Nuclear Excitation Functions and Thick-Target Yields: Zn+d and $Ar^{40}(d,\alpha)$†

DAVID C. WILLIAMS* AND JOHN W. IRVINE, JR.
Department of Chemistry and Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts

(Received 21 November 1962)

Radiochemical techniques have been used to determine partial or complete excitation functions to 15 MeV for the reactions $Ar^{40}(d,\alpha)Cl^{38}$, $Zn^{66}(d,\alpha)Cu^{64}$, $Zn^{64}(d,\alpha n)Cu^{61}$, $Zn^{67}(d,\alpha n)Cu^{64}$, $Zn^{64}(d,2p)Cu^{64}$, and $Zn^{67}(d,2p)Cu^{67}$. The results have been compared with the predictions of the statistical model of nuclear reactions. Most features of the (d,α) and $(d,\alpha n)$ excitation functions measured are consistent with the predictions of the model. The $Zn^{67}(d,2p)Cu^{67}$ reaction appears to take place essentially by a direct process, while the $Zn^{64}(d,2p)Cu^{64}$ reaction, which has a much higher cross section, agrees with the model. Support is found for a rather large value of the nuclear radius parameter, $r_0=1.7$ F. Excitation functions are presented for the reactions $Zn^{64}(d,p)Zn^{65}+Zn^{64}(d,n)Ga^{65}(\beta^+)Zn^{65}$, $Zn^{66}(d,n)Ga^{67}$, and $Zn^{66}(d,2n)Ga^{66}$. Thick-target yields from deuteron bombardment of metallic zinc are given for Cu^{61}, Cu^{64}, Cu^{67}, Zn^{65}, Ga^{66}, and Ga^{67}.

EXCITATION functions have been measured for a wide variety of nuclear reactions at moderately low energies in the medium-mass region.[1–3] The majority of these reactions involve emission of at most one unit of charge from the compound nucleus. Reactions involving a higher degree of charged-particle emission usually are inhibited by the Coulomb barrier. Unless other effects (e.g., favorable Q values) compensate, the cross sections predicted for these reactions by the statistical model of nuclear reactions are sometimes very small, and contributions from direct processes may be quite conspicuous.

In the course of the (d,He^3) reaction studies described in the preceding paper,[4] partial or complete excitation functions were obtained by radiochemical techniques for a number of other reactions, including several involving emission of two units of charge from the compound nucleus. These data are discussed in the present paper. The reactions for which significant data were obtained are summarized in Table I.

EXPERIMENTAL

The composition and preparation of the targets, bombardment techniques, chemical procedures, and scintillation counter used in these experiments have been described.[4] Scintillation counter efficiencies for Cu^{64}, Cu^{67}, and Zn^{65} were determined by counting aliquots of standard solutions of these nuclides. The Cu^{64} and Cu^{67} preparations were standardized by 4π beta counting and the Zn^{65} standard was prepared by the National Bureau of Standards. These results gave the detection efficiencies for positron annihilation radiation and for gamma rays of 0.184, 0.51, and 1.114 MeV. Interpolation was used to make a fairly reliable (±15%) estimate of the Cu^{61} counting efficiency and a rough estimate (±30%) of the Ga^{67} and Ga^{66} counting efficiencies. Decay schemes were taken from Nuclear Data Sheets.[5]

RESULTS

$Ar^{40}(d,\alpha)Cl^{38}$

The analysis of the Cl^{38}-Cl^{39} mixture has been described in the previous paper.[4] The $Ar^{40}(d,\alpha)Cl^{38}$ cross section at energies between 10.5 and 15 MeV is plotted in Fig. 1. No data were obtained at lower energies, since the primary purpose of the experiments was the study of the $Ar^{40}(d,He^3)Cl^{39}$ reaction, which was not observable at energies less than 11 MeV.

TABLE I. Deuteron reactions with Ar, Zn, and Cu.

