been shown to be zero[11]). We do not wish to go into a detailed discussion of the Ga^{66} decay here, but merely want to state that the previous beta[12] and gamma[13] work is consistent with no direct feeding of the 1.04-, 1.87-, and 2.40-Mev levels of Zn^{66} (see Fig. 3) making 2+ a likely assignment for these levels if the parity of Ga^{66} is even, as may be expected from the shell model. The 1.87-Mev level could be populated easily in the decay of Ga^{66} by transitions from the 3.78- and/or 3.24-Mev levels. In this connection it might be noted that it is quite possible that the spin of the 3.78-Mev level is 0.

A discussion of the level systematics of the other even-even Zn isotopes is postponed,[1] but it may be of interest to point out that a close similarity in energy seems to exist between at least the three lowest excited states of Zn^{64}, Zn^{66}, and Zn^{68}.[1,3,8,9]

IV. ACKNOWLEDGMENTS

We would like to thank Dr. Lloyd Chase for assisting with the source irradiations and Mr. B. Hoop for his help in taking and analyzing some of the data. The partial support of the Alfred P. Sloan Foundation to one of us (W. E. Meyerhof) is gratefully acknowledged.

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[11] Hubbs, Nierenberg, Shugart and Worcester, Phys. Rev. **105**, 1928 (1957); W. A. Nierenberg (private communication).

[12] L. M. Langer and R. D. Moffat, Phys. Rev. **80**, 651 (1950); A. Mukerji and P. Preiswerk, Helv. Phys. Acta **25**, 387 (1952).

[13] Mann, Meyerhof, and West, Phys. Rev. **92**, 1481 (1953).

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Photoproduction of Alpha Particles from Several Metallic Elements

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Photoproduction of alpha particles from copper has been investigated by using 22-Mev bremsstrahlung to irradiate a "sandwich" consisting of a thin copper foil (2.75 mg/cm²) placed between two Ilford E-1, 100-micron thick nuclear emulsions. The observed yield was $(3.9\pm0.6)\times10^4$ alpha particles per mole-roentgen. The energy distribution of the alpha particles has a maximum near 8 Mev. In addition, photoproduced alpha particles from thin foils of eleven elements, including copper, have been detected by means of their tracks in nuclear emulsions. "Sandwiches" containing two target foils on either side of a lead stopping foil were exposed to 21.5-Mev bremsstrahlung hardened by 147.4 g/cm² of graphite. The photo-alpha yields observed with the hardened spectrum are given in terms of unhardened bremsstrahlung, having been multiplied by the calculated ratio of effective photons in the two spectra. These yields, in units of 10^4 alphas per mole-roentgen, are: Al—1.3, V—0.4, Fe—1.9, Co—2.3, Ni—3.9, Cu—2.6, Cu^{63}—3.6, Zn—8.2, Nb—0.5, Rh—0.3, Ag—0.17, and In—0.09. For the seven elements having $Z\leq30$, there seems to be a correlation between the yield and the difference between the alpha and neutron binding energies.

I. INTRODUCTION

THE photodisintegration of nuclei in which alpha particles are produced has been studied primarily by means of the radioactivity of the resulting nucleus and by means of alpha-particle tracks in nuclear emulsions. Because of low yields, much of the work using radioactivity has required a chemical separation of the resulting element. Yield curves and cross sections have been obtained by this method for $Cu^{65}(\gamma,\alpha)Co^{61}$ by Haslam, Smith, and Taylor,[1] $Br^{81}(\gamma,\alpha)As^{77}$ by Taylor and Haslam,[2] $Rb^{87}(\gamma,\alpha)Br^{83}$ by Haslam and Skarsgard,[3] and $Ag^{109}(\gamma,\alpha)Rh^{105}$ by de Laboulaye and Beydon.[4] Erdos, Jordan, and Stoll[5] have recently reported values for the integrated cross section up to 31.5 Mev for the $Cl^{37}(\gamma,\alpha)P^{33}$, $K^{39}(\gamma,n\alpha)Cl^{34}$, $Br^{81}(\gamma,\alpha)As^{77}$, $Ag^{109}(\gamma,\alpha)Rh^{105}$, and $Sb^{121}(\gamma,\alpha)In^{117}$ reactions.

Many investigations of photoproduction of alpha particles from the constituents of nuclear emulsions have been undertaken. For the lighter elements the track of the recoiling nucleus, as well as the alpha track, can be observed. For alpha tracks not accompanied by a recoil track, it is not possible to determine whether the parent nucleus was silver or bromine. Since alpha tracks are clearly distinguishable from proton tracks in nuclear emulsions, photo-alpha particles have been observed as a by-product in several experiments designed to investigate photoprotons. Investigation of the photodisintegration of copper by Byerly and Stephens[6] gave an indication of the yield of photo-alpha particles. Numerous alpha particles were observed from cobalt by Toms and Stephens[7]; however, since the target thickness was chosen for protons, the

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[1] Haslam, Smith, and Taylor, Phys. Rev. **84**, 840 (1951).

