Photo-Disintegration of Silver and Aluminum*

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(Received July 3, 1950)

The energy and angular distributions of protons emitted from Ag and Al nuclei when irradiated with the x-rays from a 22-Mev betatron were determined with the use of photographic nuclear emulsions. A maximum x-ray energy of 20.8 Mev was used with Ag and energies of 20.8, 17.1, and 13.9 Mev with Al.

With silver the number of neutrons emitted in the same irradiation was determined from the (γ, n) induced activity. The ratio of numbers of protons in each Mev interval to the total number of neutrons is compared to the same ratio calculated on the basis of various assumptions as to level density and nuclear reaction cross sections. The comparison suggests that the observed proton spectrum consists of two overlapping components. One is a lower energy group in rough quantitative agreement as to spectrum shape and numbers with calculations from reasonable assumptions as to statistical-model level densities and other nuclear parameters. The second group is a high energy tail (10–14 Mev) of protons definitely outside of the spectrum expected from the statistical model. Moreover, only the high energy group shows angular asymmetry with a preference for emission at 90° to the x-ray beam, which supports the hypothesis that these protons are emitted before the excitation energy is statistically distributed in the nucleus.

The ratio of total numbers of protons to neutrons emitted by Ag under 20.8-Mev bremsstrahlung radiation is 0.023 ± 0.008.

With Al protons are emitted with spherical symmetry and with a yield, for quanta above about 14 Mev, as large or larger than the (γ, n) yield determined by Hirzel and Wäffler at 17.6 Mev. The shape of the spectrum and the ratio of (γ, p) to (γ, n) cross sections are compatible with the assumption of a constant or slowly increasing level density in the residual nucleus, as expected for a light nucleus in the energy range involved. From the maximum energy of emitted protons the proton threshold was determined to be 8.6 ± 0.5 Mev.

For use with the theoretical calculation of the proton spectra, the (γ, n) cross sections as a function of x-ray quantum energy were determined for $Ag^{107,109}$, Al^{27}, and also for Cu^{63}. The cross section of Ag^{109} was found to have a maximum of 0.32×10^{-24} cm^2 at 16.5 Mev, Cu^{63} a maximum of 0.10×10^{-24} cm^2 at 17.5 Mev. For Al^{27} the cross section is still rising at 22 Mev.

I. INTRODUCTION

MEASUREMENTS of relative cross section of (γ, p) and (γ, n) reactions in a number of elements have been reported by Hirzel and Wäffler[1] and Perlman and Friedlander.[2] In all cases of elements of medium weight, where it is appropriate to apply the statistical theory of nuclear reactions, the observed proton yields were much larger than those predicted, often by a factor of a thousand. Attempts at explaining the large yield have been made by Courant,[3] by Levinger and Bethe,[4] and by Schiff.[5] Their suggestions will be discussed in the light of the results of this paper.

The present experiments were undertaken to see whether a more detailed study of the protons emitted in a (γ, p) reaction would shed light on the processes involved in the nuclear photo-effect. We have determined the energy and angular distributions of protons emitted from silver and aluminum when excited with x-rays from a 22-Mev betatron. We shall show in the last section of the paper that the experimental results do suggest a basis for explaining the anomalously large proton yields observed for many nuclei.

Similar studies with similar techniques have been made by Toms and others[6] with magnesium and by Curtis and others[7] with rhodium.

* Assisted by the joint program of ONR and AEC.
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[1] O. Hirzel and H. Wäffler, Helv. Phys. Acta **20**, 373 (1947).
[2] M. L. Perlman and G. Friedlander, Phys. Rev. **74**, 442 (1948); **75**, 988 (1949).
[3] E. D. Courant, Phys. Rev. **74**, 1226 (1948).
[4] J. S. Levinger and H. A. Bethe, Phys. Rev. **78**, 115 (1950).
[5] L. I. Schiff, Phys. Rev. **73**, 1311 (1948).
[6] Toms, Halpern, and Stephens, Phys. Rev. **77**, 753 (1950).
[7] Curtis, Hornbostel, Lee, and Salant, Phys. Rev. **77**, 290 (1950), and private communication from Dr. Hornbostel.

II. EXPERIMENTAL METHOD

The experimental arrangement is shown in Fig. 1. The betatron target T was the source of x-rays of which a thin pencil passed through the laminated lead collimator C and lead wall W, through the 0.003-in. aluminum entrance window of the evacuated exposure chamber, along the length of foil of the metal under study, out of the chamber, and through the monitors. The primary monitor was a Victoreen 100-roentgen thimble surrounded by 4 cm of aluminum wall whose response was calculated according to Fowler, Lauritsen, and Lauritsen.[8] The beam also passed through a tantalum foil, $0.002\times1\times1$ in., inducing, by a (γ, n) reaction, an 8.2-hr. activity which served as an additional monitor.

The collimator confined the x-ray beam to a cone of angular width 0.0115 radian. The beam diameter was 0.75 cm at the entrance window and 1.115 cm at the exit window. The collimator and lead wall interposed $12\frac{1}{2}$ in. of lead in the beam, except for the transmitted pencil.

The exposure chamber was a brass tube with a port on one side which held a pair of 1×3-in. photographic plates (Ilford C-2, 200μ emulsion). The surfaces of the plates were parallel and separated by 1.80 cm. The edges of the plates nearer the beam were 3.81 cm from the center of the beam and parallel to the beam.