Reaction	Q^a (MeV)	Deut. En. (MeV)	σ(mb)	Estimated error Absolute	Relative
$Ar^{40}(d,He^3)Cl^{39}$	−6.53	14.8	0.37	20%	10%
$Ar^{40}(d,\alpha)Cl^{38}$	+5.54	14.8	11.5	20%	10%
$Zn^{68}(d,He^3)Cu^{67}$	−4.51	15.4	0.54	15%	5%
$Zn^{67}(d,2p)Cu^{67}$	−2.02	15.4	4.7[b]	20%[b]	10%[b]
$Zn^{67}(d,\alpha n)Cu^{64}$	+0.42	15.4	70	40%	large
$Zn^{66}(d,\alpha)Cu^{64}$	+7.33	8.4	36.5	15%	10%
$Zn^{64}(d,2p)Cu^{64}$	−2.02	15.4	61	25%	15%
$Zn^{64}(d,\alpha n)Cu^{61}$	−0.83	15.4	92	25%	5%
$Zn^{64}(d,p)Zn^{65}$	+5.65				
$+Zn^{64}(d,n)Ga^{65}$	+1.61	15.4	390	20%	10%
$Zn^{66}(d,n)Ga^{67}$	+2.90	15.4	195	30%	10%
$Zn^{66}(d,2n)Ga^{66}$	−8.18	15.4	880[c]	40%	10%
$Cu^{63}(d,p)Cu^{64}$	+5.68	15.2	188	15%[d]	1%
$Cu^{65}(d,2n)Zn^{65}$	−4.36	15.2	905	15%[d]	1%

[a] A. H. Wapstra, Physica 21, 385 (1955).
[b] Includes no allowance for possible error due to the $Zn^{70}(d,\alpha n)Cu^{67}$ reaction; the maximum possible effect is a 30% overestimate.
[c] Another determination of this excitation function, which may be more reliable, is given in reference 7.
[d] Largely a reflection of uncertainty in the decay schemes, as given in reference 5.

† This paper is based on a thesis submitted by D. C. W. to the Department of Chemistry in partial fulfillment of the requirements for the Ph.D. degree. The work was supported in part by the U. S. Atomic Energy Commission.
* Present address: Princeton-Pennsylvania Accelerator at Princeton, New Jersey.

[1] C. U. Anders and W. W. Meinke, Document 4999, American Documentation Institute, Washington, D. C. (1956).
[2] N. Jarmie and J. D. Seagrave, Los Alamos Scientific Laboratory Report LA-2014, University of California, Los Alamos, New Mexico, 1957 (unpublished).
[3] D. B. Smith, Los Alamos Scientific Laboratory Report LA-2424, University of California, Los Alamos, New Mexico, 1960 (unpublished).
[4] D. C. Williams and J. W. Irvine, Jr., preceding paper [Phys. Rev. 130, 259 (1963)].
[5] K. Way *et al.*, *Nuclear Data Sheets* (Printing and Publishing Offices, National Academy of Sciences–National Research Council, Washington, D. C., 1960).

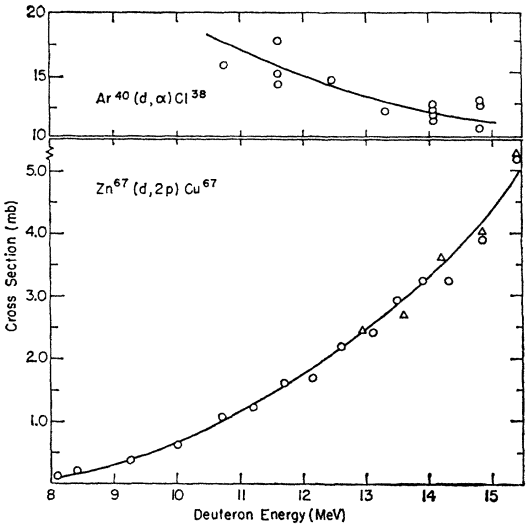

FIG. 1. Excitation functions of the reactions $Ar^{40}(d,\alpha)Cl^{38}$ and $Zn^{67}(d,2p)Cu^{67}$.

$Zn^{67}(d,2p)Cu^{67}$

The $Zn^{68}(d,He^3)Cu^{67}$ and $Zn^{67}(d,2p)Cu^{67}$ reactions were differentiated by varying the isotopic compositions of the zinc targets (see reference 4). The excitation function of the latter reaction is plotted in Fig. 1. It was assumed that the $Zn^{70}(d,\alpha n)Cu^{67}$ reaction is negligible as a source of Cu^{67}, and the reported $Zn^{67}(d,2p)Cu^{67}$ cross sections will be too large if this assumption is incorrect. The experimental data[4] indicate that error from this source is not over 30% except, possibly, for deuteron energies under 9 MeV.

