the wall of the target chamber, at $y=-l$, through angles $\varphi_x$, $\varphi_z$. It arrives at the scattering volume $dx\,dy\,dz$ with projected deflections $\theta_x$, $\theta_z$. The scattered particle leaves the scattering volume in a direction deviating from the nominal one by $\theta_\xi$, $\theta_\zeta$, is scattered in the gas so as to arrive at the exit window of the scattering chamber at coordinates $\xi_1\approx 0$, $\eta_1=m$ (chosen $\neq l$ for the sake of generality), and $\zeta_1$, with angles $\varphi_\xi$ and $\varphi_\zeta$. Multiple scattering in the foil finally deflects the particle into the detector $[\psi_\xi\approx 0,\ \psi_\zeta=\zeta_1/(R-m)]$, i.e., through the second slit onto a swath of height $h$ on the plate. After integrating over the (infinitesimal) slit widths and the swath height, one obtains the following expression for the intensity registered in the swath:

$$\begin{aligned}Y(\theta)=\frac{Nn4w^2h}{H(R-m)}\int & p(\varphi_x)p_{l+y}[x-(l+y)\varphi_x,\theta_x-\varphi_x]p(\varphi_z)\\ &\times P_{l+y}[z-(l+y)\varphi_z,\theta_z-\varphi_z]d\varphi_x d\varphi_z d\theta_x d\theta_z dx dy dz\\ &\times\sigma(\theta+\delta)d\theta_\xi d\theta_\zeta P_{m-\eta}[-\xi-(m-\eta)\theta_\xi,\ \varphi_\xi-\theta_\xi]\\ &\times P_{m-\eta}[\zeta_1-z-(m-\eta)\theta_\zeta,\ \varphi_\zeta-\theta_\zeta]p(\psi_\zeta+\varphi_\zeta)\\ &\times p(-\varphi_\xi)\cos^2\psi_\zeta d\varphi_\xi d\varphi_\zeta d\zeta_1.\end{aligned}\tag{8}$$

The probability functions for multiple scattering in the foils, $p$, and in the gas, $P$, are taken from Rossi,[25] with slight changes in notation. The variation of the mean square scattering angle per unit path length, due to the energy loss in the gas, is neglected. The integration is tedious, but straightforward. The cross section $\sigma(\theta+\delta)$ is expanded in the vicinity of $\theta$; wherever necessary, terms are expanded to second power of the deviation from the nominal scattering event. With $\Theta_w$ and $\Phi_w$ the rms angles in the entrance and exit window, $\Theta_g$, $\Phi_g$ the rms angles in the gas over the distances $l$ and $m$, and $\Theta_t$ the total rms angle, one obtains the final expression

$$I=\frac{Nn4w^2h}{HR\sin\theta}(1+\Delta_m),$$

with

$$\begin{aligned}\Delta_m=\cot^2\theta\left[\tfrac{1}{2}\Theta_t^2-\frac{m}{R}(\tfrac{1}{2}\Phi_g^2+\Phi_w^2)+\frac{l^2}{2R^2}(\tfrac{1}{3}\Theta_g^2+\Theta_w^2)\right]\\ +\frac{\cot\theta}{\sin\theta}\frac{l}{R}(\tfrac{1}{2}\Theta_g^2+\Theta_w^2)+(\cot^2\theta-1)\frac{m^2}{2R^2}(\tfrac{1}{3}\Phi_g^2+\Phi_w^2)\\ -\frac{1}{\sigma}\frac{\partial\sigma}{\partial\theta}\frac{\cot\theta}{4}\left[\Theta_t^2-\frac{l^2}{R}(\tfrac{1}{3}\Theta_g^2+\Theta_w^2)\right.\\ \left.-\frac{m^2}{R^2}(\tfrac{1}{3}\Phi_g^2+\Phi_w^2)\right]+\frac{1}{\sigma}\frac{\partial^2\sigma}{\partial\theta^2}\frac{\Theta_t^2}{4}.\end{aligned}\tag{9}$$

One may remark that no cross terms between the multiple-scattering and the geometry corrections are to be expected, if only terms up to the second power in the rms scattering angles (e.g., $\Theta_t$) or geometric angles (e.g., $w/H$) are retained. Cross terms would have to be of the form $\Theta_t\times w/H$. Since the multiple-scattering correction for any good geometry chosen contains only quadratic terms in $\Theta_t$, the subsequent integration for the finite geometry will not yield cross terms.

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[25] B. Rossi, *High-Energy Particles* (Prentice-Hall, Inc., New York, 1952), p. 71.

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# Reactions of Cu$^{63}$ and Cu$^{65}$ with Alpha Particles*

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Excitation functions have been measured for the $(\alpha,n)$, $(\alpha,2n)$, and $(\alpha,\alpha n)$ reactions on Cu$^{63}$ and Cu$^{65}$, as well as for the Cu$^{63}(\alpha,pn)$, Cu$^{65}(\alpha,2p)$, and Cu$^{65}(\alpha,2\alpha)$ reactions, for incident alpha particles of 15–41 Mev. The excitation functions for the $(\alpha,n)$, $(\alpha,2n)$, and $(\alpha,pn)$ reactions go through much sharper maxima than the excitation functions for the $(\alpha,\alpha n)$ reactions. Cross sections for the $(\alpha,2p)$ and $(\alpha,2\alpha)$ reactions increase monotomically with bombarding energy and attain values of 2.7 and 2.1 mb at 40 Mev, respectively. The value of $\sigma(\alpha,pn)/\sigma(\alpha,2n)$ for Cu$^{63}$ in the region of maximum yield is 3.3. The maximum cross sections measured for the $(\alpha,\alpha n)$ reactions are 205 mb and 143 mb for Cu$^{63}$ and Cu$^{65}$, respectively. The effects on the observed cross sections of neutron and proton binding energy differences, and of level density differences in the residual nuclei have been considered. The effect of these factors is in accord with the predictions of the statistical theory for the $(\alpha,n)$ and $(\alpha,2n)$ reactions but not for the $(\alpha,\alpha n)$ reaction.