The irradiated foil, 12 in. long, was supported by a half-cylinder of thin-walled aluminum $1\frac{1}{2}\times13$ in. It was placed in the chamber nearly, but not quite, parallel to the center of the beam. The surface of the foil was perpendicular to the surfaces of the plates. The chamber was evacuated and water vapor was admitted

[8] Fowler, Lauritsen, and Lauritsen, Rev. Mod. Phys. **20**, 263 (1948).

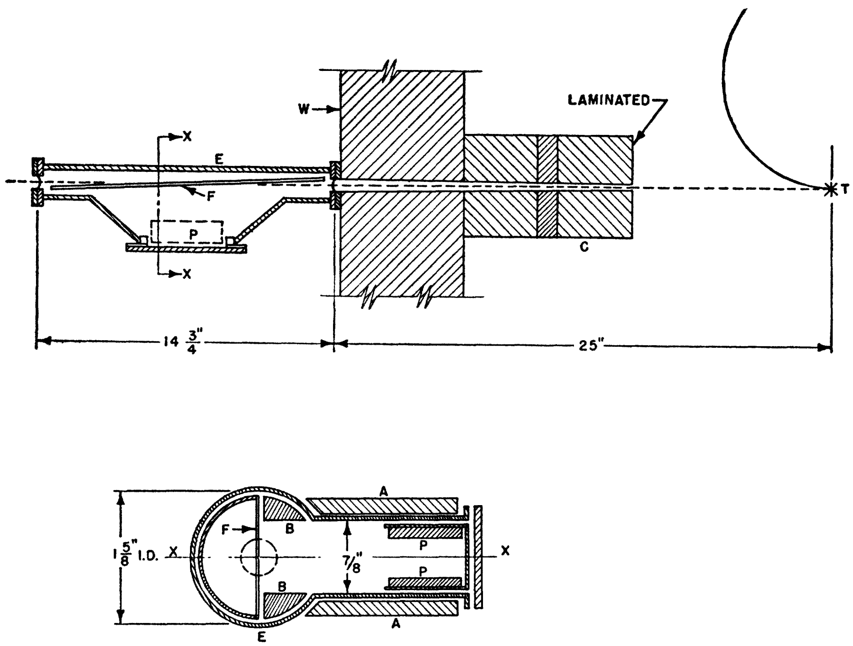


FIG. 1. Two sections of exposure chamber E and collimator C. T, betatron target; W, lead wall; F, foil; P, photographic plates; A and B, magnet pole pieces. Dashed circle indicates size of x-ray beam. The tilt of the foil is exaggerated.

to a pressure of 18 mm Hg to avoid desiccation of the emulsion.

Troublesome fogging due to low energy electrons scattered from the foil was reduced adequately by applying a magnetic field of about 2000 gauss in the half of the chamber nearer the betatron. For this purpose permanent magnetron magnets with soft iron pole strips were used.

The exposures given were 2000 to 2500 roentgens at the foil. At the end of an exposure on silver the 24.5-min. activity induced in the foil by a (γ, n) reaction was counted for each of several one-cm sections along the length of the foil. This served, first, to measure the variation of x-ray intensity along the foil and, second, to determine the number of neutrons produced in the foil by the same irradiation for which the protons were observed and counted in the emulsions. As a further check on intensity variation along the foil, the 10-min. activity of 1-cm Cu strips placed as extensions of the foil at each end were counted at the end of each run. With an Al foil the 7.5-sec. (γ, n) induced activity decayed too rapidly to measure and the Cu strips alone were used.

For each proton track observed in the emulsion the projection of the range onto the plane of the plate, the angle to the beam, and the angle of dip as the proton entered the emulsion were measured. To be accepted a track was required to start at the surface of the emulsion and to have a direction compatible with an origin in the irradiated part of the foil. Angles to the beam from 20° to 160° were accepted.

The energy loss of the protons in the emulsion was obtained from the range-energy relations of Lattes, Fowler, and Cuer.[9] To these energies were added the energy which would have been lost if the proton traversed one-half of the foil thickness at the angle involved. The Ag foil weighed 12.58 mg/cm^2 and the Al foil 4.74 mg/cm^2. The uncertainty in energy due to foil thickness is equal to the correction added and varied for the foils chosen from about 0.1 Mev to 0.6 Mev, depending on the energy and angle of the proton. A calculation showed that scattering in the foils does not materially affect the angular distribution, plotted in 20° intervals.

Background exposures were taken at each betatron energy used, by removing the metal foil from the chamber and exposing a pair of plates in an otherwise normal run. The background plates were analyzed in the same manner as plates taken with silver or aluminum foils in place.

A source of background which is not subtracted by the above procedure is the (n, p) process in the foil itself. However, from an earlier approximate measurement of the fast neutron flux and approximate knowledge of the (n, p) and (γ, p) cross sections, it is estimated that with a silver foil less than 10^{-4} of the protons observed come from (n, p) reactions. For the Al foil the fraction is less than 10^{-2}. The distribution in dip angle of the proton tracks also indicates that nearly all of the protons come from the part of the silver foil irradiated by x-rays and not from the whole foil as would be expected for (n, p) protons.