$Zn^{64}(d,\alpha n)Cu^{61}$

This reaction is the only source of Cu^{61} and presents no difficulties. The results are plotted in Fig. 2. The absolute error may be as large as 25%, since the Cu^{61} counting efficiency was only estimated, although fairly reliably.

Reactions Yielding Cu^{64}

Bombardment of zinc with 15.4 MeV deuterons may produce 12.8-h Cu^{64} by the reactions $Zn^{66}(d,\alpha)Cu^{64}$, $Zn^{67}(d,\alpha n)Cu^{64}$, and $Zn^{64}(d,2p)Cu^{64}$. An accurate study of these three excitation functions would require bombardment of enriched samples of the three target isotopes, which was not done here. However, the Zn^{64}:Zn^{66}:Zn^{67} ratios in the enriched Zn^{68} bombarded were different from the corresponding ratios in the natural zinc, and approximate excitation functions could be obtained by comparing the Cu^{64} yields resulting from bombardment of the two different isotopic compositions.

The Cu^{64} yield is proportional to $\sum f_i\sigma_i$, the sum of the cross sections, σ_i, weighted by the corresponding isotopic abundances, f_i. Let subscripts 1, 2, and 3 refer to the reactions $Zn^{66}(d,\alpha)Cu^{64}$, $Zn^{67}(d,\alpha n)Cu^{64}$ and $Zn^{64}(d,2p)Cu^{64}$, respectively. Let primed quantities refer to the enriched Zn^{68} and unprimed quantities refer to zinc of natural isotopic composition. We, then, have

$$\begin{aligned} f_2\sigma_2+f_3\sigma_3&=\sum f_i\sigma_i-f_1\sigma_1,\\ f_2'\sigma_2+f_3'\sigma_3&=\sum f_i'\sigma_i-f_1'\sigma_1. \end{aligned} \quad (1)$$

The experimentally determined quantities are $\sum f_i\sigma_i$ and $\sum f_i'\sigma_i$. If reasonable estimates of σ_1 can be obtained for all energies, these equations can be solved for σ_2 and σ_3.

A consideration of the Q values and Coulomb barriers involved indicates that the cross sections of the reactions $Zn^{64}(d,2p)Cu^{64}$ and $Zn^{67}(d,\alpha n)Cu^{64}$ are small at energies under 9 MeV. The behavior of the $Zn^{67}(d,2p)Cu^{67}$ and $Zn^{64}(d,\alpha n)Cu^{61}$ excitation functions supports this conclusion. Therefore, the reaction $Zn^{66}(d,\alpha)Cu^{64}$ is probably the only important source of Cu^{64} at deuteron energies below 8–9 MeV.

It was assumed that the shape of this excitation function at higher energies is the same as those of the (d,α) reactions $Cr^{50}(d,\alpha)V^{48}$ [6] and $Fe^{54}(d,\alpha)Mn^{52}$,[7] with the positions of the maxima determined by the effective thresholds of the most favored $(d,\alpha x)$ reaction. The "effective threshold" was defined to be the sum of all effective barriers[8] for outgoing charged particles, less the reaction Q value. Unfortunately, the determining factor in the present case is the $(d,\alpha n)$ reaction, while in the case of the comparison reactions, $Cr^{40}(d,\alpha)V^{48}$ and

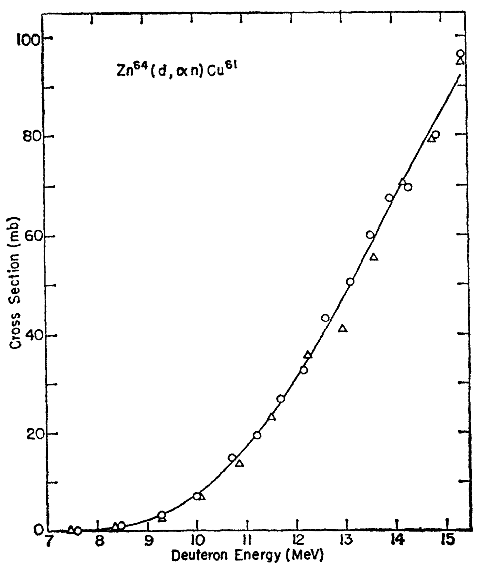

FIG. 2. Excitation function of the $Zn^{64}(d,\alpha n)Cu^{61}$ reaction.

