Alpha Excitation Functions of Silver and Copper

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The excitation functions for the production of some of the nuclei formed by alpha-particle bombardment of copper and silver have been measured for alpha energies up to 40 Mev. Comparison of these data with theoretical predictions based on (a) the assumption of relatively large radius constants ($r_0=1.5$ for Zn, $r_0=1.65$ for Cd) and (b) an energy-dependent odd-odd to even-even level density ratio allows two conclusions: (1) (α,pn) cross sections are in good agreement with predictions based on the statistical theory. This lends some support to the proposal that the large (p,p), (p,pn), (n,p) etc., cross sections recently reported are primarily due to direct interactions. (2) With an energy level density $\omega=C\exp2(aE)^{\frac{1}{2}}$, calculations based on the values of a deduced from inelastic scattering experiments do not fit the experimental curves; a derived from measured level spacing agrees with the copper, but not with the silver data. The best fit for the silver gives $a\sim2$. This result, similar to that obtained by the analysis of other experimental data, suggests that there is a considerable excess of high-energy evaporated particles.

I. INTRODUCTION

DURING the last several years, a growing number of experiments[1–5] have thrown doubt on the validity of some of the assumptions and models on which the statistical theory of nuclear reactions[6] is based, in contrast to fairly extensive earlier evidence in detailed as well as general agreement with its predictions.[7–10] The basic assumption that nuclear reactions can be interpreted in terms of the statistically independent formation and decay of a compound state, implying strong interactions, has been limited to a fairly small energy range by the successful description of both low- and high-energy reactions with weak and intermediate interaction theories.[11,12] The calculation of the cross sections for the formation of this compound nucleus[13] further assumes a sharply defined nuclear surface, which, in the light of some recent evidence,[14] may not be a sufficiently realistic approximation. Finally, calculation of the nuclear energy level density ω by the formula, derived by Weisskopf and Ewing on the basis of a Fermi gas model,

$$\omega=C\exp[2(aE)^{\frac{1}{2}}], \tag{1}$$

where E is the excitation energy and C and a are adjustable parameters, leads to considerable disagreement between the values of these parameters derived from different experiments. In particular, slow neutron resonance measurements of level spacing[15] yield values of a strongly dependent on A; energy spectra of emitted particles yield values of a which are much less dependent on mass, as well as considerably larger than the above-mentioned, and excitation function measurements[10,16] seem to imply much smaller values of this parameter. While the data on emission spectra, such as the inelastic proton and neutron scattering,[3–5] are fairly extensive, not many excitation functions which allow an unambiguous interpretation in terms of level density have been published.

The best of the latter are the (α,n) and $(\alpha,2n)$ cross sections of Ag^{109} measured by Bleuler *et al.*[16] who derived a value of $a=2.4$, assuming that the level density of the intermediate nucleus was as given by Eq. (1), and that charged particle emission was negligible at this Coulomb barrier; this value of a is at variance with $a=6.5$ suggested by Feld *et al.*[15] and $a=8$ to 10 from inelastic scattering data of Gugelot,[3] for silver. Now many recent experiments, such as the (n,pn) cross sections measured by Paul and Clarke,[2] show that charged particle emission, even for high Coulomb barriers, is in fact not negligible, at least for proton and neutron bombardment. A strong (α,pn) reaction would compete with the $(\alpha,2n)$ reaction in such a way as to make it increase more slowly with excitation energy than in the case of a negligible (α,pn) cross section. To ascertain whether this could account for the low value of a found by Bleuler *et al.* was one of the purposes of the present measurements of the (α,pn) and $(\alpha,2n)$ excitation functions of Ag^{107}. It may be pointed out that there is another rather obvious explanation of the discrepancy between the Bleuler *et al.* and Gugelot values of a, which rests on the fact that the intermediate nucleus mainly concerned in the excitation function measurement, In^{112}, is odd-odd and may have quite a different level density from that of the odd-even residual nuclei con-

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cerned in inelastic scattering If the odd-odd levels of In^{112} (about which for obvious reasons no information is available from slow neutron resonances) were relatively denser near the ground state, the emission spectrum would be distorted in favor of high emission energies, so that, as shown in Part IV of this paper, low values of a would result from the erroneous assumption of a Maxwellian emission spectrum. Some of the excitation functions of copper, in which the intermediate nuclei are also odd-odd, were therefore measured as a means of comparison.