III. EXPERIMENTAL RESULTS

Silver

An area of 291 mm^2 on two pairs of plates exposed at 20.8 Mev disclosed 676 tracks of protons, with energies greater than 3 Mev, which satisfied the selection criteria. After corrections for the measured variation of

[9] Lattes, Fowler, and Cuer, Proc. Roy. Soc. 59, 883 (1947).

x-ray intensity along the foil the number of protons per unit solid angle was plotted against angle between beam and proton emission, in Fig. 2, for three energy intervals. For energies up to 10 Mev the distribution appears to be spherically symmetrical. Above 10 Mev, however, there is pronounced asymmetry with emission at 90° to the beam most probable. The energy distribution is plotted in Fig. 3.

The total yield was 1.29 protons per *r* per mm length of foil. The number of neutrons produced in the foil in the same irradiations was found by counting, immediately after each run, the 24.5-min. activity extrapolated to saturation, induced by a (γ, n) reaction in Ag^{107}. For this purpose an end window counter was calibrated against a RaE source and its efficiency determined to be 0.135. We found 1.89 disintegrations per *r* per mm of foil leading to the observed 24.5-min. activity. The same reaction leads also to an 8.2-day isomer which we do not measure but we assume that the reaction leads with equal probability to the two isomers. We also measured the $Ag^{109}(\gamma, n)Ag^{108}$, 2.3-min. activity as well as the 24.5-min. activity in separate short irradiations with a thin foil and found the 2.3-min. activity to be 1.9 times as strong as the 24.5-min. activity. The total yield of neutrons was therefore $(2\times 1.89+1.9\times 1.89)/0.135$ or 54.6 neutrons per *r* per mm of foil.

Correcting for isotopic abundance, the 2.3-min. Ag^{108} activity was just 2.0 times the 24.5-min. Ag^{108} activity, as would be expected if (1) the two isomers of Ag^{106} are equally populated in the reaction, and (2) the (γ, n) cross sections of Ag^{107} and Ag^{109} are identical. The latter condition is supported by the observation that the (γ, n) thresholds and shapes of excitation curves (Fig. 7) of Ag^{107} and Ag^{109} are nearly identical.

Finally, the ratio of numbers of protons to neutrons emitted from silver during an exposure to a 20.8-Mev x-ray continuum is 1.29/54.6 or 0.023 ± 0.008. The largest factor in the uncertainty came from errors in the determination of the neutron yield from the beta-activity and no allowance was made for the assumption that the isomers of Ag^{106} are equally populated in the reaction. The ratio of protons to neutrons is independent of variation and uncertainty in absolute intensity of x-rays along the foil (which are considerable in this arrangement), fluctuations of source intensity, and area of foil irradiated.

Aluminum

With an aluminum foil (4.74 mg/cm^2) in the chamber, exposures were made at three betatron energies and the proton tracks were measured on four pairs of plates as shown in Table I.

The energy distributions are plotted in Fig. 4 and the angular distributions in Fig. 5. No pronounced angular asymmetry was observed.

An additional area of 549 mm^2 on the 17.1-Mev plates was searched for protons of energy more than 5 Mev to determine the maximum proton energy and hence the (γ, p) threshold. The highest energy observed was 8.5 Mev and 9 protons were found in the interval 8.0 to 8.5 Mev. We therefore estimate the proton threshold to be $17.1-8.5=8.6\pm 0.5$ Mev. This is in reasonable agreement with the value 9.2 ± 0.4 Mev computed from the (γ, n) threshold (14.0 Mev)[10] and the energy of the positron emitted from Al^{26} (3.0 Mev).

(γ, p) cross sections averaged over wide bands of x-ray energies were obtained in the following manner. First, the number of protons per atom per *r* at 17.1 Mev was subtracted from the number per atom per *r* at 20.8 Mev. The difference arises from the effect of a band of x-rays obtained by subtracting the x-ray spectra (number of quanta *vs.* energy) for the two betatron energies each normalized to represent a spectrum which would produce 1 *r* response in the aluminum-shielded monitor. The band extends from 12 to 20.8 Mev with most of the quanta in the region from 16 to 20 Mev. Similarly, the difference in yields at betatron energies of 17.1 and 13.9 Mev is associated with a band of quanta extending from 11 to 17.1 Mev but mainly between 13 and 16 Mev. Finally, the protons observed at 13.9-Mev betatron energy are due to a band of x-rays from 11 to 13.9 Mev, since no protons of energy less than 2 Mev were recorded and the proton threshold is about 9 Mev. In the three intervals the cross sections were as given in Table II.

These values should be reliable to within a factor of two. They are of the same order of magnitude as the $Al(\gamma, n)$ cross section at 17.5 Mev, 3.2×10^{-27} cm^2, found by Wäffler and Hirzel.[11]

IV. ENERGY DEPENDENCE OF PHOTO-NEUTRON CROSS SECTIONS

In order to interpret the proton energy distributions we need to know the variation with energy of the (γ, n)

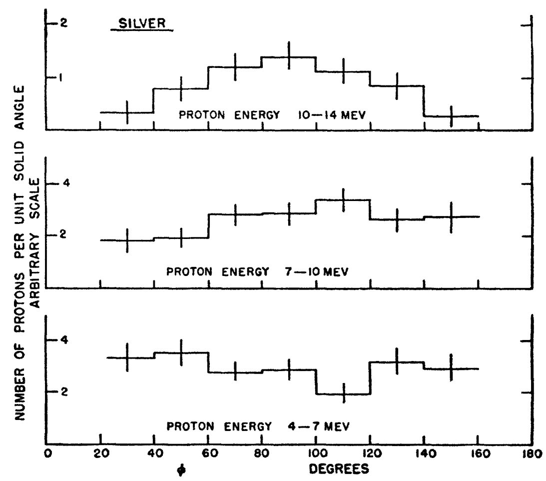


FIG. 2. Angular distribution of photo-protons from silver. Maximum x-ray energy, 20.8 Mev. ϕ is angle of proton emission with respect to x-ray beam.