[6] P. Kafalas and J. W. Irvine, Jr., Phys. Rev. **104**, 703 (1956).
[7] N. A. Vlasov, S. P. Kalinin, A. A. Ogloblin, V. M. Pankramov, V. P. Rudakov, I. N. Serikov, and V. A. Sidorov, At. Energ. (U.S.S.R.) 2, 169 (1957).
[8] I. Dostrovsky, Z. Fraenkel, and G. Friedlander, Phys. Rev. **116**, 683 (1959).

$Fe^{54}(d,\alpha)Mn^{52}$, the corresponding $(d,\alpha p)$ reactions are the secondary reactions having the lowest effective thresholds. It is uncertain at just what energy proton emission through the barrier can begin to compete successfully with gamma deexcitation. It was assumed, somewhat arbitrarily, that barrier penetration lowers the $(d,\alpha p)$ effective threshold by 1 MeV.

The Cu^{64} yield data for energies up to 8.4 MeV were plotted on semilog graph paper and the excitation functions of the comparison reactions were plotted on a second sheet. The first sheet was placed on top of the second, with the energy scales adjusted to superpose the $(d,\alpha x)$ effective thresholds and the vertical scales adjusted to give the best fit. The comparison excitation functions were then traced to give an extrapolation of the $Zn^{66}(d,\alpha)Cu^{64}$ excitation function above 8.4 MeV. These results were inserted as σ_1 in (1) and the equations solved for σ_2 at deuteron energies of 15.4 and 14.0 MeV. The $Zn^{64}(d,\alpha n)Cu^{61}$ excitation function was used to extrapolate the $Zn^{67}(d,\alpha n)Cu^{64}$ excitation function to lower energies, after shifting the energy scale to take into account the difference in Q values. Values of σ_2 were also calculated from (1) at lower energies to serve as a check, but these were not used in drawing the excitation curve.

Finally, with σ_2 approximately known, σ_3 is given by the relation

$$\sigma_3 = (\sum f_i\sigma_i - f_1\sigma_1 - f_2\sigma_2)/f_3. \qquad (2)$$

This quantity was evaluated for each experimental value of $\sum f_i\sigma_i$. Since the isotopic abundance of Zn^{67} (4.11%) is less than 10% of that of Zn^{64} (48.89%), moderate error in σ_2 results in very slight error in σ_3.

The quantities $\sum f_i\sigma_i$ and $\sum f_i'\sigma_i$ are plotted in

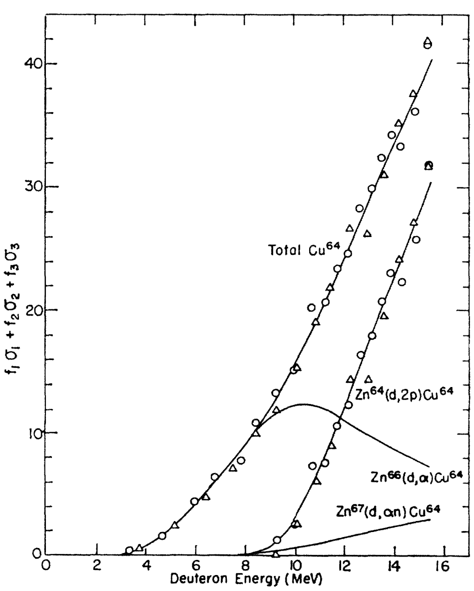

FIG. 3. $\Sigma f_i\sigma_i$ of reactions yielding Cu^{64} upon deuteron bombardment of natural zinc. The contribution of each reaction is also indicated.

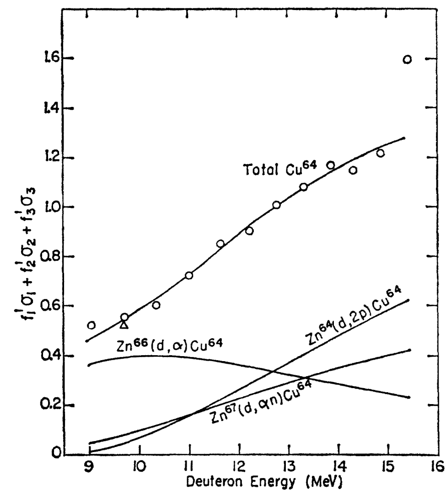

FIG. 4. $\Sigma f_i'\sigma_i$ of reactions yielding Cu^{64} upon deuteron bombardment of the enriched Zn^{68}. The contribution of each reaction is also indicated.

