be given by

$$I(E_p) = \text{const} E_p \sigma_c(E_p) \omega_R(\hbar\omega - E_p - Q), \tag{4}$$

where E_p is the proton energy, $\sigma_c(E_p)$ is the capture cross section by the residual nucleus for protons of energy E_p, and $\omega_R(\hbar\omega - E_p - Q)$ is the energy level density of the residual nucleus, Q being the binding energy of the proton. The densities of energy levels may be approximately represented by

$$\omega_R(\epsilon) = \text{const} \exp[2(a\epsilon)^{\frac{1}{2}}]. \tag{5}$$

Equation (4) gives the proton energy distribution to be expected for a single photon energy $\hbar\omega$, on the assumption that all of the photon energy goes into the formation of the compound nucleus. To find the distribution to be expected for a continuous bremsstrahlung spectrum, it is necessary to multiply this expres-

sion by the (γ,p) cross section and by the number of photons of energy $\hbar\omega$ in the beam, and then to integrate the resulting expression over all photon energies present. The shape of the bremsstrahlung spectrum was assumed to be that calculated by Schiff.[14]

In order to compare the above distribution with that observed experimentally, it was necessary to make corrections for target thickness. This was particularly important for the case of the tantalum targets in the 25-Mev irradiation, where the target thickness was an appreciable fraction of the observed mean proton energy. In that case the target was considered to consist of six equal laminations, at the centers of which were sources emitting the above proton spectrum. With the help of the range-energy-loss relationship of Lindhard and Scharff,[8] calculations were made to obtain the spectral shapes to be expected after transmission through the laminations between the sources and detectors. The contributions from the various laminar sources were then summed.

The energy distribution of the photoprotons from aluminum irradiated with 25-Mev bremsstrahlung is shown in Fig. 4. The theoretical curve was calculated from Eq. (4), using the values of Heidmann and Bethe[15] for $\sigma_c(E_p)$ and $\omega_R(\hbar\omega-E_p-Q)$, and the results of Halpern and Mann[16] for the $Al^{27}(\gamma,p)Mg^{26}$ cross-section curve. There appears to be good agreement between the theoretical spectrum shape and the experimental points, and we therefore conclude that the majority of protons observed in this irradiation originated in a statistical evaporation process.

In Fig. 5 the energy spectra of the photoprotons from the 40- and 65-Mev irradiations of aluminum are presented in a log-log plot against the proton energy. The straight lines drawn through the points indicate that it is reasonable to represent the data over limited energy regions by the formula

$$I(E_p)=\text{const}E_p^{-n}. \quad (6)$$

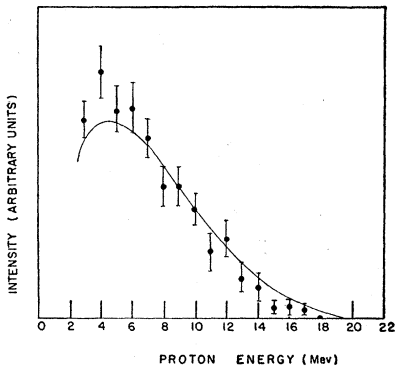

FIG. 4. Energy distribution of photoprotons from aluminum irradiated at 25 Mev. The theoretical curve is calculated from Eq. (4) for a statistical evaporation process and normalized to enclose the same area as the experimental points.

[14] L. I. Schiff, Phys. Rev. **83**, 252 (1951).
[15] J. Heidmann and H. A. Bethe, Phys. Rev. **84**, 274 (1951).
[16] J. Halpern and A. K. Mann, Phys. Rev. **83**, 370 (1951).