II. EXPERIMENTAL METHODS

Sources were activated in the external beam of the 60-inch cyclotron, using the well-known stacked-foil technique. In order to obtain a reasonable counting rate for the long half-life activities, extreme monochromatization in the cyclotron fringing field, by successive narrow collimating slits, was dispensed with, and the beam was collimated only enough to obtain currents not less than about 1 μa. The silver and copper target foils were rolled down from 1-mil sheets to about 6 to 10 mg/cm^2 thickness for energies above 15 Mev; for lower energies, 3 mg/cm^2 foils were prepared by evaporation. The beam, after collimation by carbon blocks, passed into a target chamber with water cooled walls, through the target stack, and then through 5 cm of dry air at adjustable pressures and through an exit foil. An absorber wheel and Faraday cup were bolted to the target chamber and connected with the tank vacuum. The beam energy could thus be measured continuously during the bombardment, the foil wheel providing coarse, and the variable air absorber fine readings. Faraday cup and foil wheel currents were read continuously with 100% feedback electrometers and recording voltmeters. Since there was generally about twice the theoretical straggling, the activity induced in each foil was corrected for the energy spectrum of the beam by a method similar to that given by Blaser *et al.*[17]; these corrections were important only near the threshold of a given reaction.

The Q-values of the different reactions were obtained by starting with all available measured masses, reaction thresholds, and decay data[18–20] in the vicinity of silver and copper, respectively, and plotting neutron and proton separation energies against A for each value of Z. Then, taking into account the quoted errors and reliability of the data, successive geometric approximations were made in such a way that reasonably straight lines were obtained, connecting the even-mass neutron separatione nergies, the odd-mass neutron separation energies, and the proton separation energies. As an example of how this method works, the described correlations lead one to disregard a 2-Mev positron component ascribed to In^{109} [20] and hence give a threshold of 16.4±0.3 Mev for the $Ag^{107}(\alpha,2n)In^{109}$ reaction, while a direct calculation would yield a threshold about 0.5 Mev higher. Some of the calculated thresholds, in the center-of-mass system, are given in Table I.

III. RESULTS

(a) Copper Cross Sections

Stacks of about 20 copper foils were activated as described above, and then counted with a Geiger tube in calibrated geometry. In order to discriminate between 9.8-hr Ga^{66} and 13-hr Cu^{64}, a series of counts was taken with 1.7 g Al absorber, which transmitted only the 4.14-Mev positrons of Ga^{66}; the difference between the "bare" counts and the absorber counts, corrected for partial absorption of the Ga^{66} activity, was ascribed to Cu^{64}. As a check, the e^-/e^+ ratio of some foils was measured in a trochoidal spectrometer.[21] Cross sections for $Cu^{63}(\alpha,n)Ga^{66}$, $Cu^{65}(\alpha,n)Cu^{64}$, and $Cu^{65}(\alpha,3n)Ga^{66}$ were then calculated from a graphical analysis of these data for each foil, recent decay schemes of Ga^{66} [22] and Cu^{64},[20] isotopic composition of copper,[20] foil weight, bombardment current and the geometrical factor; the usual corrections for source self-absorption and back scattering, Geiger tube dead-time, and decay during the bombardment were applied, and long-lived background, chiefly due to Ga^{67}, was subtracted graphically. Because of somewhat incomplete information about the 68-min Ga^{68} activity, the scale for the $Cu^{65}(\alpha,n)Ga^{68}$ cross section was found only approximately, by the same method.