[10] McElhinney, Hanson, Duffield, and Diven, Phys. Rev. **75**, 542 (1949).
[11] H. Wäffler and O. Hirzel, Helv. Phys. Acta **21**, 200 (1948).

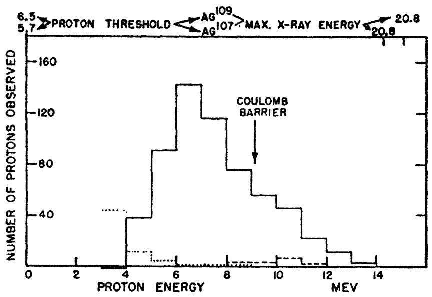


FIG. 3. Energy distribution of photo-protons emitted from silver between angles to the beam of 20° and 160°. Solid lines are numbers of proton tracks less background (dotted line). Dashed line represents tracks which penetrate entire emulsion plotted according to length of track in emulsion, and not included in solid-line plot.

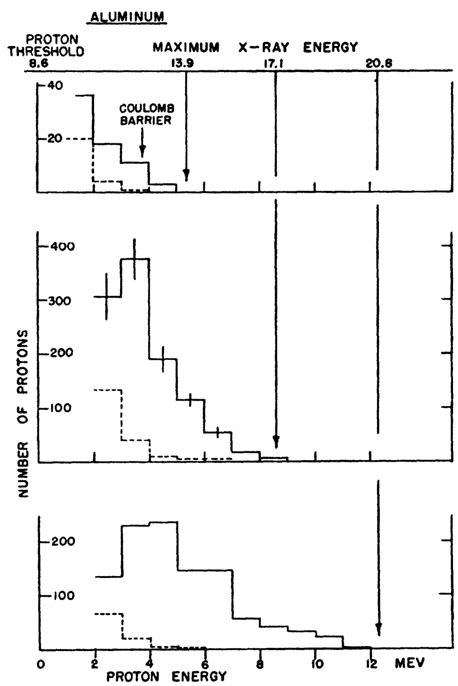


FIG. 4. Energy distribution of photo-protons from aluminum at maximum x-ray energies of 13.9, 17.1, 20.8 Mev, and between angles of 20° and 160° to the beam. Solid lines are observed numbers of tracks less background (dotted lines) for 13.9- and 20.8-Mev histograms. At 17.1 Mev an additional area of plate was searched only for protons of energy >5 Mev; histogram and background are normalized below 5 Mev to correspond to observed numbers of protons above 5 Mev. Maximum observed proton energy was 8.5 Mev, from which (γ, p) threshold is 8.6 ± 0.5 Mev.

cross sections. To determine these cross sections, a sample of silver or aluminum, and also Cu, $0.005''\times\frac{3}{4}''\times 1''$, was irradiated in the carefully monitored x-ray beam at various maximum x-ray energies and the activity following a (γ, n) reaction was determined at each energy. From the activation curves and the x-ray spectrum, the energy dependence of the (γ, n) cross section can be deduced.

The observed saturated activity per r per min. per atom from a (γ, n) reaction of cross section $\sigma(E)$ induced by the spectrum of x-rays with $N(E, E_m)$ quanta per unit energy interval per unit area is,

$$A=K\int_{B_n}^{E_m}\sigma_{\gamma,n}(E)N(E,E_m)dE\Big/\int_0^{E_m}N(E,E_m)i(E)dE,$$

where E is the quantum energy, E_m the maximum x-ray energy, B_n the (γ, n) threshold, and $i(E)$ the sensitivity of the monitor in r per quantum of energy E per unit area of beam. We have computed the monitor response $i(E)$, following Fowler, Lauritsen, and Lauritsen.[8] The x-ray spectrum used was that given by Schiff.[12] Normalization was accomplished by computing the spectrum $N(E, E_m)$ for each E_m which would make the denominator in the expression for A correspond to 1 r. K is then the counter efficiency. $\sigma(E)$ was obtained by replacing the integral expression for A with the following equations and solving them step by

TABLE I. Protons from aluminum.

Betatron energy (Mev)	Exposure (r)	Area searched (mm²)	Protons observed	Net protons per atom per $r\times10^{19}$
20.8	2010	114	560	2.8
20.8	2580	86	574	
17.1	2360	217	429	1.7
13.9	1500	217	109	0.3

TABLE II. Cross section for the (γ, p) reaction in Al.