[2] J. G. V. Taylor and R. N. H. Haslam, Phys. Rev. **87**, 1138 (1952).

[3] R. N. H. Haslam and H. M. Skarsgard, Phys. Rev. **81**, 479 (1951).

[4] H. de Laboulaye and J. Beydon, Compt. rend. **239**, 411 (1954).

[5] Erdos, Jordan, and Stoll, Helv. Phys. Acta **28**, 322 (1955); J. phys. radium **16**, 169 (1955).

[6] P. R. Byerly, Jr., and W. E. Stephens, Phys. Rev. **83**, 54 (1951).

[7] M. E. Toms and W. E. Stephens, Phys. Rev. **95**, 1209 (1954).

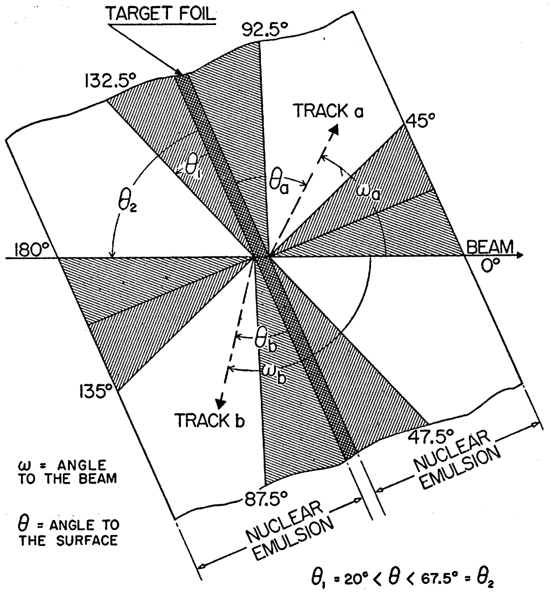

FIG. 1. Diagram showing, as clear regions, the acceptable angles to the surfaces of the emulsions for photo-alpha particles from a thin foil. The angle to the beam, ω, for acceptable tracks may have a value anywhere between 0° and 180°.

absorption for alphas was so great that the assigned energies and the total yield of alphas had large uncertainties.

The yields of alpha particles from photonuclear reactions with 23-Mev bremsstrahlung have been discussed by Greenberg, Taylor, and Haslam.[8] They compared values obtained by radioactivity and by the detection in nuclear emulsions of alpha particles from the emulsion constituents and from external targets. Their value of yield from the $Ag^{109}(\gamma,\alpha)Rh^{105}$ reaction using chemical separation was much lower than the value found by de Laboulaye and Beydon.[4]

The following experiment consisted of two parts. The first part was an investigation of the distribution in angle to the beam and in energy of photo-alpha particles from copper. This part was an attempt to test the adequancy of the evaporation theory in explaining the characteristics of the photo-alpha reaction for a medium-weight element. The second part was a survey of photo-alpha yields from eleven elements, including copper, in which the same conditions of exposure and detection permitted a direct comparison of the yield values.

II. EXPERIMENT

In order to detect photo-alpha particles having small energy uncertainties due to losses in a target, a "sandwich," consisting of a thin target foil placed between two emulsions, was exposed directly in the x-ray beam from the U. S. Naval Research Laboratory 22-Mev betatron. Since Millar and Cameron[9] were able to distinguish alpha tracks in 100-micron thick, Ilford E-1 nuclear emulsions in the presence of fogging produced by 240 roentgens, their grain-gradation developer formula was used for this experiment with the same type of emulsion. In addition, a temperature-change development method was used and the plates were soaked in 20% glycerine to cause the processed plates to have thicknesses approximately the same as during exposure. The use of glycerine permitted depth measurements to be made with greater precision and served to reduce the amount of fogging observed when viewed with a microscope. An objective having a small depth of focus was used to further increase the visibility of alpha tracks. It was found that alpha tracks were clearly discernible against the fogging produced by 710 roentgens of 22-Mev bremsstrahlung.

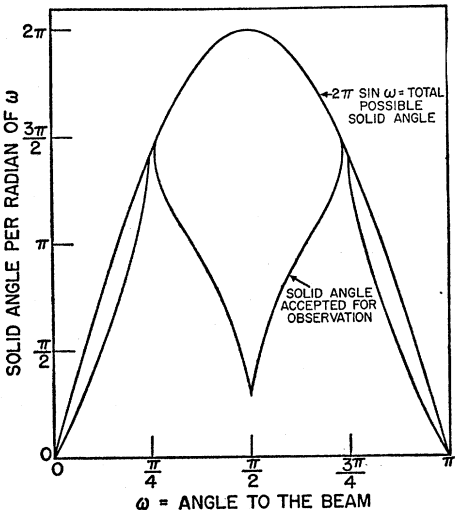

FIG. 2. Solid angle per radian as a function of ω, the angle between the alpha particle and the beam.