A method for monitoring the energy of the incident beam based on the variation with energy of the ratio of cross sections for several of the above reactions is described.

## I. INTRODUCTION

THE statistical theory of nuclear reactions indicates that the shape of the excitation functions as well as the magnitude of the cross sections for reactions induced by particles with incident energies less than 50 or 60 Mev should be determined by a large number of factors. These include the excitation energy of the compound nucleus, the binding energies of all particles that may be emitted at a given excitation energy, the

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even-even, odd-odd, or odd-mass nature of the residual nucleus, the value of the level density parameter for the residual nucleus, the Coulomb barrier for incident and emitted charged particles, and the occurrence of closed nuclear shells at the proton or neutron number corresponding to a given residual nucleus. In order to test the applicability of the statistical theory to reactions in this energy range, it is clearly desirable to investigate situations where it is possible, to a certain extent, to observe the individual effect of these parameters.

The present work, dealing with the reactions of $Cu^{63}$ and $Cu^{65}$ with alpha particles, was undertaken with this purpose in mind. A comparison of the $(\alpha,n)$ and $(\alpha,2n)$ reactions on $Cu^{63}$ and $Cu^{65}$ thus bears primarily on the effect of binding energies on the relative yields for these two target nuclides. The effect of the other parameters should be about the same in both cases since $Cu^{63}$ and $Cu^{65}$ are odd-mass nuclides, having the same nuclear charge and nearly the same mass number. The reactions of $Zn^{64}$ with alpha particles have recently been extensively studied by one of the authors.[1] A comparison of these reactions with those of the copper isotopes is of interest since the effects ascribable to the nuclear charge and mass number of the target nucleus should be very similar in both cases. In contrast to $Cu^{63}$ and $Cu^{65}$ however, $Zn^{64}$ is an even-even nuclide. The large yield of an odd-odd nuclide relative to that of the adjacent isobaric even-even nuclide is thus observed in this instance in the case of the $(\alpha,pn)$ and $(\alpha,2n)$ reactions. In the case of the copper isotopes, on the other hand, this effect is observed in the case of the $(\alpha,n)$ and $(\alpha,p)$ reactions. A comparison of the $(\alpha,n)$ and $(\alpha,2n)$ reactions for $Cu^{63}$ and $Cu^{65}$ with the corresponding reactions for $Zn^{64}$, should thus be of value in assessing the effect of even-odd differences.

Reactions involving alpha-particle emission have recently been found to be very probable in alpha-induced reactions.[1–3] The present work includes the study of the $(\alpha,\alpha n)$ reactions on $Cu^{63}$ and $Cu^{65}$, and the effect of a number of parameters on the cross sections for these reactions is considered. In the course of this study excitation functions were also determined for the relatively rare $(\alpha,2p)$ and $(\alpha,2\alpha)$ reactions on $Cu^{65}$.

Several reactions of copper with alpha particles have previously been investigated by Porges.[4] The latter work is unsuitable for some of the comparisons with the reactions of zinc-64 since in several instances the cross sections for the formation of individual products were not determined. Furthermore, the authors have been advised that there is an error of a factor of two in the reported cross sections.[5] It was therefore felt desirable to remeasure most of the excitation functions previously determined by Porges as part of this study.

In the course of this work a technique was developed for the monitoring of the energy of the incident beam. This technique is based on the variation of the ratio of cross sections of several alpha-induced reactions with the energy of the incident beam. The procedure is described in detail in Sec. II-B.

## II. EXPERIMENTAL

### A. General

The irradiations were performed with the deflected alpha-particle beam of the Brookhaven 60-inch cyclotron. A detailed description of the target assembly and the Faraday cup used to monitor the beam intensity is given elsewhere.[6] The beam intensity varied between 0.1 and 1.5 microamperes. Irradiation times varied between 15 seconds and 1 hour. The initial energy of the incident alpha-particles was 41 Mev. In order to perform experiments at bombarding energies below 41 Mev, the beam was degraded in energy by use of aluminum absorbers. The curves of Aron *et al.*[7] were used to determine the energy of the degraded beam. The stacked-foil technique was used to irradiate between one and twelve target foils in any one experiment, depending on the reaction under investigation. The target foils were generally thick enough to make the loss of recoils negligible. In the course of this work a total of 32 irradiations was performed.

The targets consisted of high-purity copper foils 0.00025 inch thick. Since the energy loss in such a foil becomes greater than 1 Mev for energies below 25 Mev, these foils were not used for lower bombarding energies. Thin copper foils ($\sim 2$ mg/cm$^2$) were prepared by vacuum evaporation onto aluminum and subsequent peeling of the copper foil off the backing. These foils were used to study reactions for incident energies below 25 Mev. Any given foil was usually placed between two other copper foils in order to compensate for the loss of recoils from the foil. The $(\alpha,\alpha n)$ and $(\alpha,2\alpha)$ reactions on $Cu^{65}$ were investigated by the use of enriched $Cu^{65}$ since the products of these reactions are also formed by the $(\alpha,2pn)$ and $(\alpha,\alpha 2p)$ reactions on $Cu^{63}$. In these cases the targets consisted of copper, enriched to 99.4% in $Cu^{65}$,[8] electroplated on 0.0005-inch gold foils.