Energy (Mev) Range (Mev)	Average (Mev)	$\sigma_{\gamma,p}$ (millibarns)
12–20.8	18	6
11–17.1	14.5	6
11–13.9	12.5	1.5

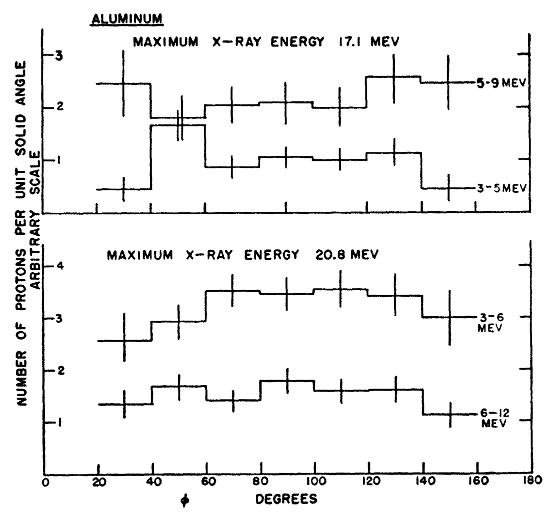
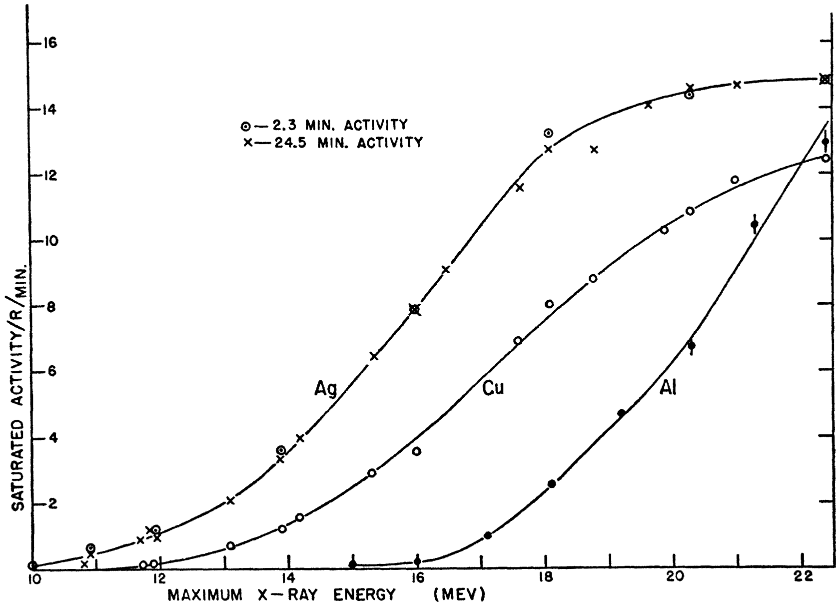


FIG. 5. Angular distribution of photo-protons from aluminum.

[12] L. I. Schiff, Phys. Rev. **70**, 87 (1946); see G. D. Adams. Phys. Rev. **74**, 1710 (1948).

Fig. 6. Excitation curves for (γ, n) activities in silver, aluminum, and copper. The activity curve for Ag^{107} has been multiplied by a constant factor to show its similarity in shape to the activity curve for Ag^{109}. Some points for silver and copper are from unpublished data of J. McElhinney.



step:

$$A_1/K = N_{11}\sigma_1, \quad A_2/K = N_{21}\sigma_1 + N_{22}\sigma_2, \quad \text{etc.,}$$

where A_1 is the activity per r induced by an x-ray spectrum whose E_m is 1 Mev above B_n and which has N_{11} quanta in this 1-Mev interval. σ_1 is the average cross section for the interval. A_2 is the activity for the spectrum for which $E_m = B_n + 2$ Mev, with N_{21} and N_{22} quanta in the first and second 1-Mev intervals above B_n. σ_2 is the cross section for the interval 1 to 2 Mev and so on.

Absolute values of cross section were obtained for Ag and Cu, since activities were determined with a calibrated counter and the monitor response $i(E)$ fixes the number of quanta at each energy of the spectrum when its shape is assumed. The uncertainty in the calculated cross section becomes very large at high energies, but it is certain that it drops rapidly to a low value a few Mev above the peak.

The activation and cross section curves are shown in Figs. 6 and 7 for the Ag isotopes, for Al^{27}, and also for Cu^{33}. The principal features for Ag^{109} and Cu^{63} are shown in Table III. As stated earlier, the activity per atom per r with Ag^{107} is just one-half that with Ag^{109}, and if it is assumed that both isomers of Ag^{106} are equally populated in the (γ, n) reaction, we conclude that the characteristics of the $\sigma_{\gamma,n}$-curve are the same for Ag^{107} as listed for Ag^{109}. Their activation curves are identical in shape, within errors of measurement.

The neutron yields for Cu and Ag, measured by Price and Kerst by neutron detection, are listed in comparison with ours in the above table. They did not distinguish the isotopes, but according to our interpretation the (γ, n) cross sections and yields should be the same for Ag^{107} and Ag^{109}. There is some uncertainty about the contribution of neutrons per atom of Cu^{65}, relative to Cu^{63}, but since the isotopic abundance of Cu^{65} is only 30 percent, the agreement in the yields for Cu can hardly be disturbed by more than the experimental errors in their determination.