Fig. 3 and Fig. 4, respectively. The estimated Cu^{64} contribution from each reaction is also indicated. The three excitation functions themselves are plotted in Fig. 5.

This analysis is sensitive to error in the f_i', which were not known with high precision. The value of f_3' used here was determined by comparing the Cu^{61} yields obtained from the natural zinc with the yields obtained from the enriched Zn^{68}. Cu^{61} is produced only by the $Zn^{64}(d,\alpha n)Cu^{61}$ reaction, and thus serves as a measure of the Zn^{64} content. Unfortunately, the result, 1.03±0.05%, does not agree well with the value of 1.7±0.05% quoted in the mass analysis supplied with the enriched Zn^{68} by Oak Ridge National Laboratory, which casts some doubt upon the reliability of the other figures quoted in the mass analysis. Out of necessity, the quoted values of the Zn^{66} content (0.9%) and the Zn^{67} content (0.6%) were used here. The Cu^{64} yields at deuteron energies of 9 to 10 MeV should be approximately proportional to the Zn^{66} content, since σ_2 and σ_3 are small at this energy, and the measured Cu^{64} yields are consistent with the quoted value of f_1'.

A consideration of these and other possible sources of error indicated that the uncertainty in the absolute $Zn^{67}(d,\alpha n)Cu^{64}$ excitation function is about 40%. The $Zn^{64}(d,2p)Cu^{64}$ excitation function is much less sensitive to error in the f_i' but is somewhat more sensitive to error in the extrapolated value of σ_1, and its uncertainty is about 25% (larger near threshold). Finally, the $Zn^{66}(d,\alpha)Cu^{64}$ excitation function is as reliable as the experimental yield data (±15%) for energies up to about 8 MeV, but is an extrapolation at higher energies.

Other Reactions

Copper foils were used to monitor the beam intensity in these experiments.[4] The $Cu^{63}(d,p)Cu^{64}$ and

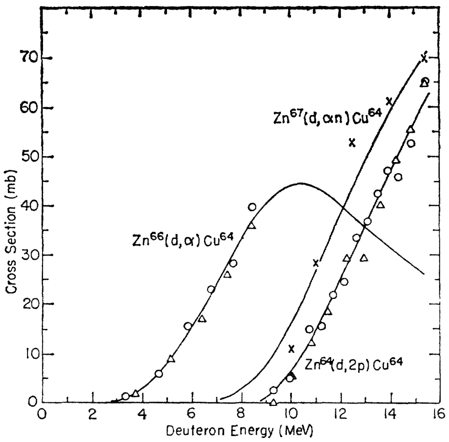

FIG. 5. Excitation functions of the reactions $Zn^{66}(d,\alpha)Cu^{64}$, $Zn^{67}(d,\alpha n)Cu^{64}$, and $Zn^{64}(d,2p)Cu^{64}$. The $Zn^{66}(d,\alpha)Cu^{64}$ curve is an extrapolation above 8.4 MeV. The crosses represent values of the $Zn^{67}(d,\alpha n)Cu^{64}$ cross section determined as described in the text.

$Cu^{65}(d,2n)Zn^{65}$ cross sections at 15.2 MeV were calculated from the measured Cu^{64} and Zn^{65} yields in the monitor foils, and the results are given in Table I.

Following one of the natural zinc bombardments, approximate assays of the Zn^{65}, Ga^{67}, and Ga^{66} yields were made in order to estimate excitation functions for the reactions $Zn^{64}(d,p)Zn^{65}+Zn^{64}(d,n)Ga^{65}(\beta^+)Zn^{65}$, $Zn^{66}(d,n)Ga^{67}$, and $Zn^{66}(d,2n)Ga^{66}$. The results are given in Fig. 6. The $Zn^{66}(d,n)Ga^{67}$ curve has been corrected for the production of Ga^{67} by the reaction $Zn^{67}(d,2n)Ga^{67}$. Production of Ga^{67} by the $Zn^{67}(d,2n)$-Ga^{67} reaction was estimated from the $Cu^{65}(d,2n)Zn^{65}$ cross-section measurements reported here and elsewhere,[9] and this estimate was subtracted from the total Ga^{67} yield in order to obtain the $Zn^{66}(d,n)Ga^{67}$ excitation function.