After irradiation the target foils were dissolved in acid in the presence of carrier, and separation of the desired elements was carried out. Gallium was separated by extraction from 7*N* HCl solution into isopropyl ether. Copper was separated by precipitation of CuCNS from 0.5*N* HCl solution following the extraction of

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[1] N. T. Porile, Phys. Rev. **115**, 939 (1959).

[2] Blann, Thomas, and Seaborg, Abstract of the American Chemical Society, San Francisco meeting, 1958.

[3] F. Houck and J. M. Miller (private communication).

[4] K. G. Porges, Phys. Rev. **101**, 225 (1956).

[5] K. G. Porges (private communication).

[6] S. Amiel and N. T. Porile, Revs. Sci. Instr. **29**, 1112 (1958).

[7] Aron, Hoffman, and Williams, Atomic Energy Commission Report AECU-663, 1949 (unpublished).

[8] Obtained from the Atomic Energy Research Establishment, Harwell, England.

gallium. Cobalt was separated by precipitation of CoS following the above decontamination steps for Ga and Cu; separation from Zn and Ni was effected through anion exchange by elution of Co with 3*N* HCl solution, following a washing with 7*N* HCl.[9] Zinc was not separated chemically and the radiations of 245-day $Zn^{65}$ were measured following the decay of all other activities. The chemical yield was determined by spectrophotometric or polarographic determination.

The disintegration rates of the samples were determined with NaI scintillation counters, which were usually connected to a 100-channel pulse-height analyzer so that the decay of a particular photopeak could be followed. Most of the nuclides of interest were positron emitters and in these cases the activity measurements were calibrated by comparison of the annihilation radiation counting rate with that of a standard $Na^{22}$ source. The latter was counted in the same geometry as the sample in question and in both cases the positrons were allowed to annihilate in aluminum absorbers placed on either side of the source. The relative counting rates of the two sources were found to be independent of geometry even if the positron end-point energies differed widely, thereby proving the validity of this calibration procedure. The $Na^{22}$ source was calibrated by 511–511–$\gamma$ triple-coincidence measurements. The activity measurements for nuclides that did not emit positrons were calibrated by comparing the intensity of a particular gamma ray with the intensity of a gamma ray of nearly the same energy emitted by a source of known disintegration rate. An empirically determined curve was used to correct for the variation of counting efficiency with photon energy. The calibrated sources used were $Na^{22}$ and $Am^{241}$. The latest decay-scheme data[10] were used to determine positron branching ratios and gamma-ray intensities. The calibration procedures are in general expected to be accurate to within 10%. In many cases cross-section measurements were performed in duplicate and the results usually agreed to within 5%.

### B. Energy Monitoring

The energy of the incident beam was monitored by measurements of the gross activity of copper foils irradiated with alpha particles of approximately either 25 or 39 Mev. The activity measurements were made with beta proportional counters both one and six days after bombardment. In the bombardment at 25 Mev, the activity one day after an irradiation was primarily due to $Ga^{66}$, formed by the $(\alpha,n)$ reaction on $Cu^{63}$, and to $Cu^{64}$, formed by the $(\alpha,\alpha n)$ reaction on $Cu^{65}$. The activity six days after bombardment was primarily due to $Ga^{67}$, with a small contribution from $Zn^{65}$. The same nuclides are responsible for the observed activity in the irradiation at 39 Mev, except that at this energy the main reactions responsible for the formation of $Ga^{66}$ and $Cu^{64}$ are $Cu^{65}(\alpha,3n)$ and $Cu^{65}(\alpha,\alpha n)+Cu^{63}(\alpha,2pn)$, respectively.

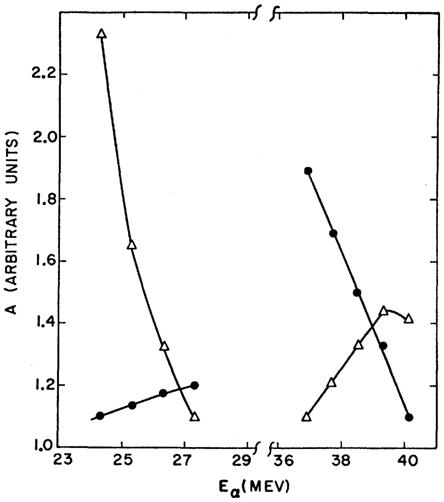

FIG. 1. Gross activity of copper foils measured 1 or 6 days after bombardment with alpha particles at the listed energies. The activity units are arbitrary and the scales are different for the two energy regions. △—1 day after bombardment; ●—6 days after bombardment.

The gross excitation functions in the energy regions under consideration are given in Fig. 1 for both the short-lived and the long-lived mixtures of activities. The activity units are arbitrary and the scale factor is different for each excitation function. The actual excitation functions for the individual reactions are presented in the following section. The contribution of the short-lived component to the activity observed one day after bombardment ranged from about 84 to 91% in both bombarding-energy regions. The activity observed six days after bombardment was essentially completely that of the long-lived component. The cross sections for the short-lived and long-lived components are seen to vary in an opposite way with bombarding energy for both energy regions under consideration. The ratio of activities measured one and six days after bombardment thus is a single-valued function of the bombarding energy in each of the two energy regions and may therefore be used to monitor the energy of the incident beam. In practice, a copper foil, 0.00025 inch in thickness, is incorporated in the stack of foils to be bombarded at a position corresponding to a given nominal energy, falling within either of the two energy regions, and the beam energy is determined from the measured ratio of activities.

The ratio of activities obtained one and six days after bombardment is given as a function of bombarding energy in Fig. 2. The ratios are based on arbitrary units

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[9] K. A. Kraus and F. Nelson, *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1955* (United Nationas, New York, 1956), Vol. 7, p. 113.