The cross section curves are of the resonance type as first shown by Baldwin and Klaiber[13] for Cu^{63} and C^{12}. They found the peak for Cu^{63} at 22 Mev. The betatron group at Saskatoon[14] has, however, obtained a cross

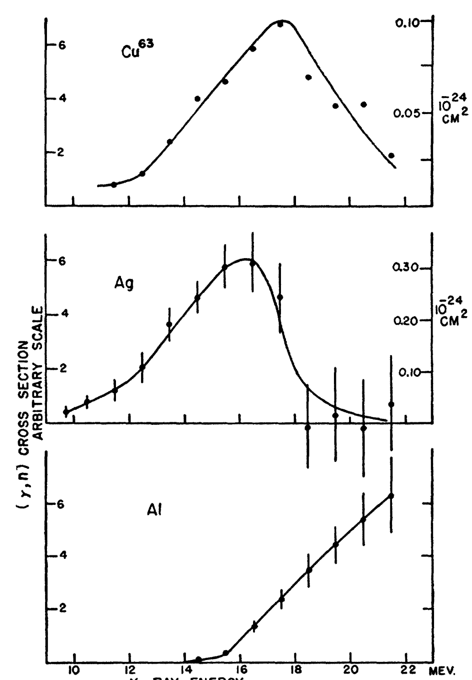


Fig. 7. (γ, n) cross sections for silver, aluminum and copper.

[13] G. C. Baldwin and G. S. Klaiber, Phys. Rev. **73**, 1156 (1948).
[14] Leon Katz, University of Saskatchewan, Saskatoon (private communication).

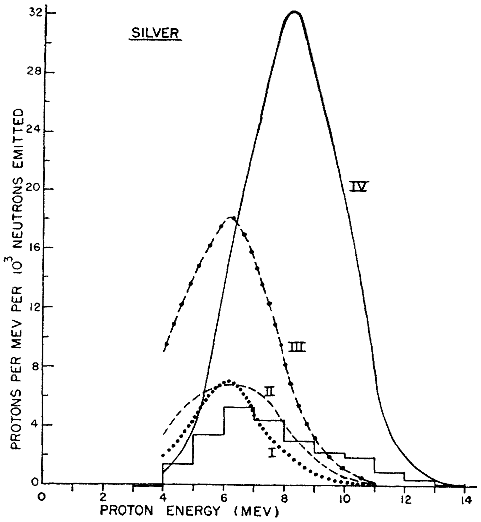


FIG. 8. Ratio of protons per Mev interval to total number of neutrons emitted in same irradiation. Histogram is observed distribution. Theoretical curves calculated with parameters given in text for cases I, II, III, IV.

TABLE III. Results for Ag^{109} and Cu^{63}.

	Ag^{109}	Cu^{63}
Energy at peak (Mev)	16.5	17.5
$\sigma_{\gamma,n}$ at peak (barns)	0.32	0.10
$\int \sigma_{\gamma,n} dE$ (Mev-barns)	1.65	0.6
Neutrons/mole/$r\times 10^{-6}$		
This work—20.8 Mev	7.3	2.6
Price and Kerst[a]—22 Mev	6.7	2.5

[a] G. A. Price and D. W. Kerst, Phys. Rev. **77**, 806 (1950).

section curve nearly identical in shape and absolute values with that in Fig. 7. Strauch[15] estimates, by an entirely different method, that the principal absorption of x-rays by Cu nuclei occurs near 20 Mev and by Ag near 18 Mev.

V. COMPARISON WITH THEORY

Silver

We have compared the observed energy distributions with those calculated according to the statistical theory of nuclei, using several level density functions. Following Weisskopf and Ewing[16] the energy distribution of protons from a nucleus excited with monoenergetic x-rays is

$$I(\epsilon_p) = \text{const}\,\epsilon_p \sigma_p \omega_R,$$

where ϵ_p is the proton energy, σ_p is the reaction cross section for the inverse process consisting of excitation of the nucleus by absorption of a proton of energy ϵ_p, and ω_R is the level density of the residual nucleus at the excitation energy which remains when a proton of energy ϵ_p is emitted from the compound nucleus. For the continuous spectrum of x-rays used in this experiment we must use the appropriate integral of $I(\epsilon_p)$ over the x-ray spectrum. The average value of the emission probability per unit time of a particle b from a particular excited state is

$$\Gamma_b = \text{const} \int_0^{\epsilon_b\,\max} \epsilon_b \sigma_b \omega_R d\epsilon_b.$$

Then the energy distribution of protons per nucleus in the x-ray beam, excited with cross section $\sigma_\gamma(E)$ by a spectrum with $N(E, E_m)$ quanta per cm² per Mev interval at energy E and a maximum energy E_m, is

$$F(\epsilon_p) = \epsilon_p \sigma_p \int_{B_p}^{E_m} \frac{\sigma_\gamma(E) N(E, E_m) \omega_R(E - B_p - \epsilon_p)}{\sum_{b'} \Gamma_{b'}} dE,$$

where B_p is the (γ, p) threshold and the b'-summation is over all modes of disintegration of the excited nucleus, here assumed to be restricted to (γ, p) and (γ, n) processes. Then since

$$\sigma_\gamma / \sigma_{\gamma,n} = \sum_{b'} \Gamma_{b'} / \Gamma_n,$$

$$F(\epsilon_p) = \epsilon_p \sigma_p \int_{B_p}^{E_m} \frac{\sigma_{\gamma,n}(E) N(E, E_m) \omega_R(E - B_p - \epsilon_p)}{\Gamma_n} dE.$$

The total number of neutrons emitted is

$$N_n = \int_{B_n}^{E_m} \sigma_{\gamma,n}(E) N(E, E_m) dE,$$

or, alternatively, $\sum_{\epsilon_n} F(\epsilon_n)$, where $F(\epsilon_n)$ is calculated in a way similar to $F(\epsilon_p)$.

The calculations were carried through for each isotope and the distributions, weighted for isotopic abundance, were added. The calculated ratios of protons per Mev energy interval to total neutrons may be compared to the experimental ratio obtained directly without use of the absolute (γ, n) cross sections.