To obtain the absolute cross section for the $Cu^{65}(\alpha,2n)Ga^{67}$ reaction, a delay-coincidence count was taken, for several of the sources, using pulse-height selection in each channel. The delayed channel accepted only the 300-kev photons, present in 13.9% of all Ga^{67} decays,[23] which connect the 0.39-Mev level of Zn^{67} to the 10-microsecond 92-kev isomeric level; the other channel was set to accept the 92-kev photons by which the isomeric level decays to the ground state. This measurement discriminated against 60-hr Cu^{67} which decays into the 92-kev isomeric level but not into the

TABLE I. Calculated reaction thresholds in Mev; center of mass.

	(α,p)	(α,n)	(α,pn)	$(\alpha,2n)$	$(\alpha,3n)$
Cu^{63}	1.71	7.65	12.87	16.85	28.79
Cu^{65}	2.10	5.78	12.25	14.06	25.19
Ag^{107}	3.4	8.1	12.9	16.4	26.4
Ag^{109}	3.2	6.7	12.3	14.3	24.2

[17] Blaser, Boehm, Marmier, and Scherrer, Helv. Phys. Acta **24**, 441 (1951).
[18] Collins, Johnson and Nier, Phys. Rev. **86**, 408 (1952); Phys. Rev. **94**, 398 (1954); R. E. Halsted, Phys. Rev. **88**, 666 (1952).
[19] Several papers in Revs. Modern Phys. **26**, October, 1954.
[20] Hollander, Perlman, and Seaborg, *Table of Istopes*, University of California Radiation Laboratory Report, UCRL-1928, 1952 [Revs. Modern Phys. **25**, 469 (1953)].
[21] B. Craseman, thesis, University of California, 1953 [Rev. Sci. Instr. **24**, 470 (1953)].
[22] Mann, Meyerhof, and West, Phys. Rev. **92**, 1481 (1953).
[23] Meyerhof, Mann, and West, Phys. Rev. **92**, 758 (1953).

390-kev level[24]; allowance was also made for contamination of the 92-kev channel by the unresolved 90-kev photons occurring in 3.5% of Ga^{67} decays. The error of this determination was estimated to be about 25%. Absorption curves indicated that Cu^{67} could account for at most 5% of the total activity in the vicinity of the $(\alpha,2n)$ peak. In view of the double penetration of the Coulomb barrier involved in the $Cu^{65}(\alpha,pp)Cu^{67}$ reaction, this result was not unexpected.

The 250-day Zn^{65} activity, consisting of the product of the (α,pn) reaction on Cu^{63} and the daughter of 5-min Ga^{65} produced by $Cu^{63}(\alpha,2n)Ga^{65}$, was measured with a crystal counter and pulse-height selector, with a narrow channel centered on the 1.1-Mev line of the Zn^{65} decay in order to reduce the background. Geometry and crystal efficiency were determined by comparison of the Zn^{65} spectrum with the spectrum of a standard Co^{60} source of the same size as the copper foils; relative contribution to the photopeak was taken from the curves of Maeder and Wintersteiger.[25]

These various excitation functions are shown in Fig. 1. The dark and light arrows on the abcissa are the calculated thresholds for the cross sections indicated just above the arrows, of Cu^{63} and Cu^{65}, respectively.

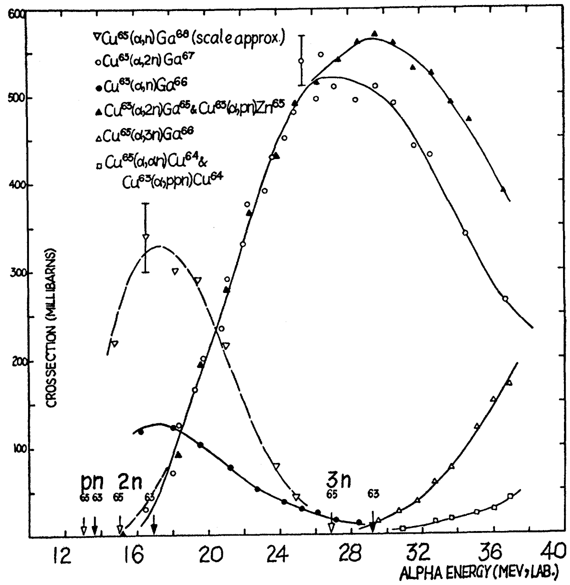

FIG. 1. Copper excitation functions. The dark and light arrows on the abcissa give the calculated thresholds for reactions indicated above the arrows, for Cu^{63} and Cu^{65}, respectively.