[10] *Nuclear Level Schemes, A=40—A=92,* compiled by Way, King, McGinnis, and Van Lieshout, Atomic Energy Commission Report TID-5300, 1955 (U. S. Government Printing Office, Washington, D. C., 1955), and subsequent revisions; Strominger, Hollander, and Seaborg, Revs. Modern Phys. **30**, 585 (1958).

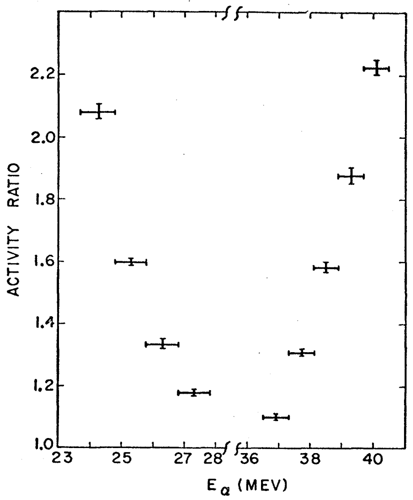

FIG. 2. Ratio of gross activities of copper measured one and six days after bombardment. The activity units are arbitrary. The vertical lines represent the standard deviations of four determinations and the horizontal lines give the energy loss in each target foil.

for the activity values and the scale factor is different in the two energy regions. The points represent an average of four experiments, and the standard deviation is indicated by the vertical lines. The horizontal lines through the points indicate the energy degradation in each foil. The energy scale was calibrated by measurement of the range in aluminum of the incident alpha particles. The beam was degraded to the desired energy as described previously. The sensitivity of the technique was checked by repeating a set of ratio measurements under the same conditions, except that the energy of the incident beam was degraded by 200 kev by use of a thin aluminum degrading foil. The results for the average of four experiments are summarized in Table I. It is seen that a difference of 200 kev in the energy of the incident beam leads to a difference in the observed ratio of activities of about 8% and 5%, for a degraded beam energy of 26 and 39 Mev, respectively. It can be seen from Fig. 2 that the ratio of activities varies more sharply with energy as the latter is decreased below 25 Mev. The sensitivity of this technique can thus be increased above the values indicated in Table I by a choice of a somewhat lower energy. In any case, the method is sensitive enough to detect changes in the energy of the incident beam of the order of 100 kev.

Two additional factors should be pointed out in connection with this technique. First, the activity ratios were determined for short irradiations. The saturation correction for the short-lived component is about 1% for a 15-minute bombardment, and a correction is required for longer bombardment times. In view of the fact that more than one nuclide is responsible for the activity of the short-lived component, it would appear desirable to determine the activity ratios as a function of irradiation time, as well as bombarding energy, for the application of this technique to long irradiations. The choice of a somewhat lower incident energy than 25 Mev for the measurement of the activity ratio would obviate this difficulty since the contribution of $Cu^{64}$ would become entirely negligible relative to that of $Ga^{66}$.

The energy of the incident beam will in general fluctuate during the course of an irradiation. It can be shown that the measured energy is the average energy, weighted solely by the beam intensity, provided that the excitation functions for the two components are linear over the range in energies of the incident beam. It is seen in Fig. 1 that this situation holds in the 37–39 Mev region. The excitation functions in the 25–27 Mev region are not linear, but the deviations from linearity are small enough so that a fluctuation of about 0.2–0.3 Mev does not materially affect the results.

## III. RESULTS

A total of 101 cross sections was measured in this study. These are presented in Table II, together with the thresholds for the corresponding reactions. The latter were obtained from the masses of stable nuclides listed by Wapstra[11] coupled with the latest decay energy measurements.[10] The errors in the listed cross-section values are estimated as 12%, in view of the previously mentioned errors in the calibration procedure and the agreement between duplicate measurements. The points on a given excitation function have a relative error of 5% with respect to each other. The listed bombarding energies are most accurate for values close to the energy of the undegraded beam. The energy values below 16 Mev may be in error by over 1 Mev due to the magnification by the straggling process of a small error in the assumed value of the incident energy.

The excitation functions are plotted in Fig. 3 for $Cu^{63}$ and in Fig. 4 for $Cu^{65}$. The excitation functions for the $(\alpha,n)$, $(\alpha,2n)$, and $(\alpha,pn)$ reactions are similar in shape to the excitation functions for similar reactions of zinc-64 with alpha particles.[1] The cross sections for these reactions go through a maximum as the bombarding energy is raised above the threshold of competing reactions involving further particle emission. The position of this maximum relative to the threshold depends

TABLE I. Sensitivity of activity ratios for monitoring the beam energy.

| $E_\alpha$ at Cu[a] (Mev) | $E^0$ (Mev) | $E^0-\Delta E$ (Mev) | $R(E^0)$[b] | $R(E^0-\Delta E)$ | Percentage difference |
|---|---|---|---|---|---|
| 26.3 | 40.5 | 40.3 | 1.336±0.017 | 1.444±0.017 | (8.1±1.9)% |
| 39.3 | 40.5 | 40.3 | 1.877±0.027 | 1.780±0.024 | (5.2±1.9)% |

[a] The average beam energy in the Cu foils is given for an incident energy, $E^0$, of 40.5 Mev.
[b] $R(E^0)$ and $R(E^0-\Delta E)$ are the ratios of the activity measured one and six days after bombardment for an incident energy of 40.5 and 40.3 Mev, respectively. The listed values are an average of four determinations.

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[11] A. H. Wapstra, Physica **21**, 367 (1956).