Four combinations of energy level density and reaction cross section have been used, as follows:[17–19]

$\omega_1 = C \exp(aE)^{\frac{1}{2}}$, $a = A/5$ (reference 16); σ_p with $r_0 = 1.42\times 10^{-13}$ cm, and σ_n from reference 17. (I)

$\omega_2 = C \exp(aE)^{\frac{1}{2}}$, $a = 1.6(A-40)^{\frac{1}{2}}$ (reference 18); σ_p with $r_0 = 1.30\times 10^{-13}$ cm from reference 18, σ_n from reference 19. (II)

Same as (II), except $r_0 = 1.50\times 10^{-13}$ cm (reference 18). (III)

[15] K. Strauch, Phys. Rev. **79**, 241 (1950).
[16] V. F. Weisskopf and D. H. Ewing, Phys. Rev. **57**, 472 (1940).
[17] Lecture Series in Nuclear Physics (MDDC 1175) U. S. Gov't Printing Office, pp. 100–105.
[18] V. F. Weisskopf, private communication, March, 1950, proposed ω_2 as giving better agreement with other current experiments and supplied recently calculated reaction cross sections, σ_p.
[19] H. Feshbach and V. F. Weisskopf, Phys. Rev. **76**, 1550 (1949).

$\omega_3 = C \ln(E+b)/b$, $b=20/A$ (reference 5); σ_p and σ_n as in I. (IV)

The (γ, n) thresholds for Ag^{107} (9.5 Mev) and Ag^{109} (9.3 Mev) have been determined by Baldwin and Koch.[20] The (γ, p) threshold for Ag^{107} is computed from the (γ, n) threshold and the positron energy of Ag^{106} (2.0 Mev) to be 5.7 Mev, which agrees to within 0.1 Mev of the value obtained from Fermi's semi-empirical formula.[21] From the latter formula the (γ, p) threshold of Ag^{109} is 6.5 Mev. The computed shape of the proton spectrum is not very sensitive to the thresholds, but the computed ratio of protons to neutrons is quite sensitive. The difference of 1.0 Mev in $B_n - B_p$ reduces the proton yield of Ag^{109} as compared with Ag^{107} by a factor of four.

The comparison of calculated and observed ratios of protons per Mev to total neutrons is presented in Fig. 8. There is no arbitrary fitting of curves at any point; the theoretical and experimental curves are entirely independent.

The areas under the curves, which are ratios of the total numbers of protons to the total numbers of neutrons emitted during 20.8-Mev bremsstrahlung irradiation, are:

Level density	N_p/N_n
(I) ω_1	0.022
(II) $\omega_2(r_0 = 1.3\times10^{-13}$ cm)	0.030
(III) $\omega_2(r_0 = 1.5\times10^{-13}$ cm)	0.075
(IV) ω_3	0.13
Observed	0.023±0.008.

The disagreement between the observed proton spectrum and calculations (III) or (IV) appears to be definite. The agreements in cases (I) or (II) are satisfactory up to 8 or 9 Mev when one considers the uncertainties in the experiment and in the calculation, especially at low proton energies. At higher energies there are definitely more protons than are predicted from a statistical model (ω_1 or ω_2). A calculation showed that even if the (γ, n) cross section is assumed to rise linearly to 20.8 Mev instead of dropping rapidly from a peak at 16.5 Mev, there are definitely more protons observed than predicted above 10 Mev.

The significance of the results will be discussed in the following section.

Aluminum

A statistical treatment of energy levels is not appropriate in light nuclei in the energy range of interest, since the levels are widely spaced. For example, the nuclei[22,23] of Al^{27} and Si^{28} have been shown to have a rather widely spaced (~1 Mev) and slowly converging level structure for several Mev above the ground state. No structure in our observed proton spectrum is to be expected, however, since the nucleus is excited by a continuum of x-rays.

To get a rough idea of the proton spectrum to be expected with 20.8-Mev bremsstrahlung a calculation of $F(\epsilon_p)$ was made with the following simplifying assumptions: ω_R = constant, $\sigma_{\gamma,n}$ as in Fig. 7 for $E > 15$ Mev, σ_γ = constant from 11 to 15 Mev and equal to σ_γ at 15 Mev. The reaction cross section σ_n is obtained from reference 19 and σ_p from the W. K. B. method (see reference 17), admittedly unreliable for such a light element but unimportant since most of the protons have energy greater than the barrier height. The (γ, n) threshold is 14 Mev and the (γ, p) threshold is 9 Mev.

The calculated proton spectrum is shown in Fig. 9, normalized arbitrarily, since the neutrons emitted during the exposures were not counted, as they were for silver. If the level density were assumed to increase slowly with energy, as it certainly must, a better fit would be obtained, for the curve would be concave toward the axis above a proton energy of 4 or 5 Mev.

The simple assumption of a constant level density leads also to the result that at an x-ray energy of 17 or 18 Mev the yield of protons should be about 1½ times the yield of neutrons, in qualitative agreement with the ratio of two between our $\sigma_{\gamma,p}$ at 16 to 20 Mev and the value of $\sigma_{\gamma,n}$ at 17.6 Mev found by Hirzel and Wäffler.[11] The emission of protons is favored by the fact that the proton threshold is about 5 Mev less than the neutron threshold, which outweighs the restraining effect on protons of the Coulomb barrier.