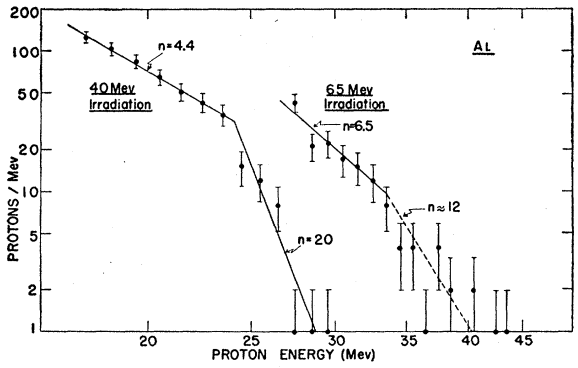

FIG. 5. Energy distributions of photoprotons from aluminum irradiated at 40 and 65 Mev. The data have been fitted as well as possible by straight lines according to Eq. (6).

It may be observed that each curve appears to have a break, with an increase in the value of n, at a proton energy which is a little more than half of the maximum energy available at the upper limit of the bremsstrahlung spectrum. Similar breaks are obtained in experiments at higher energies,[4] but the values of n obtained here are considerably larger than the values of approximately 2 and 4 obtained with 300-Mev bremsstrahlung.

The breaks obtained in higher-energy experiments have been interpreted as giving qualitative support to the Levinger quasi-deuteron model.[3] It has been argued that the two components of the quasi-deuteron will usually receive nearly equal shares of the incoming photon energy, but that occasionally the proton component will have a large momentum inside the nucleus and hence will receive considerably more than half of the photon energy. The results obtained here do not give quantitative support to this argument. On the foregoing picture one would expect the break to occur approximately at a proton energy equal to half of the bremsstrahlung energy, minus the proton binding energy in aluminum. Thus for the 40-Mev irradiation the break is expected to be at about $E_p=12$ Mev, whereas the observed break is at $E_p=24$ Mev. For the 65-Mev irradiation one would expect the break at $E_p=25$ Mev as compared to the observed position at $E_p=33$ Mev. However, the present data are not sufficient to be considered in definite disagreement with the Levinger model, since no protons were observed at energies where the breaks were predicted. Thus one cannot be sure that the observed breaks are not secondary phenomena.

In Fig. 6 is plotted the photoproton energy distribution obtained from tantalum in the 25-Mev irradiation. The theoretical distribution was calculated from Eq. (4) using values of $\sigma_c(E_p)$ interpolated for a nuclear radius of $1.3\times10^{-13}A^{\frac{1}{3}}$ cm in tables given by Blatt and Weisskopf.[5] Similar calculations made with a nuclear radius of $1.5\times10^{-13}A^{\frac{1}{3}}$ cm gave nearly identical results. The level densities for the residual hafnium nucleus were assumed to be given by Eq. (5) with $a=11$. The

cross-section curve for the (γ,p) reaction in tantalum is not known, nor is it known for any element in the immediate neighborhood of tantalum. It therefore was assumed that the (γ,p) cross-section curve measured for lead[17] would not be greatly different from that for tantalum, and hence that it might be used to weigh the energy distributions computed for different photon energies. This was checked by observing that the distributions expected to be produced by 20- and 30-Mev photons differed in energy at the peak by only 1 Mev and were very similar in relative shape. It is therefore believed that the errors introduced by this assumption are of a minor nature.

The theoretical curve, after corrections had been made, was normalized to enclose an area equal to that under the histogram of the experimental points of Fig. 6. It may be seen that this curve does not agree with the experimental points. There are fewer protons with low energies and more with high energies than are expected to result from a statistical evaporation process. This is the form that the disagreement would take if there was a substantial proportion of directly ejected protons present, which would tend to come off with more than normal evaporation energies.

Accordingly, the theoretical curve was normalized to the observed number of protons at 5 Mev (lower curve of Fig. 6). This energy is lower than is likely to arise in direct ejection. Although the point of normalization is highly uncertain, it is apparent that, if the lower curve of Fig. 6 correctly represents the numbers of evaporated protons, there are approximately equal numbers of evaporated and directly ejected protons. This is in qualitative agreement with the corresponding angular distribution in Fig. 3 if the evaporated protons have the isotropic distribution and the directly ejected protons have the $\sin^2\theta$ distribution.