TABLE II. Cross sections (in millibarns) and thresholds for reactions of $Cu^{63}$ and $Cu^{65}$ with alpha particles.

| Reaction<br>Threshold (Mev)<br>Bombarding energy (Mev) | $Cu^{63}(\alpha,n)$ $+Cu^{65}(\alpha,3n)$<br>5.7, 26.9 | $Cu^{65}(\alpha,n)$<br>6.3 | $Cu^{63}(\alpha,2n)$<br>15.5 | $Cu^{65}(\alpha,2n)$<br>15.1 | $Cu^{63}(\alpha,pn)$<br>11.2 | $Cu^{65}(\alpha,2p)$<br>13.0 | $Cu^{63}(\alpha,\alpha n)$<br>8.9 | $Cu^{65}(\alpha,\alpha n)$<br>10.4 | $Cu^{65}(\alpha,2\alpha)$<br>6.6 |
|---|---|---|---|---|---|---|---|---|---|
| 15.2 | 325 | 555 | | 1.2 | 0.8 | | | | |
| 16.1 | | | | | 2.8 | | | | |
| 17.5 | 375 | 780 | | 22 | | | | | |
| 18.3 | | | | 83 | | | | | |
| 18.8 | | | | | 97 | | | | |
| 19.3 | 441 | 865 | | | | | | | |
| 19.8 | | | | 161 | | | | | |
| 21.0 | 417 | 790 | | 307 | | 0.021 | 0.95 | | |
| 21.4 | | | 3.1 | | 337 | | | | |
| 22.6 | | | 19 | | | | | | |
| 23.1 | 313 | 665 | 33 | | | | | | |
| 23.6 | | | | 461 | 570 | 0.072 | 8.3 | 21 | |
| 24.5 | 210 | 405 | 60 | | | | | | |
| 25.6 | 162 | 263 | 81 | 562 | 733 | 0.15 | | 48 | 0.055 |
| 26.4 | 102 | 188 | | | | | | | |
| 26.8 | | | 128 | | | | 85 | | |
| 27.2 | | | | | | | | | 0.087 |
| 28.1 | | | | 630 | 836 | 0.47 | | 78 | 0.094 |
| 28.8 | 55 | 114 | 204 | | | | | | |
| 29.6 | | | | 609 | 855 | 0.67 | 162 | | |
| 30.4 | | | 251 | | | | | 110 | 0.29 |
| 31.2 | | | 266 | 498 | 813 | 1.0 | | | |
| 31.5 | 77 | 67 | | | | | | | |
| 32.4 | | | | | | | 192 | 127 | 0.51 |
| 32.8 | | | 238 | | | | | | |
| 33.3 | | | | | | | | | 0.67 |
| 34.0 | 118 | 49 | 225 | 434 | 749 | 1.9 | | 140 | 0.83 |
| 35.3 | | | | | | | 205 | | |
| 36.0 | | | | | | | | 143 | 1.1 |
| 37.2 | 231 | 34 | 171 | 280 | 575 | 2.6 | | | |
| 37.9 | | | | | | | 192 | 137 | 1.6 |
| 39.2 | | | | | | | | | 2.6 |
| 40.1 | 418 | 27 | 121 | 199 | 400 | 2.7 | 165 | | |
| 40.8 | | | | | | | | 152 | 2.3 |

on a number of factors such as the nuclear temperature and the Coulomb barrier for emitted protons. The previous measurements on zinc-64 and the present results on copper targets indicate that excitation functions for $(\alpha,p)$, $(\alpha,n)$, $(\alpha,pn)$, and $(\alpha,2n)$ reactions go through a maximum some 4 to 5 Mev above the effective threshold of the next competing reaction. The effective threshold is given by the actual energy threshold plus 2 Mev per emitted proton, added in order to compensate for the low penetrability of the Coulomb barrier for low-energy protons.

The excitation functions for the $(\alpha,\alpha n)$ reactions attain their maximum value at about 35 Mev and decrease only very slowly at higher energies. This behavior is similar to that of the $(\alpha,\alpha n)$ excitation function for zinc-64, and has been attributed[1] to the fact that the alpha particles appear to be emitted as the result of a direct interaction process.[12] The excitation functions attain their peak value some 9 Mev above the effective threshold of the next competing reaction. The effective threshold is obtained in this case from the actual energy threshold by adding 7 Mev per emitted alpha particle and 2 Mev per emitted proton. These values were chosen since the penetrabilities of a 7-Mev alpha particle and a 2-Mev proton are approximately equal in this mass region. It can be seen from the position of the maximum relative to the threshold of the next competing reaction that the particles emitted in an $(\alpha,\alpha n)$ reaction carry off more energy than the particles emitted in the previously mentioned reactions, as would be expected from the suggested difference in mechanisms.

The $(\alpha,2p)$ and $(\alpha,2\alpha)$ reactions on $Cu^{65}$ have much smaller cross sections than the other reactions studied. The main factor responsible for these low cross sections is undoubtedly the effect of the Coulomb barrier in depressing the probability for the emission of two charged particles, since these reactions are, in fact, slightly favored by $Q$ value considerations over other reactions involving the emission of two particles. The excitation functions for these reactions show a continuous increase with energy, and only appear to approach their maximum values at the highest energies. The previously mentioned systematics for the energy corresponding to the maximum in the excitation functions lead to expected maxima at 33 Mev and 40 Mev for the $(\alpha,2p)$ and $(\alpha,2\alpha)$ reactions, respectively. It is thus seen that the $(\alpha,2p)$ reaction does not conform to the systematic behavior of the other reactions.

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[12] G. Igo, Phys. Rev. **106**, 256 (1957).