(b) Silver Cross Sections

The excitation functions for $Ag^{109}(\alpha,n)In^{112}$ and $Ag^{109}(\alpha,2n)In^{111}$ have been measured absolutely by Bleuler *et al.*[16] up to 18-Mev bombardment energy. Earlier measurements on a relative scale of excitation functions for the production of 1-hr, 5-hr, and 2.8-day activities by Ghoshal[26] were interpreted by Bleuler *et al.*[27] as follows: 1-hr activity—In^{110} and In^{108}; 5-hr activity—In^{109} and In^{110m}; 2.8-day activity—In^{111}.

In order to distinguish, in the present measurements, between 4.3-hr In^{109} and 4.9-hr In^{110m}, the decay of ten foils selected from an α-irradiated stack was followed for several weeks in the vicinity of strongly converted lines associated with these activities, as well as the lines of In^{111} and Cd^{109}, on a beta-ray spectrometer. The foil sources were mounted on a rapid source changing device designed by Temmer[28]; the spectrometer was that described by Hayward.[28] Two bombardments were made, yielding relative excitation functions for $Ag^{107}(\alpha,n)In^{110m}$, $Ag^{107}(\alpha,2n)In^{109}$, $[Ag^{107}(\alpha,2n)In^{109}+Ag^{107}(\alpha,pn)Cd^{109}]$, $Ag^{109}(\alpha,3n)In^{110m}$ and $Ag^{109}(\alpha,2n)In^{111}$. The 1-hr In^{110} activity was followed only for a few foils above 25 Mev; comparison to the relative In^{110m} excitation function gave a ratio of isomeric to ground level production of about 3.4 to 1 near 28 Mev. A scale was put on the cross section for In^{110m} production by integrating the areas under the 661-kev In^{110} line and the 247-kev In^{111} line, correcting for source absorption and scattering, Geiger window absorption, resolution and decay during the bombardment, and using the absolute $Ag^{109}(\alpha,2n)In^{111}$ cross section found by Bleuler *et al.*[16] to find the geometrical factor of the spectrometer. The excitation function for the production of 1-hr activity found by Ghoshal[26] was used to obtain, somewhat ambiguously, the total (α,n) cross section for Ag^{107}: subtraction of the In^{108} component gave a relative cross section for 66-min In^{110} production, this cross section was then scaled by 1:3.4 to the In^{110m} cross section at 27 Mev, and the two were added. This is shown in Fig. 2(a). It may be noted that the In^{110m} cross section increases steadily relative to the In^{110} cross section, in agreement with the assignment of a higher spin to the isomeric level.[27]

In order to observe the region near the threshold of the $(\alpha,2n)$ and (α,pn) reactions and look, especially, for deuteron emission, the Cd^{109} activities induced in a foil stack which covered bombarding energies from 10 to 25 Mev were followed with a thin-window Geiger counter and a NaI(Tl) crystal counter; the long-lived Cd^{109} residue was counted with a crystal and a pulse-height selector set, for purposes of reducing background count, to accept only the Ag *K* x-rays following either the *K*-capture of Cd^{109} or the *K*-conversion of the 87-kev transition of the 40-sec isomer of Ag^{109}. Graphical analysis of the decay in each foil then gave excitation functions for $Ag^{109}(\alpha,2n)In^{111}$ and for $Ag^{107}(\alpha,2n)In^{109}\rightarrow Cd^{109}+Ag^{107}(\alpha,pn)Cd^{109}$; straggling corrections were applied as described in the previous section. A residual In^{111} activity, several Mev below the $Ag(^{109}(\alpha,2n)In^{111}$

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[25] Maeder, Müller, and Wintersteiger, Helv. Phys. Acta **27**, 3–44 (1954).
[26] S. A. Ghoshal, Phys. Rev. **73**, 417 (1948).
[27] Bleuler, Blue, Chowdary, Johnson, and Tendam, Phys. Rev. **90**, 464 (1953).
[28] G. Temmer, Phys. Rev. **76**, 424 (1949); R. W. Hayward, thesis, University of California, Berkeley, 1949 (unpublished).