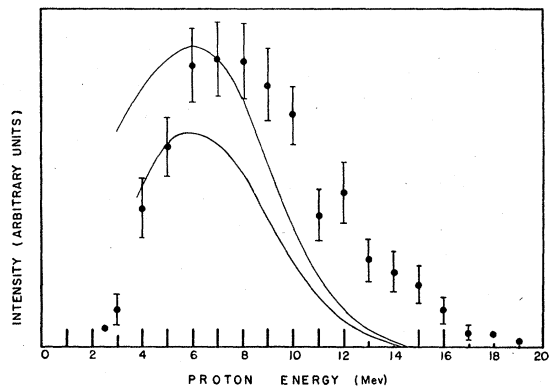

FIG. 6. Energy distribution of photoprotons from tantalum irradiated at 25 Mev. A theoretical curve has been calculated from Eq. (4) for a statistical evaporation process. The upper curve is this expression normalized to enclose the same area as the experimental points. The lower curve is this expression normalized to the experimental data at 5 Mev.

[17] Cameron, Harms, and Katz, Phys. Rev. **83**, 1264 (1951). Curve (a) of Fig. 1 of this reference was used.

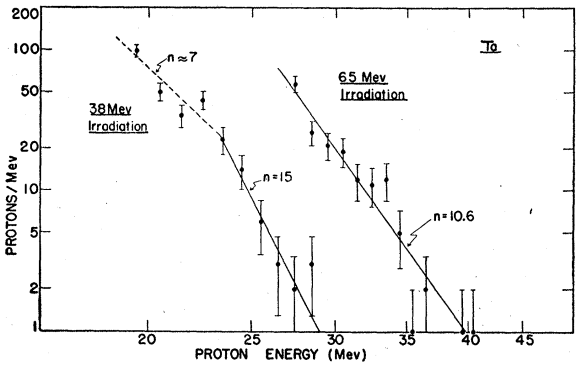

FIG. 7. Energy distributions of photoprotons from tantalum irradiated at 38 and 65 Mev. The data have been fitted as well as possible by straight lines according to Eq. (6).

In Fig. 7 the energy spectra of the photoprotons from the 38- and 65-Mev irradiations of tantalum are presented. The data appear to be reasonably well fitted by Eq. (6). The 38-Mev data appears to contain a break in slope at the same proton energy as did the 40-Mev aluminum data, but the change in slope is much less than in the aluminum case. However, there appears to be either no break at all in the 65-Mev data, or else one which involves too small a change of slope to be determined by the experimental points. If the Levinger quasi-deuteron model[3] were valid for tantalum, then according to the argument given previously one would expect that the 38- and 65-Mev data would have breaks at approximately 13 and 27 Mev, respectively. Since these proton energies were not observed, nothing definite can be said about the applicability of this model from the energy distribution data. However, the much smaller changes in slope of the tantalum data may well be related to the differing angular distributions of the high energy photoprotons from tantalum and aluminum.

The values of the slopes and break energies obtained in Figs. 5 and 7 are summarized in Table II. In the cases of both aluminum and tantalum, there is some qualitative evidence that the energy distributions of the high-energy photoprotons are a little steeper (larger n) in the forward and backwards directions than at 90°. The individual statistics are not sufficient to permit a quantitative estimation of this effect.

C. Photoproton Yields

During the synchrotron runs the x-ray dose received by the targets was monitored by tantalum foils, in which an 8-hour activity was produced by the $Ta^{181}(\gamma,n)Ta^{180}$ reaction. These foils were calibrated against the $Cu^{63}(\gamma,n)Cu^{62}$ activity, which in turn was determined absolutely in terms of the dose measured at 22 Mev by a Victoreen ionization chamber placed at the center of an 8-cm block of Lucite.[18] From the

[18] Johns, Katz, Douglas, and Haslam, Phys. Rev. **80**, 1062 (1950).

TABLE II. The slopes n of Eq. (6) and the break energies for the higher-energy photoprotons.