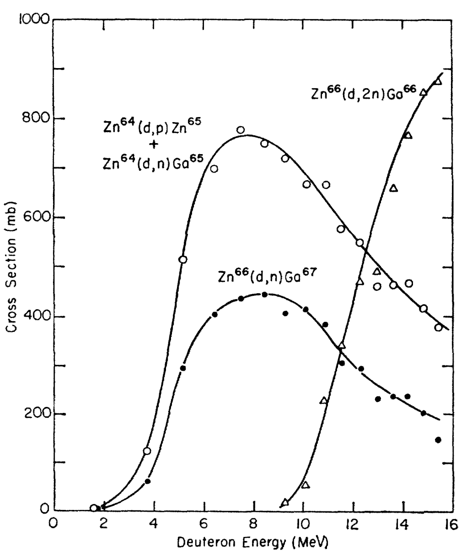

FIG. 6. Excitation functions of the reactions $Zn^{64}(d,p)Zn^{65}$ $+Zn^{64}(d,n)Ga^{65}(\beta^+)Zn^{65}$, $Zn^{66}(d,n)Ga^{67}$, and $Zn^{66}(d,2n)Ga^{66}$.

[9] J. W. Irvine, Jr., J. Chem. Soc. (London) S 356 (1949).

The results of all the cross-section measurements made in the present work, including the (d,He^3) measurements, are summarized in Table I. The absolute errors indicated were estimated from a consideration of all factors affecting the measurement, but this estimate is inevitably somewhat subjective. The uncertainty in the deuteron beam energy is about 0.1 MeV at 15 MeV and about 0.15–0.2 MeV at 10 MeV. This uncertainty increases rapidly with decreasing energy below 5 MeV.

Thick-Target Yields

Thick-target yields were obtained by integrating the thin-target yield vs target depth curves. Thick-target yields of Cu^{61}, Cu^{64}, Cu^{67}, Zn^{65}, Ga^{66}, and Ga^{67} for deuteron bombardment of zinc metal are given in Figs. 7 and 8.

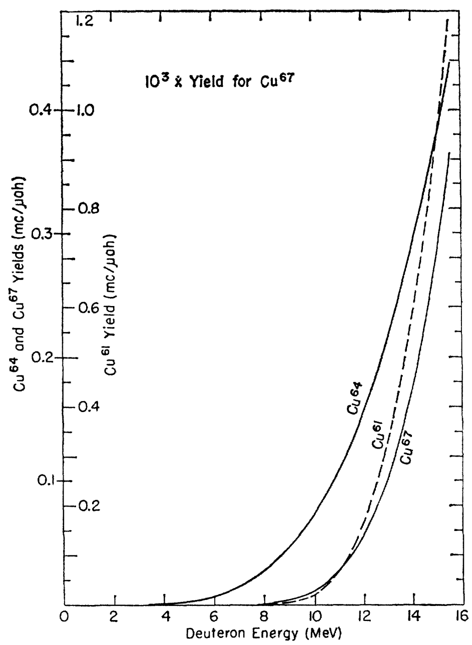

FIG. 7. Thick-target yields of Cu^{61}, Cu^{64}, and Cu^{67} from deuteron bombardment of metallic zinc.

DISCUSSION

Theoretical Calculation of Cross Sections

Statistical model calculations were carried out for the $Ar^{40}(d,\alpha)Cl^{38}$ and $Zn(d,X)Cu$ excitation functions measured here. The approach used was based upon that of Dostrovsky, Fraenkel, and Friedlander,[8] henceforth referred to as DFF.

Excitation functions for (d,α) reactions were calculated using the formulas for the particle emission widths given by DFF. The effect of secondary reactions was allowed for by assuming that the (d,α) product

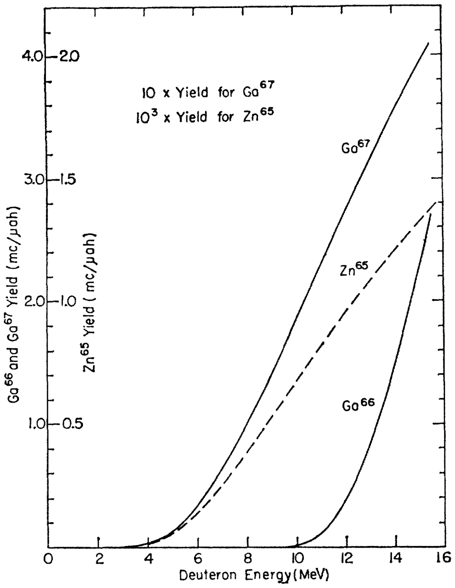

FIG. 8. Thick-target yields of Zn^{65}, Ga^{66}, and Ga^{67} from deuteron bombardment of metallic zinc.

would emit a neutron, and thus be lost, if it possessed sufficient excitation energy to do so.