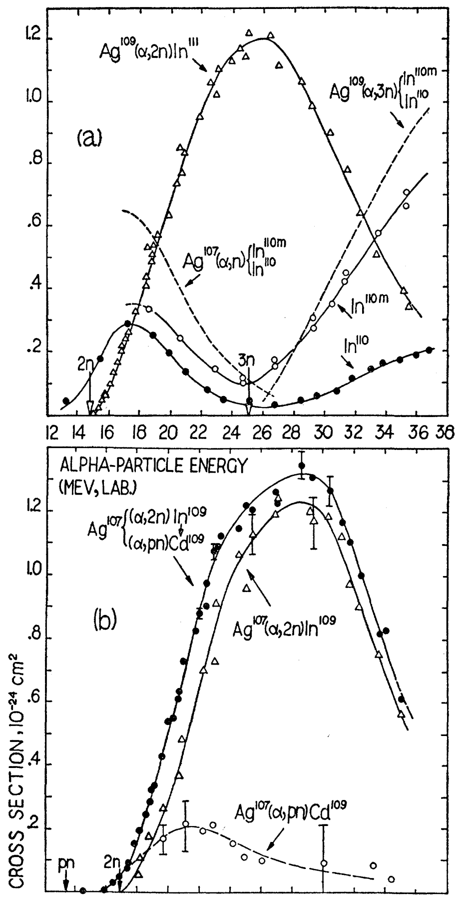

FIG. 2. (a) Excitation functions for the production of In^{110}, In^{110m}, and In^{111}. The excitation function for the production of In^{110} was taken from reference 26, corrected for estimated admixture of In^{108} and provided with a scale as explained in the text. The total (α,n) cross section of Ag^{107} and $(\alpha,3n)$ cross section of Ag^{109}, shown as broken lines, were obtained by adding In^{110} and In^{110m} curves and extrapolating to the $(\alpha,3n)$ threshold of Ag^{109}. Calculated $(\alpha,2n)$ and $(\alpha,3n)$ thresholds of Ag^{109} are shown by arrows on the abcissa. (b) Excitation functions for the production of In^{109} and Cd^{109}. Arrows on the abcissa indicate the (α,pn) and $(\alpha,2n)$ thresholds of Ag^{107}.

threshold, of a few tenths of a millibarn, was ascribed to the $Ag^{107}(\alpha,\gamma)In^{111}$ reaction; absence of any detectable activity below the $Ag^{107}(\alpha,pn)Cd^{109}$ threshold allowed the tentative conclusion that the (α,d) reaction is negligible. Two bombardments were made for this determination and yielded the same result. The $Ag^{109}(\alpha,2n)In^{111}$ excitation function obtained from these runs and from the spectrometer runs is also shown in Fig. 2(a).

The absolute value of the sum of $(\alpha,2n)$ and (α,pn) cross sections of Ag^{107} was determined by coincidence and absorption-coincidence counting of the K-conversion electrons and K x-rays from the 40-sec isomeric level of Ag^{109} which follows Cd^{109} decay. Values of the fluorescent yield,[29] $(L+M)/K$ conversion ratio, L/K capture ratio and K-conversion coefficient[20] were taken from the literature. The K-conversion coefficient has been measured as 11 by Siegbahn, 6 by Huber *et al.*[20] and calculated, for an $E3$ transition, as about 11 by Goldhaber and Sunyar.[30] The Cd^{109} photon spectrum was measured with different NaI(Tl) crystals and pulse-height analyzers; from the ratio of the areas under the 87-kev gamma and 22-kev x-ray peaks, measured absorption of these radiations in the known thickness of aluminum covering the crystal, and the above mentioned L/K capture, $(L+M)/K$ conversion and fluorescent yield data, a value of $\alpha_K=5.9\pm1.0$ was calculated, in agreement with Huber *et al.*[20] Finally, several foils were subjected to a short bombardment, the In and Cd activities separated by a fast, quantitative chemical technique due to Hicks *et al.*,[31] and counted after allowing the In^{109} of the In fraction to decay completely to Cd^{109}. The $\sigma(\alpha,pn)/\sigma(\alpha,2n)$ ratio calculated from these data, together with the absolute cross section for Cd^{109} production, provided a scale for the relative $(\alpha,2n)$ cross section found previously; the (α,pn) cross section was then obtained by subtraction. The different excitation functions for the production of Cd^{109} are shown in Fig. 2(b).