The exposure arrangement of the emulsions and the target, a 2.75-mg/cm² thick copper foil, is shown in Fig. 1. The "sandwich" was placed at an angle to the beam of 67.5°. With this arrangement, it was possible to observe an alpha track having an angle to the beam, ω, lying anywhere between 0° and 180°. Typical tracks, *a* and *b*, are shown on the diagram with the indication of their angles to the beam and to the surface of the emulsion in which each track lies. Tracks lying in the shaded cones were eliminated from observation by the criterion that θ, the angle the track makes with respect to the emulsion surface, must have a value between 20° and 67.5°. Since it is difficult to make accurate measurements on steep tracks, those having an angle $\theta > 67.5°$ were excluded. Shallow tracks, having $\theta < 20°$, were excluded because the increased effective target thickness led to a large uncertainty in energy. The

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[8] Greenberg, Taylor, and Haslam, Phys. Rev. **95**, 1540 (1954).

[9] C. H. Millar and A. G. W. Cameron, Can. J. Phys. **31**, 723 (1953).

elimination of the steep and shallow tracks from the data selectively changed the differential solid angle available at each angle. The solid angle accepted for observation is shown in Fig. 2 as a function of the angle to the beam, ω. The area under the $2\pi\sin\omega$ curve is the total possible solid angle.

A total of 220 acceptable alpha tracks were observed in areas covered by the target foil. From observations of tracks in areas not covered by the foil, it was estimated that 64 of the above tracks were background. The angle to the beam and the angle to the surface of the emulsion were obtained for each track. The observed number of tracks, grouped in 20° intervals of ω, was corrected by the ratio of the "$2\pi\sin\omega$" curve to the "solid angle accepted" curve. The alpha-particle energies, obtained from their ranges in the emulsion, were grouped in half-Mev intervals to correct for the energy loss due to traversing half the target thickness. For this purpose, the tracks were grouped in the following intervals: $20°\leq\theta<30°$, $30°\leq\theta<40°$, $40°\leq\theta<50°$, $50°\leq\theta<60°$, and $60°\leq\theta<67.5°$. The angular distribution of alpha particles of energy greater than 6 Mev is shown in Fig. 3. Although there appears to be a tendency toward peaking at 90°, this is not considered significant because of the limited number of tracks and the resulting statistical uncertainties. The observed distribution in energy of the alpha particles after subtracting background is shown as the histogram of Fig. 4. The area of the histogram equals the observed yield of $(3.9\pm0.6)\times10^4$ alpha particles per mole-roentgen.

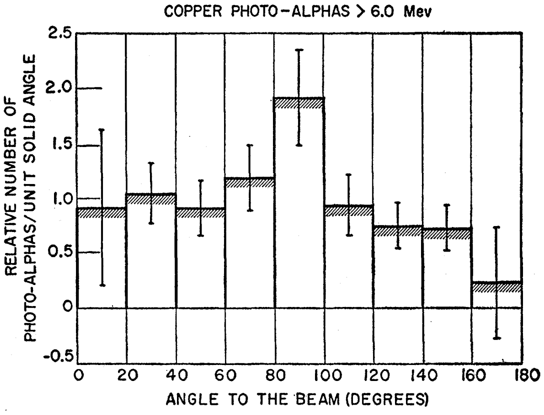

FIG. 3. The angular distribution of photo-alphas from copper having energies > 6.0 Mev.

The number of background tracks found in the investigation of the photoproduction of alpha particles from copper described above was quite tolerable for that exposure. However, for elements having lower photo-alpha yields, such a background would prevent significant results from being obtained. The background may be thought to consist of three types: (1) very short alpha tracks for which it is not possible to determine whether the alpha particle went into or came out of the emulsion; (2) fairly long tracks whose grain density near the surface of the emulsion was low, similar to the track of an alpha particle entering the emulsion, and which ended with a dense portion caused by a recoiling light nucleus rather than by a slowed-down alpha particle; (3) tracks of alpha particles which entered the emulsion but which originated in the other emulsion and traversed the thin target foil. The first two types cannot be eliminated but can be estimated by observations of similar tracks which lie wholly within the emulsion. The third type of background can be eliminated by using a lead stopping foil as shown in Fig. 5. The lead foil, 2.75 mil (78.2 mg/cm^2) thick, would stop a 17-Mev alpha particle. A target foil was placed on either side of the lead. To prevent certain elements (Al, Co, Zn, and In) from reacting chemically with the emulsions, thin Mylar films (0.8 mg/cm^2) were used to keep these target foils from touching the emulsions. Background exposures were made with the lead stopping foil both with and without Mylar.