Target material	Synchrotron energy (Mev)	Break energy (Mev)	Slope Below break	Slope Above break
Al	40	24	4.4	20
Al	65	33	6.5	12
Ta	38	24	7	15
Ta	65	?	?	10.6

$Cu^{63}(\gamma,n)Cu^{62}$ and $Ta^{181}(\gamma,n)Ta^{180}$ cross-section curves[19] and the Schiff bremsstrahlung spectra it was possible to compare the number of protons observed per mole of target to the number of neutrons which would have been produced per mole of Cu^{63} had the target been composed of that substance. Since the (γ,n) yields had to be extrapolated to higher bremsstrahlung energies, the photoproton yields may not be very accurate, but they are probably correct to within a factor two. They are given in Table III, together with other results obtained in this experiment.

These yields allow estimates to be made of the (γ,p) cross sections, as distinct from the (γ,pn) cross sections, in aluminum and tantalum. These estimates are of interest because they are obtained here for energies in the "tail" of the (γ,p) cross-section curves, a region which cannot be determined accurately by ordinary yield curve analysis.[19]

A lower limit to the (γ,p) cross section is obtained by counting the number of protons in the range

$$E_0-Q(\gamma,p)-x\leq E_p\leq E_0-Q(\gamma,p),$$

and an upper limit is obtained by counting the number of protons in the range

$$E_0-Q(\gamma,pn)-x\leq E_p\leq E_0-Q(\gamma,p).$$

Here E_0 is the upper limit of the bremsstrahlung spectrum, $Q(\gamma,p)$ and $Q(\gamma,pn)$ are the binding energies, respectively, of a proton and of a proton and neutron, and x is an energy interval varied here from 4 to 10 Mev. In these criteria it is assumed that if a nucleus, following the emission of a proton, is left sufficiently excited to emit a further particle, such emission will take place (thus removing the event from classification as a (γ,p) reaction).

It was found that the upper and lower cross-section limits which were obtained by this procedure did not depend very strongly on the value of the energy interval x. Rough average estimates of these limits are given in Table IV. They may be compared to the peak cross section of the $Al^{27}(\gamma,p)Mg^{26}$ reaction of 22 millibarns at 21 Mev, and to that of the (γ,p) reaction in lead of 5 millibarns in the neighborhood of 26 Mev. It appears from the large differences obtained between the upper and lower cross section limits that the (γ,pn) cross sections are considerably larger than the (γ,p) cross sections at these energies.

TABLE III. Angular distributions and partial yields of the photoprotons.

Target material	Synchrotron energy (Mev)	Proton energies (Mev)	Angular distribution	Partial yield[a]
Al	25	0 to 17	isotropic	0.3
Al	40	16 to 28.5	$p=0.7$	0.03
Al	65	27 to 43	$p=0.6$	0.008
Ta	25	0 to 19	$B/A=1.7$	0.06
Ta	38	18.6 to 28	$B/A=8$	0.006
Ta	65	27 to 40	$B/A=\infty$	0.004

[a] Yield of protons in observed energy range per mole of target compared to yield of neutrons per mole of Cu^{63} had the target been composed of the latter substance.

[19] L. Katz and A. G. W. Cameron, Can. J. Phys. **29**, 518 (1951).

IV. DISCUSSION

From the foregoing results it may be seen that the photoprotons emitted by each element can be attributed to two sources. The lower-energy protons appear to be isotropically distributed and are presumed to have evaporated from a compound nucleus. The higher-energy protons fall off very rapidly with increasing energy, are nonisotropically distributed, and presumably result directly from the interaction between photons and nuclear matter.

TABLE IV. Estimates of the upper and lower limits of the (γ,p) cross sections.