[29] C. E. Roos, Phys. Rev. **93**, 405 (1954).

IV. DISCUSSION

Excitation functions allow two theoretical inferences: the sum of all the important reactions of a given nucleus may be compared with the capture cross section, calculated by continuum theory; and the shape of cross sections compared to calculations on the basis of statistical evaporation theory.

The former type of comparison is illustrated in Fig. 3, for the reactions of Ag^{107}. The sum of the (α,n), $(\alpha,2n)$ and (α,pn) cross sections is seen to exceed the theoretical capture cross section for $r_0=1.5$, shown as a broken line and asymptotically corresponds to a radius constant

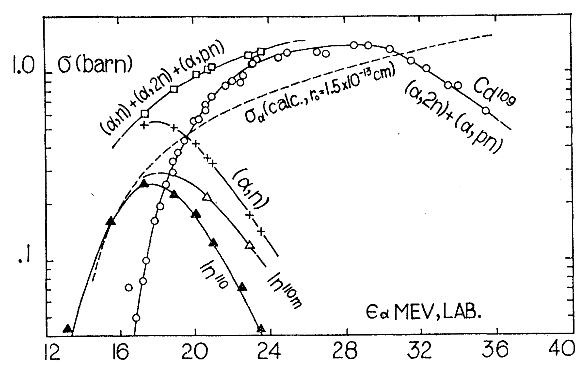

FIG. 3. Comparison of the sum of Ag^{107} cross sections with the theoretical capture cross section. $\triangle=Ag^{107}(\alpha,n)In^{110}$; $\blacktriangle=Ag^{107}(\alpha,n)In^{110m}$; $+=$total (α,n) cross section; $\circ=(\alpha,2n)+(\alpha,pn)$ cross section; $\square=$sum of all cross sections$=$measured capture cross section. The theoretical capture cross section for $r_0=1.5\times10^{-13}$ cm has been drawn as a broken line.

[30] M. Goldhaber and A. W. Sunyar, Phys. **83**, 906 (1951).

[31] Hicks, Gilbert, Stevenson, and Hutchin, Livermore Research Report LRL-65 (unpublished).

of about 1.65×10^{-13} cm. A similar analysis of the sums of the Cu^{63} and Cu^{65} reactions, respectively, yields radius constants near 1.5×10^{-13} cm. Such large radius constants have been found in many recent determinations of nuclear size by means of reactions.[16,32] It may be pointed out that a comparison of the sum of measured reaction cross sections to the continuum-theory capture cross section for a certain radius is not unambiguous if the measured cross sections are only in part due to compound nuclear processes, and in part to other mechanisms. For alpha-particle reactions, any such mechanisms may perhaps be discounted as unimportant in comparison to compound nucleus formation; the theoretical capture cross section corresponding to the sum of measured cross sections then measures the nuclear radius substantially correctly—within the approximation of the hard-sphere model assumed in the theory. This justifies the calculation of charged-particle transmission factors on the basis of large radius constants, in the following section.