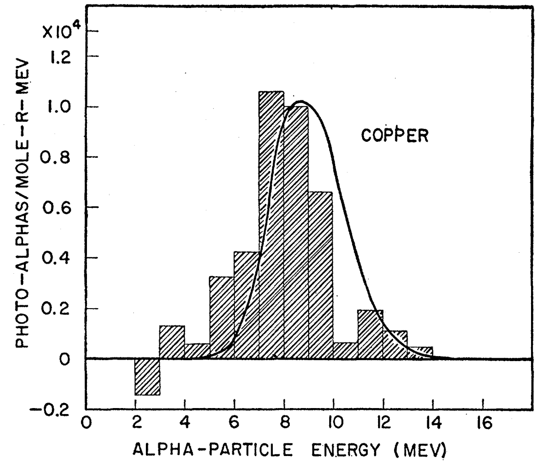

FIG. 4. The distribution in energy of photo-alphas from copper. The histogram shows the observed data and the curve shows the calculated distribution for evaporation from a compound nucleus.

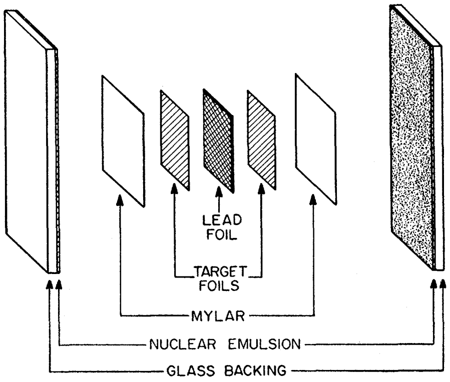

FIG. 5. The expanded "sandwich" arrangement used for the photo-alpha exposures with the hardened x-ray beam.

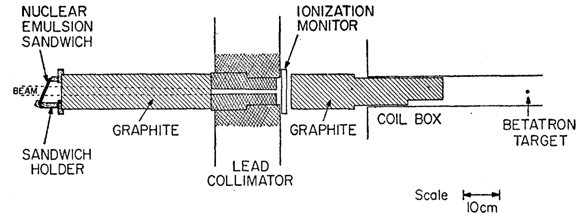

FIG. 6. The experimental arrangement for the photo-alpha exposures using a 21.5-Mev-bremsstrahlung beam hardened by 86.2 cm (147.4 g/cm^2) of graphite.

In order to increase the number of alpha-particle tracks for a given amount of emulsion fogging, the x-ray beam was hardened by 147.4 g/cm^2 of graphite. Since low-energy photons are absorbed more strongly by graphite than the photons effective in producing photonuclear reactions, a better ratio of effective photons to total photons in the x-ray beam was expected. The experimental arrangement, Fig. 6, shows the graphite in position, about half of it before the ion-chamber monitor and the other half after the collimator. The beam was limited by the lead collimator to a clearly defined circle (2.1 cm in diameter) at the emulsion position. The aluminum holder, which located the emulsion "sandwich" at an angle of 67.5° to the beam, fitted onto the last piece of graphite. To determine the intensity of the betatron x-ray beam during the exposures, data were taken under various conditions using activity produced in a copper cylinder as a secondary standard and relating the intensity to measurements of the unhardened beam by a Victoreen ion chamber in an 11-cm square Lucite block.

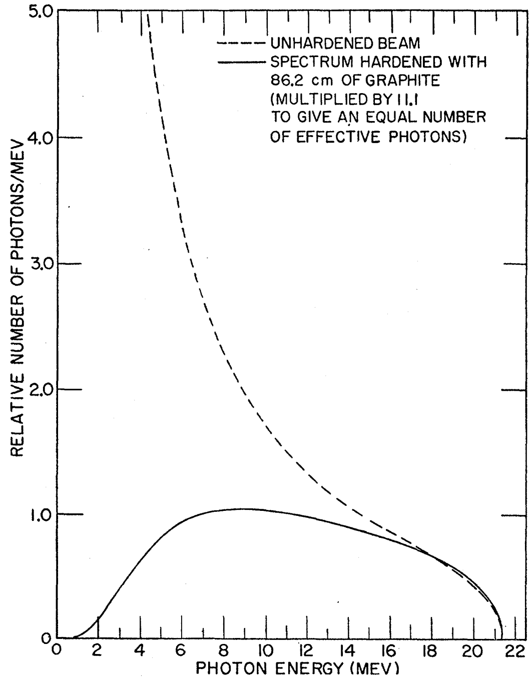

FIG. 7. The effect of beam hardening. The dashed curve is the theoretical unhardened bremsstrahlung and the solid curve is the hardened spectrum normalized to an equal number of effective photons.