Target material	Effective photon energy (Mev)	Cross-section limit (millibarns) minimum	maximum
Al	~35	0.05	10
Al	~60	0	0.05
Ta	~35	0.08	2.4
Ta	~60	0	0.02

The angular distribution of the protons directly ejected from aluminum may be well represented by Eq. (1), whereas those from tantalum can be fitted very well with Eq. (3). The first remarkable feature of this situation is the apparent lack of an isotropic component at higher energies. One might expect that a good fraction of the protons directly excited in the nucleus would make one or two "glancing" collisions with other nucleons before escaping, sufficient to change the angle of emission by a considerable amount but not sufficient to reduce the energy very much. This would have the effect of broadening the nonisotropic distribution; with only a few angular points available for analysis the result would probably look like a small isotropic component. The irradiations at 40 and 38 Mev reveal small isotropic components, but these are of a reasonable size to represent the high-energy tail of the statistical evaporation process. Neither of the irradiations at 65 Mev reveals any trace of an isotropic component.

The second remarkable feature of the situation is the difference in form of the nonisotropic distributions for

aluminum and tantalum. In the case of aluminum the angular distribution supports Levinger's quasi-deuteron model, and the energy distribution is not definitely in disagreement with it. This happens in an energy region where the model was not intended to be applied. If this theory is interpreted in a literal fashion, the magnitude of the asymmetric peaking at 60° indicates that electric quadrupole absorption is about nine percent as strong as electric dipole absorption of photons. This is of the order of magnitude to be expected from sum-rule considerations.[20]

It is then rather strange to find that this theory seems not to apply to tantalum. In this substance the directly ejected protons appear to obey a pure $\sin^2\theta$ law. This is characteristic of electric dipole absorption but it tells little about the nature of the absorption mechanism. The independent-particle model calculations of Courant appear to be excluded by the result, and similar calculations based on an alpha-particle model may well be similarly excluded. The quasi-deuteron model can explain the results only if $p\approx 0$, which, if the literal interpretation of the theory is correct, implies that the electric quadrupole absorption in tantalum is much less than one would expect.

It therefore appears that none of the postulated photon interaction mechanisms gives suitable predictions applicable to any element in the "intermediate" energy range.

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Beta-Gamma Polarization Correlations*

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The polarization of the gamma ray emitted at an angle of 90 degrees to the preceding beta particle has been measured for certain beta-gamma cascades in potassium-42, arsenic-76, rubidium-86, antimony-124, and cesium-134, as selected by beta absorbers when necessary. The polarimeter was checked by observing the polarization of the gamma rays of cesium-137 and cobalt-60 when Compton-scattered through 90 degrees. Of the gammas investigated, those of potassium-42 and cesium-134 have no observable polarization. For the other three elements, the sign of the polarization correlation, taken in combination with the sign of the angular correlation reported by other observers, uniquely determines that no parity change occurs in the gamma emission, corresponding to electric quadrupole radiation in decay of the excited state.

INTRODUCTION

THE gamma-gamma and beta-gamma angular correlations[1,2] have become recognized tools of nuclear spectroscopy and of the search for the fundamental beta interaction; concerning the gamma rays involved, these angular correlations usually tell the angular momenta of the levels involved and the multipole order of the gammas. If the gamma detector is in addition polarization-sensitive, then one may expect to learn whether the given multipole is electric or magnetic (that is, the parity change in the transition), for the fields of the electric and magnetic type of given order multipole differ by interchange of E and H and hence by a 90 degree rotation of polarization, and differ in parity.

Information concerning multipole order and parity change may also be obtained from internal conversion data. This procedure involves elaborate calculations using relativistic electron wave functions and is, in principle, perhaps not quite so direct as a measurement of gamma angular distribution and polarization; but with the exact calculations now available, the interpretation of experiments seems just as satisfactory. The principal difference between the two methods lies, therefore, in convenience of use; and one relevant factor here is the energy dependence of the two effects. Internal conversion coefficients become small for high energies and low Z; for example, for an electric quadrupole gamma the coefficient α_k has values[3] 2×10^{-6} and 0.11 for 2.5 Mev, $Z=10$ and 0.25 Mev, $Z=96$, respec-

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