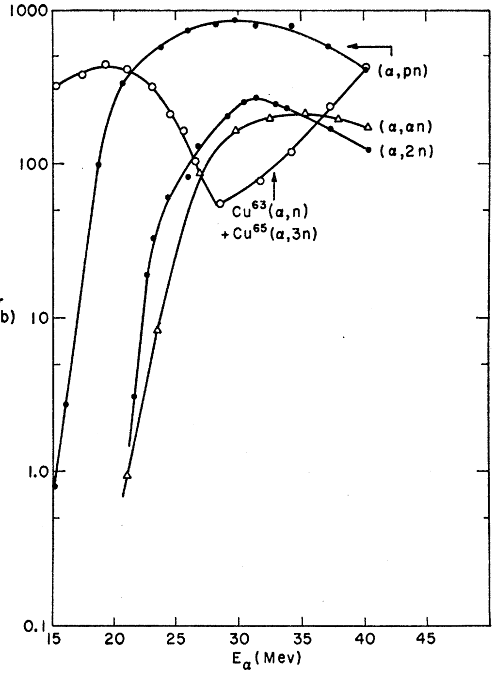

FIG. 3. Excitation functions for reactions of $Cu^{63}$ with alpha particles. The excitation function for $Cu^{63}(\alpha,n)Ga^{66}$ includes the contribution of the $Cu^{65}(\alpha,3n)$ reaction at high energies.

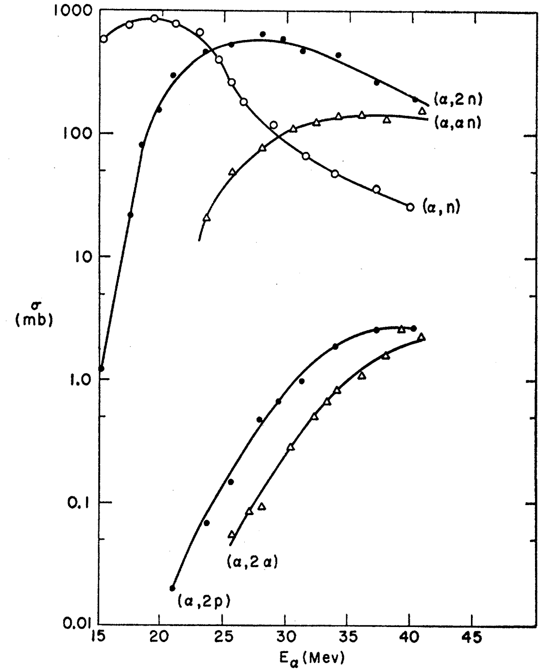

FIG. 4. Excitation functions for reactions of $Cu^{65}$ with alpha particles. The excitation function for the $(\alpha,2n)$ reaction includes the contribution of the $Cu^{63}(\alpha,\gamma)$ reaction.

The maximum cross sections for the $(\alpha,n)$ reactions on $Cu^{63}$ and $Cu^{65}$ are about 450 mb and 870 mb, respectively. These values imply $(\alpha,n)/(\alpha,p)$ cross-section ratios of about 1 and 20, respectively, assuming a nuclear radius parameter of about $1.6\times10^{-13}$ cm.[1] The $(\alpha,n)$ reaction is favored in these two instances by the fact that the residual nuclides are odd-odd, whereas the nuclides resulting from an $(\alpha,p)$ reaction are even-even. The value of $\sigma(\alpha,n)/\sigma(\alpha,p)$ for $Zn^{64}$, where on the other hand both product nuclides have odd mass number, is only 0.6.[1] The observed yield of $Ga^{66}$ includes the contribution of both the $Cu^{63}(\alpha,n)$ and $Cu^{65}(\alpha,3n)$ reactions for bombarding energies above 27 Mev. The increase in the observed yield above this energy is in fact directly attributable to the $Cu^{65}(\alpha,3n)$ reaction. The listed cross sections above 29 Mev were calculated on the assumption that the observed yield was, in fact, entirely ascribable to the latter reaction. The value of $\sigma(\alpha,2n)/\sigma(\alpha,2p)$ for $Cu^{65}$ at the energy corresponding to the highest value of the $(\alpha,2n)$ cross section is about 1300. This large ratio is not unexpected in view of the already large ratio of $(\alpha,n)$ and $(\alpha,p)$ cross sections. The ratio of $(\alpha,pn)$ and $(\alpha,2n)$ reactions on $Cu^{63}$ is about 3.3 in the region of maximum yield. This ratio has been measured in a number of cases in this mass region and ranges from 2 for $Ge^{70}$ [13] to 60 for $Fe^{54}$.[14] The threshold of the $Cu^{65}(\alpha,2n)$ reaction is 15.1 Mev, and the measured cross section at 15.2 Mev is 1.2 mb. This value appears to be rather high in view of the fact that the $Cu^{63}(\alpha,2n)$ reaction does not appear to attain this value until the incident energy is at least some 5 Mev above the threshold. It is believed that this high value of the cross section at 15.2 Mev is due to the formation of $Ga^{67}$ by the $Cu^{63}(\alpha,\gamma)$ reaction. This cross section has been measured for $Zn^{64}$ [1] and found to be about 0.9 mb in the energy region in question. If it is assumed that the total yield of $Ga^{67}$ observed at 15.2 Mev is due to the $Cu^{63}(\alpha,\gamma)$ reaction, then the cross section for the latter is 0.5 mb.

Several of the excitation functions presented in this work have previously been measured by Proges.[4] The present cross-section values are in substantial disagreement with the previous measurements, even if allowance is made for an error of a factor of 2 in the previously reported work.[5] The cross-section values corresponding to the peak in the excitation functions actually reported by Porges are thus lower than the present values by factors ranging from 3.4 for the $Cu^{63}(\alpha,n)$ reaction, to 1.2 for the $Cu^{65}(\alpha,2n)$ reaction.