The dashed curve in Fig. 7 shows the theoretical unhardened spectrum of 21.5-Mev bremsstrahlung.[10] The solid curve shows the spectrum hardened by 147.4 g/cm^2 of graphite. This spectrum was calculated using the absorption coefficients tabulated by White.[11] Corrections were made for single Compton scattering and amounted to less than 3.2% at any photon energy. The hardened spectrum is shown multiplied by the factor 11.1 in order to display spectra which should give the same photo-alpha yield. The factor, $F=11.1$, is a measure of the relative effectiveness of the two spectra in producing photo-alphas and was determined as follows:

$$F=\int_0^{21.5}\sigma_{\gamma,\alpha}(k)N(k)dk\Big/\int_0^{21.5}\sigma_{\gamma,\alpha}(k)N'(k)dk,$$

where $\sigma_{\gamma,\alpha}(k)$ is a typical alpha-particle photoproduction cross section, $N(k)$ is the number of photons per Mev interval with energy k in the unhardened beam, and $N'(k)$ is the number of photons per Mev interval in the hardened beam. The shape of the cross section for photo-alphas from Ag^{109} as given by de Laboulaye and Beydon[4] is very similar to that for photo alphas from Cu^{65} given by Haslam *et al.*[1]; hence, the $\sigma_{\gamma,\alpha}$ for Cu^{65} was used as being typical for all the elements investigated in this experiment.

TABLE I. Exposure conditions for and results of the survey of photo-alpha particles using the hardened 21.5-Mev bremsstrahlung.

Target	Thickness (mg/cm^2)	R at target foil position (unhardened beam)	Equivalent exposure (hardened beam)	Net tracks	Yield (10^4 α/mole-r)
Al[a]	2.71	14 880	1340	100	1.25 ±0.16
V	3.60	13 130	1183	21	0.42 ±0.15
Fe	3.55	14 880	1340	97	1.90 ±0.23
Co[a]	2.40	13 130	1183	67	2.29 ±0.37
Ni	3.09	14 980	1349	168	3.94 ±0.34
Cu	2.75	14 880	1340	90	2.59 ±0.33
Cu^{63}	4.35	13 130	1183	175	3.58 ±0.30
Zn[a]	2.42	13 390	1206	220	8.22 ±0.61
Nb	3.99	13 130	1183	14	0.46 ±0.24
Rh	5.59	14 890	1341	24	0.27 ±0.13
Ag	11.03	14 880	1340	28	0.17 ±0.07
In[a]	19.35	14 880	1340	26	0.09 ±0.05

[a] Exposure made with Mylar in "sandwich."

In Table I, the target materials are listed together with their thicknesses in mg/cm^2. For all except silver and indium, the thickness was chosen such that the energy loss of an 8-Mev alpha in traversing half the target thickness would be in the neighborhood of one-half Mev. Since silver and indium have very low yields of photoproduced alpha particles, thicker targets were

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[10] L. I. Schiff, Phys. Rev. 83, 252 (1951).

[11] C. M. Davisson, in *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (Interscience Publishers, Inc., New York, 1955), Appendix I.

needed to give numbers of tracks significantly higher than background. The third column of the table indicates the exposure in terms of betatron output, that is, the amount of x-rays of 21.5-Mev bremsstrahlung that would have reached the target foil position if the graphite had not been in place. The fourth column lists the values of the third column divided by the factor $F=11.1$. Hence, these values show the equivalence of the hardened beam exposure in terms of an equally effective unhardened beam exposure.

Since the purpose of this portion of the investigation was to survey the yield of photo-alpha particles from a number of elements under nearly identical conditions, the angle criterion of acceptability was not used. Tracks of all alpha particles which entered the emulsion were considered acceptable both for the background exposures and for the exposures with target foils. The background was found to have been considerably reduced by the use of the lead stopping foil. The fifth column of Table I gives the net number of tracks observed for each exposure, the appropriate background having been subtracted. The yield values with their statistical uncertainties, given in the sixth column, are in units of 10^4 alpha particles per mole-roentgen. Since the equivalent intensities of unhardened bremsstrahlung were used, these yield values can be compared with yield values obtained with unhardened beams. No corrections were made for absorption of alpha particles in the targets.

III. DISCUSSION

The investigation of the photoproduction of alpha particles from copper irradiated with 22-Mev bremsstrahlung has served to prove the feasibility of a "sandwich"-type exposure for obtaining angular and energy distributions and the absolute yield of photo-alpha particles. The curve shown in Fig. 4 is the energy distribution calculated on the basis of "evaporation" from a compound nucleus. The area of the curve is normalized to the area of the histogram, the total yield.