The comparison of some of the cross sections with statistical evaporation theory is shown in Figs. 4(a) to 4(d); relative emission probabilities predicted by evaporation theory have been plotted as broken lines, and the experimental cross sections, divided by the capture cross sections so as to represent experimental emission probabilities, as solid lines. Theoretical relative emission probabilities were calculated on the basis of the following: (a) Nuclear barrier transmission was taken from tables[13] with $r_0=1.65\times10^{-13}$ cm for In and Cd and $r_0=1.5\times10^{-13}$ cm for Ga and Zn, assuming that the transmission is independent of excitation energy. (b) Only neutrons, protons, and alpha particles were considered in competition for emission from Ga intermediate nuclei, and only neutrons and protons for In; following proton emission, only neutrons were considered to be emitted. (c) The emission probabilities to an odd-odd and even-even residual nucleus were approximated by the device of intergrating to a limit $(\epsilon_\alpha-T_i+\delta)$ and $(\epsilon_\alpha-T_i-\delta)$ respectively, where ϵ_α is the bombarding energy, T_i the threshold for emission of particle i calculated by the method described in Sec. II, and $\delta=33.5/A^{\frac{3}{4}}$. This amounts to counting odd-odd and even-even level densities from a "reference level" below or above the ground level, respectively, following a suggestion of Meadows[33] based on an argument of Bethe and Hurwitz.[34] For excitations below 25 Mev, the result is roughly the same as when a ratio $\omega_{oo}/\omega_{ee}=4$ is assumed throughout. (d) De-excitation by photon emission was allowed for by shifting the threshold for secondary proton emission upward, 1 Mev for Ga and 2 Mev for In. This considers that if the evaporation of a neutron leaves an intermediate In nucleus, for instance, with an energy less than 2-Mev larger than the separation energy of a secondary proton, the radiation width will be larger than the proton emission width, as a result of the Coulomb barrier. (Neutron emission widths exceed radiation widths within 100 kev above the neutron emission threshold.)

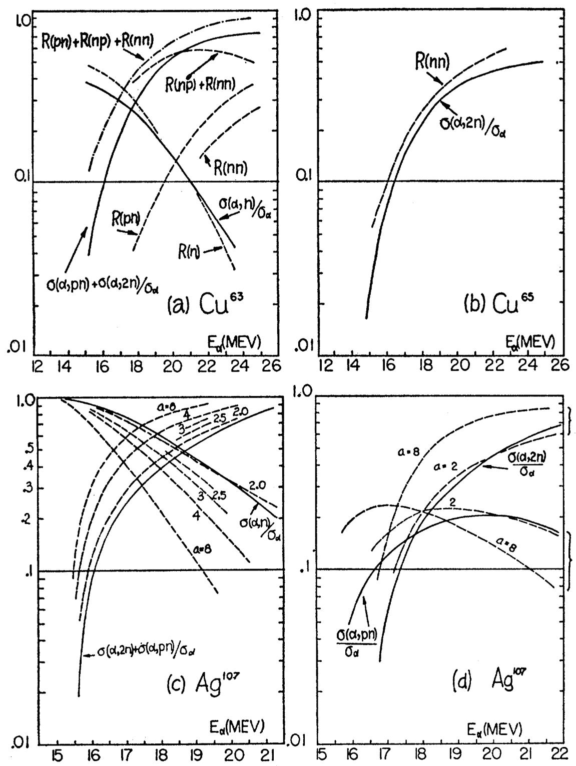

FIG. 4. Theoretical and experimental relative emission probabilities. Solid lines: measured cross sections for the reactions indicated by the labels, divided by the sum of measured cross sections. Broken lines are calculated relative emission probabilities R. In Fig. 4(a), the sequence of emission is as indicated by the labels, e.g., $R(pn)$=proton followed by neutron, etc. The theoretical curves were calculated on the basis $a=2.2$ for Cu; for Ag, curves for different values of a are shown. [a is defined by Eq. (1).]

Under these conditions, theoretical proton emission cross sections are of the same order as the experimental ones, as may be seen from Figs. 4(a) and 4(d). This agreement, in view of the strong dependence of the calculations on some of the assumptions enumerated above, is not claimed to be very meaningful; it merely shows that such theoretical predictions are not necessarily in disagreement with experiment. On the other hand, the logarithmic derivatives of two-particle emission probabilities with respect to bombardment energy may be shown by differentiation to be fairly insensitive to the foregoing assumptions, and roughly proportional to a [this last is seen to be the case in Fig. 4(c)]. Thus, conclusions drawn from comparisons of theoretical and experimental emission probabilities are relatively more meaningful than absolute cross-section comparisons. The most obvious inference of this sort is that the copper measurements are fairly well reproduced by cal-