## IV. DISCUSSION

The effects of variations in neutron and proton binding energies and of the even-even or odd-odd nature of the residual nuclei on the cross sections for $(\alpha,n)$, $(\alpha,2n)$, and $(\alpha,\alpha n)$ reactions on $Zn^{64}$, $Cu^{63}$, and $Cu^{65}$ may be estimated by use of the statistical theory. The equations giving the cross sections for different reactions

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[13] S. Amiel (private communication).

[14] J. M. Miller and F. S. Houck, Bull. Am. Phys. Soc. Ser. II, 2, 60 (1957).

are given in reference 1. A simplified approximate solution to these equations may be obtained for a value of the excitation energy corresponding to the maximum cross section of a particular reaction. It can be shown that the maximum cross section for an $(\alpha,n)$ reaction is directly proportional to a quantity $K$ given by

$$K_{(\alpha,n)}=\left[1+\left(\frac{U-S_{p1}-B_1}{U-S_{n1}}\right)\times\exp\{(4a)^{\frac{1}{2}}[(U-S_{p1}-B_1)^{\frac{1}{2}}-(U-S_{n1})^{\frac{1}{2}}]\}\right]^{-1},$$

where $U$ is the excitation energy of the compound nucleus, $S_{p1}$ and $S_{n1}$ are the energies required to separate a proton or a neutron from the compound nucleus, $B_1$ is an effective proton barrier, and $a$ is the level density parameter. This equation is only applicable to target nuclides having nearly the same charge and mass number, in which case the total inelastic cross section, the cross sections for all inverse reactions, and the Coulomb barrier for charged particles, are about the same for all targets. The effect of even-odd differences, as expressed in the value of the characteristic level parameter $\delta$, is not taken into account in this expression. The even-odd effect should thus appear as a perturbation in the linear relation between $\sigma(\alpha,n)$ and $K$. This equation further assumes that the cross section for an $(\alpha,n)$ reaction depends solely on the competition between neutron and proton emission, and neglects the effect of further particle emission. This effect causes only minor perturbations on the observed maximum yields for reactions having substantial cross sections, since the probability for further particle emission is still small for the bombarding energy under consideration.

Similar equations may be obtained for the maximum cross sections of $(\alpha,2n)$ and $(\alpha,\alpha n)$ reactions. The maximum cross section for an $(\alpha,2n)$ reaction thus is proportional to

$$K_{(\alpha,2n)}=K_{(\alpha,n)}'\left[1+\left(\frac{U-S_{n1}-\epsilon_{n1}-S_{p2}-B_2}{U-S_{n1}-\epsilon_{n1}-S_{n2}}\right)\times\exp\{(4a)^{\frac{1}{2}}[(U-S_{n1}-\epsilon_{n1}-S_{p2}-B_2)^{\frac{1}{2}}-(U-S_{n1}-\epsilon_{n1}-S_{n2})^{\frac{1}{2}}]\}\right]^{-1},$$

and the maximum cross section of an $(\alpha,\alpha n)$ reaction is proportional to

$$K_{(\alpha,\alpha n)}=\left[1+\left(\frac{U-S_{p1}-B_{p1}}{U-S_\alpha-B_\alpha}\right)\times\exp\{(4a)^{\frac{1}{2}}[(U-S_{p1}-B_{p1})^{\frac{1}{2}}-(U-S_\alpha-B_\alpha)^{\frac{1}{2}}]\}\times\left(\frac{U-S_{n1}}{U-S_\alpha-B_\alpha}\right)\exp\{(4a)^{\frac{1}{2}}\times[(U-S_{n1})^{\frac{1}{2}}-(U-S_\alpha-B_\alpha)^{\frac{1}{2}}]\}\right]^{-1}\times\left[1+\left(\frac{U-S_\alpha-\epsilon_\alpha-S_{p2}-B_{p2}}{U-S_\alpha-\epsilon_\alpha-S_{n2}}\right)\times\exp\{(4a)^{\frac{1}{2}}[(U-S_\alpha-\epsilon_\alpha-S_{p2}-B_{p2})^{\frac{1}{2}}-(U-S_\alpha-\epsilon_\alpha-S_{n2})]\}\right]^{-1}.$$

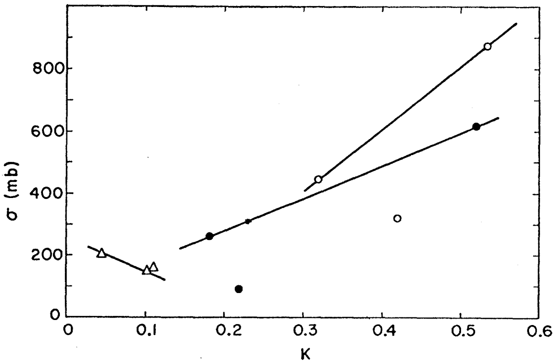

FIG. 5. Variation of $\sigma$ with $K$. ○—$(\alpha,n)$ reaction; ●—$(\alpha,2n)$ reaction; △—$(\alpha,\alpha n)$ reaction. The lines are drawn through the points for $\mathrm{Cu}^{63}$ and $\mathrm{Cu}^{65}$ in all cases. The points off the line are for $\mathrm{Zn}^{64}$ target.