A curve similar to the one shown was calculated using the cross section values for alpha capture given by Blatt and Weisskopf[12] for an interaction radius $R=(1.5A^{\frac{1}{3}}+1.2)\times 10^{-13}$ cm. The curve calculated for this value of R peaked about a half Mev higher than the one shown. The value of yield predicted by the theory of evaporation from a compound nucleus, using these values of the cross section, was 0.89×10^4 alpha particles per mole-roentgen compared with the observed value of $(3.9\pm 0.6)\times 10^4$ alpha particles/mole-r. Not only was an improved fit to the data desired, but also a closer agreement of the predicted yield to the observed yield.

Calculations of the energy distribution and yield of photo-particles using the theory of evaporation from a compound nucleus are based on the principle of detailed balance. This principle assumes that the cross section for the formation of a compound nucleus by the capture of a particle may be used to describe the decay of that compound nucleus by the ejection of the same particle. The energy distribution of photoproduced particles b, of energy ϵ_b, emerging from a compound nucleus is given by Diven and Almy[13] as

$$F(\epsilon_b)=\epsilon_b\sigma_b(\epsilon)\int_0^{E_{\max}}\sigma_\gamma(E)\frac{N(E,E_{\max})\omega_R(E-B_b-\epsilon_b)}{\sum_{b'}\Gamma_{b'}}dE,$$

where $\sigma_b(\epsilon)$ is the cross section for formation of a compound nucleus by the capture of particle b, $\sigma_\gamma(E)$ is the cross section for capture of photons of energy E, $N(E,E_{\max})$ is the number of photons per cm^2 per Mev energy interval per roentgen in the x-ray beam, $E_{\max}$ is the maximum photon energy, $\omega_R(E-B_b-\epsilon_b)$ is the level density of the residual nucleus at an excitation energy determined by the ejection of a particle b bound by energy B_b with a kinetic energy ϵ_b from a compound nucleus of excitation E, and $\sum_{b'}\Gamma_{b'}$ is the summation of the probabilities of all modes of decay of the compound nucleus. The predicted yield of photoparticles b per nucleus-roentgen is the summation of the $F(\epsilon_b)$ values over the energy intervals involved.

Weisskopf and Ewing[14] have expressed the level density in the form, $\omega_R(\mathcal{E})=C\exp[(a\mathcal{E})^{\frac{1}{2}}]$, where $\mathcal{E}$ is the excitation energy of the residual nucleus $(\mathcal{E}=E-B_b-\epsilon_b)$ and C and a are constants. Diven and Almy[13] used Weisskopf's value for a for medium and heavy elements, $a=1.6(A-40)^{\frac{1}{2}}$. This formula for a was used by Byerly and Stephens[6] to calculate the energy distribution of photoneutrons from copper. Since their calculated distribution was a good fit to their data, we have considered that this value of a would be suitable for photoproduction of alpha particles from copper. The calculation of the $F(\epsilon_b)$ values, following the method of Diven and Almy[13] in which the ratio $\sigma_\gamma(E)/\sum_{b'}\Gamma_{b'}$ is replaced by $\sigma_{\gamma,n}/\Gamma_n$, involves the level density for the residual nucleus for photoneutrons in the calculation of Γ_n. Hence, only the ratio of $C_{\gamma,b}$ to $C_{\gamma,n}$ is involved in this calculation. We have assumed this ratio to be unity.

Blatt and Weisskopf[12] give an expression for the cross section for capture of a particle to form a compound nucleus,

$$\sigma_c(\epsilon)=\pi\lambda\!\!\!^-{}^2\sum_{l=0}^{\infty}(2l+1)T_l(\epsilon).$$

Here $\lambda\!\!\!^-$ is the rationalized de Broglie wavelength, l is the orbital angular momentum of the incident particle in units of $\hbar$, and T_l is the "transmission coefficient" or penetrability of the incident particle. The penetrabilities

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[12] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952), Chap. 8.

[13] B. C. Diven and G. M. Almy, Phys. Rev. **80**, 407 (1950).

[14] V. F. Weisskopf and D. H. Ewing, Phys. Rev. **57**, 472 (1940).

have been tabulated by Feshbach, Shapiro, and Weisskopf[15] for $\epsilon/B=0.2$ to 1.8, where B is the barrier energy.

The value of the cross section, $\sigma_b(\epsilon)$, is dependent upon the interaction radius, R. Since measured values of the interaction radius depend upon the bombarding particle, we have used the interaction radius determined from elastic scattering of alpha particles. Kerlee, Blair, and Farwell[16] obtained a good fit to the scattering data by using the value, $R=(1.414A^{\frac{1}{3}}+2.19)\times10^{-13}$ cm. The T_l values for this value of R, using the A of the residual nucleus, were found for $l=0$ through $l=6$ by interpolation from the tabulated values. The l values from zero through six are involved in alpha transitions to the three lowest states of Co^{59} and Co^{61} from the compound nuclei of Cu^{63} and Cu^{65} excited by $E1$, $M1$, and $E2$ multipole radiation. The curve shown in Fig. 4 was computed using the $\sigma_b(\epsilon)$ values obtained as above and was normalized to the area of the histogram. The calculated yield value is 1.41×10^4 alpha particles per mole-roentgen. A distribution calculated for a larger interaction radius, $R=(1.5A^{\frac{1}{3}}+2.5)\times10^{-13}$ cm, produced a curve similar in shape, but the total calculated yield was less.