[32] Millburn, Birnbaum, Crandell, and Schecter, Phys. Rev. **95**, 1268 (1954).
[33] J. W. Meadows, Phys. Rev. **91**, 885 (1953).
[34] H. Hurwitz and H. A. Bethe, Phys. Rev. **81**, 898 (1951).

culations based on $a=2.2$, as recommended by Feld *et al.*,[15] while silver measurements match badly with $a=6.5$ theoretical curves,[15] and even worse with $a\sim 8$[3] curves, but can be reproduced by the choice $a\sim 2$. This compares with the value of Bleuler *et al.* of $a=2.4$, for Ag^{109}, where the (α,pn) cross section was assumed negligible; the inclusion of the latter reaction in the present measurements [Fig. 4(c)] thus shows that this neglect cannot account for the low value of a. In fact, analogous comparisons between theory and two other published $(\alpha,2n)$ cross sections, those of indium[28] and bismuth,[35] also yield values of a of about 2, the latter in even stronger disagreement with Feld *et al.* ($a=12$ for Bi).

In attempting to interpret this result, the suggestion that the excitation functions actually measure Maxwellian level densities with $a\sim 2$ encounters the difficulty that such a value, inserted in Weisskopf's[1] expression for the lifetime of the compound nucleus, yields a life $\tau\sim 10^{-22}$ sec at about 20-Mev excitation, contrary to the Bohr assumption $\tau\gg 10^{-22}$ sec. Evidently then, there is an excess of high-energy emitted particles, which is not significant for copper but increases with A in such a way that the rise of $(\alpha,2n)$ cross sections can be matched anywhere by *assuming* a statistical distribution of emitted particles with unreasonably low parameters a. As a possible cause for high-energy emission, direct interactions at the nuclear surface[36] are not, as already discussed, as plausible in the present situation as with neutron or proton initiated reactions. A review of the assumptions embodied in the calculations enumerated above may thus be profitable.

According to Hill and Wheeler,[37] the assumption (a) that the nuclear barrier transmission is independent of excitation energy may not be valid. An increase of transmission with excitation would, however, tend to increase the emission of low-energy particles, and hence make $(\alpha,2n)$ excitation functions rise even more steeply. Modification of assumption (b) in favor of including the emission of charged particles other than protons in the case of In and Cd compound and intermediate nuclei would change the results only negligibly, as is evident from the fact that the value of a is not increased by including proton emission in comparison with pure neutron emission calculations. A special energy level distribution for odd-odd species, rather than that assumed in (c), is not plausible in view of the adequacy of (c) for interpreting the copper reactions; for the same reason, the reference level formula of Beard[38] does not look very promising. Assumption (d) is based on the best estimates of radiation widths[39] and on measured neutron emission widths; thus a stronger competition of photon with neutron emission, while capable of accounting for the slow increase of $(\alpha,2n)$ excitation functions, would be in disagreement with other experience. It thus appears that the most straightforward explanation would be that surface interactions are important even with alpha particles, or else that the strong interactions compound nucleus picture is not quite adequate as a description of nuclear reactions, especially for heavy nuclei. In a literal and probably unduly naive interpretation of weakened interactions or longer mean free paths, the first nucleon struck by the entering alpha particle would have enough time to escape before the alpha particle could distribute its remaining energy, so that the residual nucleus would be fairly near the ground state. One would expect the chance for such a process to depend, very roughly, on the number of nucleons within a mean free path of the surface, and thus to increase with some power of A. This sort of trivial picture does not, of course, provide anything like an explanation for the present observations. A more quantitative treatment would have to take into account the results of other experiments, such as, for instance, the fact that the angular distribution of neutrons from (α,n) reactions can be approximately reproduced with statistical theory.[40] The energy spectra of particles emitted from nuclei of different masses by alpha excitation and inelastic alpha scattering are at present still mostly unexplored, so that a comprehensive theory must, perhaps, await the collection of more data.

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[35] E. Kelly and E. Segrè, Phys. Rev. **75**, 999 (1949).
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