VI. SUMMARY AND DISCUSSION

The observations on protons from the (γ, p) reaction in silver, excited by a 20.8-Mev bremsstrahlung spectrum which covers the resonance absorption with a maximum at 16.5 Mev, can be summarized qualitatively as follows:

(a) Protons of low energy (<8 or 9 Mev) are emitted with equal probability at all angles and with an energy distribution similar to that expected with reasonable

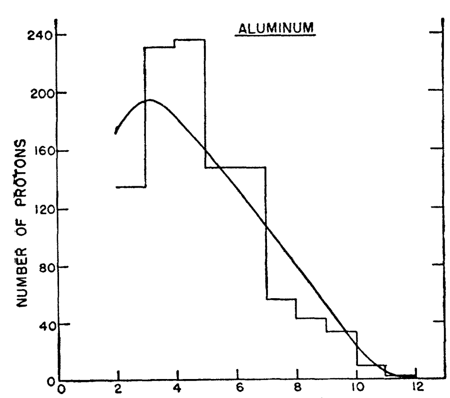


FIG. 9. Energy distribution of protons from aluminum with maximum x-ray energy 20.8 Mev, compared with distribution computed for constant level density.

[20] G. C. Baldwin and H. W. Koch, Phys. Rev. **67**, 1 (1945).
[21] "Table of Atomic Masses," N. Metropolis and others (unpublished).
[22] C. P. Swann and C. E. Mandeville, Phys. Rev. **79**, 240 (1950).
[23] R. A. Peck, Jr., Phys. Rev. **76**, 1279 (1949).

statistical level densities in the residual nucleus. These protons comprise more than half of the total number.

(b) There is a high energy tail on the proton spectrum (10–14 Mev) with numbers of protons definitely in excess of the prediction from statistical level densities. Only these protons show a pronounced angular asymmetry with a maximum at 90° to the x-ray beam.

(c) The ratio of total numbers of protons to neutrons (average of $\sigma_{\gamma,p}/\sigma_{\gamma,n}$ over the spectrum) is of the order predicted from statistical level densities and reaction cross sections in the range appropriate to other nuclear reactions. The Schiff assumption[5] of an effective, nearly constant, level density for a photo-nuclear processes predicts about 6 times as many protons as observed and at higher average energy.

Remarkably similar energy and angular distributions of protons from Rh^{103} have been obtained by Curtis and others.[7] According to the atomic mass calculations of reference 21, the proton and neutron thresholds are about the same in Rh^{103} as in the silver isotopes.

The essential features of nuclear absorption suggested by the observations on silver are (1) a resonance excitation as shown in Fig. 7, followed by (2) an emission of a group of protons of high energy and angular asymmetry which fall outside the distribution predicted from the statistical nuclear model, and (3) an emission of a group of protons of lower energy which in energy distribution and in numbers relative to the number of emitted neutrons fit approximately predictions based on the statistical model (Fig. 8).

Whatever the exact nature of the nuclear absorption process, the high energy spherically asymmetric protons which fall outside of the expected distribution provide an experimental basis for a possible interpretation of the high (γ, p) yields at 17.6 Mev, of many middle weight nuclei. In every such case which Hirzel and Wäffler[1] examined, the proton threshold, B_p, was greater than the neutron threshold, B_n. Consequently, the ratio $\sigma_{\gamma,p}/\sigma_{\gamma,n}$ predicted on the statistical model was extremely small, but a high energy, asymmetric group may still be present, as in silver, and in sufficient numbers to account for the observed yield. For silver B_p is about 3 Mev less than B_n, with the consequence that a substantial emission of protons can occur even on the statistical model. Hence, both groups of protons are to be expected and both are observed.

Levinger and Bethe, and Courant (reference 4, p. 128) propose a picture which contains just the above features for the purpose of explaining the high yield of protons in medium weight nuclei. The picture proceeds naturally from their view that the main process of nuclear absorption is the excitation of a single proton in the nucleus. The proton occasionally escapes immediately without transferring its excitation energy to the rest of the nucleus. In this process protons of high energy would be favored and they might be expected to emerge preferentially at 90° to the x-ray beam. Usually, however, the proton does interact with other nucleons and then the subsequent emission of neutrons and protons is in accordance with the statistical model.

In the case of the (γ, p) reaction in Al^{27}, excited with continua of x-rays which do not extend to the peak of the resonance absorption, the principal results may be stated as follows:

(a) Protons are emitted with energies up to the maximum available (maximum x-ray energy minus proton threshold) and the shape of the proton spectrum is compatible with the assumption of a constant or slowly increasing level density in the residual nucleus.

(b) The (γ, p) cross section in the range of x-ray energies 16 to 20 Mev is as large or larger than the (γ, n) cross section at 17.6 Mev, in agreement with calculation on the basis of constant level density.

(c) Protons of all energies observed, with x-ray excitation up to 20.8 Mev, are emitted with spherical symmetry.

Since the calculated emission of protons is large without the special assumption that a few escape immediately upon excitation of the nucleus, nearly spherical symmetry of the protons is to be expected. For, even though a few escape immediately and preferentially at 90° to the beam, they would not stand out among the great number which can emerge, after distribution of the excitation energy, with energies up to the maximum and with spherical symmetry.

According to Toms, Halpern, and Stephens[6] the protons from a (γ, p) reaction on the Mg isotopes are also approximately spherically symmetric.