If the ratio of the magnitudes of the level densities $C_{\gamma,\alpha}/C_{\gamma,n}$ for copper should be around two, the agreement of theory with observations would be quite good and would lead one to conclude that the photo-alpha disintegration of copper can be explained as evaporation from a compound nucleus. However, there is some question as to whether alpha-particle disintegration is truly an inverse reaction to alpha-particle capture, since inside the nucleus the nucleons are considered not to exist in alpha-particle subgroups for any appreciable time.

The yield of $(3.9\pm0.6)\times10^4$ alphas/mole-roentgen for natural copper at 22 Mev seems to be somewhat high compared with the value of 4.0×10^4 alphas/mole-roentgen at 24 Mev found by Byerly and Stephens,[6] if one considers the rather sharp increase in yield with bremsstrahlung energy. The yield at 22 Mev also seems high compared with $(2.6\pm0.3)\times10^4$ alphas/mole-roentgen obtained from the measurement at 21.5 Mev with the hardened spectrum. With 24-Mev bremsstrahlung, Haslam *et al.*[1] observed a yield of 2.4×10^4 alphas per mole-roentgen from Cu^{65} by detecting the radioactivity of the residual nucleus, Co^{61}. It was suggested that the higher yield observed by direct detection of the alpha particles might be due to a contribution from the $(\gamma,n\alpha)$ process. This reaction would not be detected in the experiment using radioactivity. To test this explanation, targets both of natural copper and of copper enriched to contain 99.5% of the Cu^{63} isotope were bombarded with 21.5-Mev bremsstrahlung hardened with graphite. At this energy, elements having an atomic number of 30 or less are expected to have no appreciable multiple photoreactions. For copper, the $(\gamma,n\alpha)$ Q-values are about 16 Mev; and, since very few alpha particles of energy less than 5 Mev were observed with the exposure using the unhardened 22-Mev bremsstrahlung, it can be concluded that at this energy the $(\gamma,n\alpha)$ reaction contributes a negligible amount to the yield. The average at 21.5 Mev of our yield for Cu^{63}, $(3.6\pm0.3)\times10^4$ alphas per mole-roentgen, and of the yield for Cu^{65}, 1.5×10^4 alphas per mole-roentgen, determined by Haslam *et al.*,[1] weighted by isotopic abundances, agrees with our yield for natural copper, $(2.6\pm0.3)\times10^4$ alphas per mole-roentgen. Since the ratios of the yield for natural copper to that for Cu^{65} at 21.5 Mev and 24 Mev are nearly equal, the assumption of a contribution from the $(\gamma,n\alpha)$ process to the yield at 24 Mev is not needed.

The yields of photo-alpha particles, listed in Table I, are shown plotted against atomic number in Fig. 8. The values follow a general trend of increasing with atomic number up to 30 but there are considerable variations superimposed. On the basis of photo-alpha yields at 23 Mev tabulated by Greenberg *et al.*,[8] the high yields from aluminum and zinc were unexpected, as was the low yield from vanadium. One would expect the yields to increase with an increase in the number of nucleons and with a decrease in alpha-particle binding energy up to a point where the Coulomb barrier becomes the dominant influence on the yield. For elements having an atomic number greater than forty, the inhibiting effect of the higher Coulomb barrier is much stronger than the enhancing effect of the lower alpha-particle binding energy. The photo-alpha yield from natural silver, $(0.17\pm0.07)\times10^4$ alphas per mole-roentgen, is in agreement with the yield at the same energy from Ag^{109}, 0.15×10^4 alphas per mole-roentgen, obtained by de Laboulaye and Beydon.[4] Since the values of the neutron and alpha-particle binding energies for Ag^{107} and Ag^{109} are quite close, one would expect the two isotopes to contribute nearly equally to the yield.

In an attempt to account for the variations in yield for the lighter elements, the yields of photo-alpha

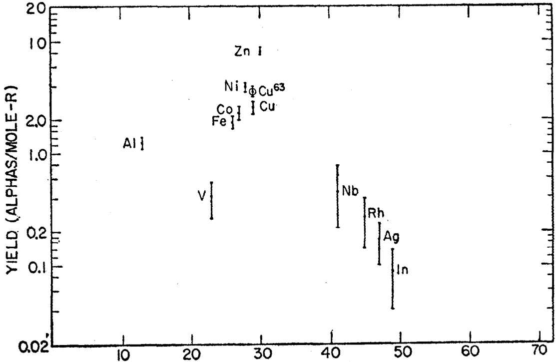

FIG. 8. Photo-alpha yields plotted against atomic numbers for the exposures of the survey.