In these equations, the excitation energy spectrum resulting from the emission of the first particle has been replaced by the single energy $U-S-\epsilon$, where $\epsilon$ is the average kinetic energy of the first emitted particle. $K'(\alpha,n)$ is given by $K(\alpha,n)$ evaluated at an excitation energy $U$, appropriate to the maximum in the $(\alpha,2n)$ excitation function. All other symbols have the same meanings as before, with the subscripts referring to the order in which particles are emitted. All the previously discussed assumptions apply to these equations. In addition, it is assumed in the equation for the $(\alpha,\alpha n)$ reaction that the alpha particle is the first emitted particle. This is certainly the more predominant process since the Coulomb barrier depresses the probability for alpha emission at low excitation energies.

The values of $a$ used to evaluate these expressions were taken from the analysis of the excitation function data for zinc-64,[1] and ranged from 1.0 to 2.8. The values of the average kinetic energy for the first emitted particle were taken as twice the nuclear temperature and the latter was obtained from the values of $a$ according to the relation $T=(E_{\max}/a)^{\frac{1}{2}}$, where $E_{\max}$ is the maximum residual excitation energy following the emission of the first particle. The binding energy values were obtained from experimental masses[11] and decay-energy data,[10] and the effective barriers for proton and alpha emission were taken as 0.7 $B_p$ and 1.66 $B_p$,[15] where $B_p$ is the classical Coulomb barrier for protons.

The cross sections for the reactions in question are plotted against $K$ in Fig. 5. The cross sections for the $(\alpha,n)$ and $(\alpha,2n)$ reactions show the expected variation with $K$. In both cases the point for zinc-64 is seen to lie below the line defined by the values for copper-63 and copper-65. This fact is attributed to the effect of even-odd differences between the nuclides in question. The products of the $(\alpha,n)$ reactions on the copper isotopes thus are odd-odd and are favored by level density considerations over the odd-mass product of the $(\alpha,n)$ reaction on zinc-64. Similarly, the nuclides resulting from the $(\alpha,2n)$ reaction on copper-63 and copper-65 have odd mass number, and are favored over the even-even nuclide resulting from the $\mathrm{Zn}^{64}(\alpha,2n)$ reaction. In order to bring the points for zinc-64 into line with the other values it is necessary to subtract an energy $\delta$ from the excitation energy $U$ for zinc-64. $\delta$ is the energy difference between the ground state and the characteristic level at which the exponential level-density expression sets in, and may be evaluated from the data in Fig. 5, and the relation between $K$ and $U$. The differences in the values of $\delta$ for $\mathrm{Zn}^{64}$ and the copper isotopes, $\Delta\delta$, obtained in this fashion are 1.5 Mev and 1.6 Mev for the $(\alpha,n)$ and $(\alpha,2n)$ reactions, respectively. These values are only approximately correct, in view of the approximations in the calculation. Since the even-odd effect is ascribed to the presence of unpaired nucleons in the product nuclides, it is of interest to compare the values of $\Delta\delta$ with the pairing energy values obtained by Cameron[16] from mass-formula considerations. The difference in the pairing energy of $\mathrm{Ge}^{67}$ and $\mathrm{Ga}^{66}$ or $\mathrm{Ga}^{68}$ is 1.4 Mev, while the corresponding value for $\mathrm{Ge}^{66}$ and $\mathrm{Ga}^{65}$ or $\mathrm{Ga}^{67}$ is 1.3 Mev, in good agreement with the values of $\Delta\delta$ obtained in the present work. The effect of $\Delta\delta$ on the cross sections of the reactions in question may be obtained from the vertical displacement of the points for $\mathrm{Zn}^{64}$ from the lines for the copper isotopes, in Fig. 5. The effect of $\Delta\delta$ on the $(\alpha,n)$ cross section is 320 mb, or 214 mb/Mev. The effect of $\Delta\delta$ on the $(\alpha,2n)$ cross section is 210 mb, or 140 mb/Mev. The effect of the differences in neutron and proton binding energies for $\mathrm{Cu}^{63}$ and $\mathrm{Cu}^{65}$ is the same per Mev as the effect of differences in the $\delta$ values, since these two factors enter in the same way into the expression for $K$.

The results for the $(\alpha,\alpha n)$ reaction appear to be qualitatively different from those for the other reactions under consideration. It is seen in Fig. 5 that contrary to expectation, the cross section for this reaction decreases as $K$ increases. Furthermore, the point for zinc-64 is seen to lie above the line defined by the points for the copper isotopes. The difference in pairing energy between $\mathrm{Zn}^{63}$ and $\mathrm{Cu}^{62}$ or $\mathrm{Cu}^{64}$ favors the latter by 1.1 Mev, and the point for zinc-64 should thus lie below the line through the points for $\mathrm{Cu}^{63}$ and $\mathrm{Cu}^{65}$, as in the case of the $(\alpha,n)$ and $(\alpha,2n)$ reactions. The binding energy consideration that determine the value of $K$ favor the $(\alpha,\alpha n)$ reaction on copper-65. However, the difference in the values of $K$ for $\mathrm{Cu}^{65}$ and $\mathrm{Cu}^{63}$ is small enough so that the observed discrepancy may perhaps not be significant. The above considerations may, in fact, not be entirely applicable to the $(\alpha,\alpha n)$ reactions in view of the measurements of the angular distribution and energy spectra of alpha particles emitted in alpha-induced reactions[12] which indicate that the alpha particles are primarily emitted by a direct interaction mechanism. It would be of interest to determine the total alpha emission probability for alpha induced reactions on $\mathrm{Cu}^{63}$ and $\mathrm{Cu}^{65}$, in order to determine if the lower $(\alpha,\alpha n)$ cross section for $\mathrm{Cu}^{65}$ merely reflects a lower total emission probability for alpha particles. This, unfortunately, cannot be done radiochemically because the products of the $(\alpha,\alpha p)$ reactions are stable.

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