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[15] Feshbach, Shapiro, and Weisskopf, Atomic Energy Commission Report NYO-3077 (NDA-15B-5), June 15, 1953 (unpublished).

[16] Kerlee, Blair, and Farwell, Phys. Rev. **107**, 1343 (1957).

particles were plotted against the difference between the binding energies for neutrons and alpha particles. This plot is shown in Fig. 9. The binding-energy values were obtained from the mass values given by Wapstra.[17] The four values which lie below the curve are for the heavier elements for which the Coulomb barrier has become the dominant factor in determining the yields. Whenever an element had more than one stable isotope, binding-energy values were weighted in accordance with the abundances. The apparent correlation of yield with differences in binding energies for the medium-weight elements might, at first, lead one to suspect that at energies below the neutron binding energy the alpha-particle yield would be enhanced. However, the Coulomb barrier for alpha particles would tend to prevent this enhancement. This effect of the barrier is shown by the fact that the value of the photo-alpha cross section for Cu^{65} determined by Haslam *et al.*[1] is not appreciable below 14 Mev. Also, the energy distribution of photo-alphas from copper, Fig. 4, shows no enhancement of low-energy alpha particles; instead, the maximum is around 8 Mev. It appears, therefore, that competition between the emission of alpha particles and neutrons, which takes place at energies above the neutron binding energy, is in some way dependent upon the difference in their binding energies.

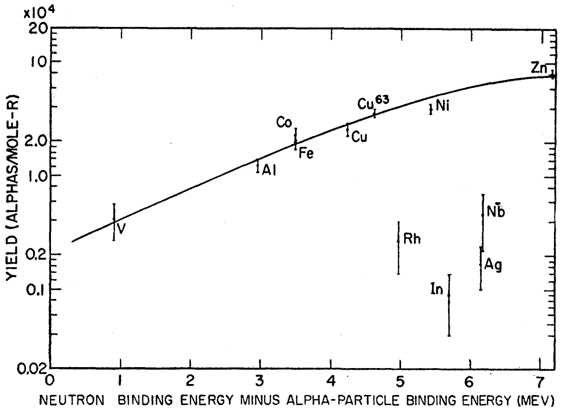

FIG. 9. Photo-alpha yields plotted against the difference in binding energies of neutrons and alpha particles.

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[17] A. H. Wapstra, Physica 21, 367 and 385 (1955).

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High-Energy Alpha Particles from B^{12}†

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An earlier investigation of the alpha-particle spectrum associated with the beta decay of B^{12} has been extended to an alpha-particle energy of approximately 3 Mev. The high-energy spectrum appears to indicate a broad level in C^{12} having an excitation energy of 10.1 ± 0.2 Mev and a width at half-maximum of $\Gamma\approx2.5$ Mev. The most probable spin and parity assignment for this level is $J=0^+$, although $J=2^+$ cannot be definitely excluded; for $J=0^+$ the width is approximately the Wigner limit. It is found that $(0.13\pm0.04)\%$ of all decays of B^{12} lead to this state.

INTRODUCTION

BORON-12 has a half-life of 20.6 milliseconds and a decay energy of 13.38 Mev. The decay proceeds mainly to the ground state ($J=0^+$) of C^{12}, with a 1.5% branch to the $J=2^+$, 4.43-Mev excited state, which subsequently decays by emission of gamma radiation. In addition, as was reported in a previous paper,[1] a 1.3% branch leads to a $J=0^+$ state at 7.653 Mev which is unstable with respect to Be^8+He^4 by 278 kev. The decay of this level and the subsequent breakup of Be^8 result in a distribution of alpha particles extending from zero energy to a well-defined upper limit at about 200 kev. It was also observed in the earlier work that a smaller number of alpha particles were emitted with considerably higher energy than could be accounted for by this level, and the present investigation was undertaken to determine the source of these higher-energy particles.

EXPERIMENTAL ARRANGEMENT

As in the previous work,[1] the B^{12} was produced in the reaction $B^{11}(d,p)B^{12}$ and the delayed alpha particles were detected in a magnetic spectrometer. The target was bombarded at the focal point of the spectrometer and was provided with a rotating shutter to permit alternate exposure to the deuteron beam and to the spectrometer. In each cycle of 1/60 sec, the target was bombarded for 6.1 milliseconds, and, 2.9 milliseconds later, exposed to the spectrometer for 6.1 milliseconds. Most of the observations were made with a natural boron target evaporated on a thick Be backing. The

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[1] Cook, Fowler, Lauritsen, and Lauritsen, Phys. Rev. 107, 508 (1957).