Excitation functions of reactions involving emission of two particles were calculated using a Monte Carlo program written for the IBM 7090 by Gordon and Rogers.[10] This program is essentially the same as that described by DFF, and uses their formulas for the particle emission widths and spectra. These formulas contain sharp cutoffs, such as "opaque" Coulomb barriers, that make them of little value near thresholds, especially for reactions involving emission of charged particles. The results should, however, have order-of-magnitude significance when at least a few MeV of excitation energy are available to the final product.

Cameron δ's[11] were used in allowing for the effect of pairing energies upon level densities. The level-density parameters assumed were $a=A/10$ in the argon region and $a=A/8$ in the zinc region, in agreement with recent determinations of a from (n,n') scattering data and neutron resonance spacings.[12] Excitation-function shapes usually imply smaller values of the level-density parameter,[8,13] but there is some evidence that this is due to the effects of gamma-ray competition when particle emission is inhibited by high angular momentum barriers.[14]

The nuclear radius parameter r_0 was taken to be 1.7 F. DFF report that, when Cameron δ's are assumed, this value gave considerably better agreement between theory and experiment than did $r_0=1.5$ F. In addition, a number of charged-particle total reaction cross sections[8,13,15,16] at energies near the Coulomb barrier height considerably exceed the total reaction cross sections predicted by continuum theory[17] for $r_0=1.5$ F. This rather large value, 1.7 F, probably results from the diffuseness of the true nuclear potential, which has no sharp cutoff. The effect of a diffuse nuclear surface upon charged-particle barriers may be approximated by a square-well model with a radius somewhat greater than that determined by other types of experiment.[18,19]

The cross section for the formation of the compound nucleus, σ_{cn}, was estimated from continuum theory, using Shapiro's tables[17] with $r_0=1.7$ F. In deuteron reactions, σ_{cn} is reduced considerably by stripping, and there will be a tendency to overestimate the cross sections of reactions that can proceed only through the formation of the compound nucleus.

($d,\alpha n$) Reactions

The experimental and theoretical $(d,\alpha n)$ excitation functions are compared in Fig. 9. Agreement is probably within the limits of the calculation, although the theoretical $Zn^{64}(d,\alpha n)Cu^{61}$ cross section does exceed the experimental by a factor of about 2.5 at 15.4 MeV. Rather small amounts of excitation energy are available to the final product, and the threshold effects mentioned above, including the angular momentum effect, may be relevant to the evaporation of the second particle. The reaction $Zn^{64}(d,\alpha p)Ni^{61}$ is favored by 3 MeV over the

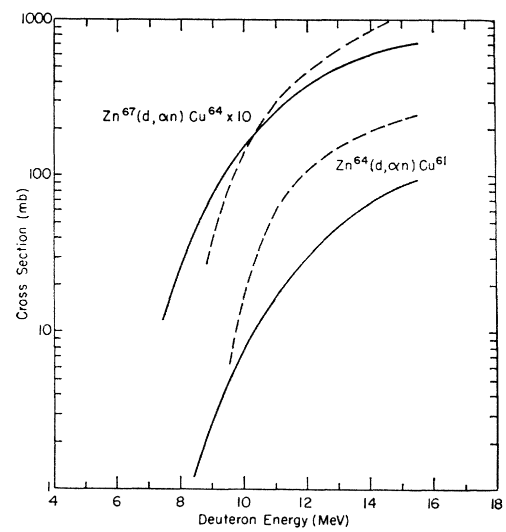

FIG. 9. Comparison of the $Zn^{64}(d,\alpha n)Cu^{61}$ and $Zn^{67}(d,\alpha n)Cu^{64}$ excitation functions with the predictions of the statistical model. Solid curves are experimental and broken curves are theoretical.

[10] G. E. Gordon and P. C. Rogers, Massachusetts Institute of Technology Laboratory for Nuclear Science Progress Report, Nov. 1961 (unpublished).
[11] A. G. W. Cameron, Can. J. Phys. **36**, 1040 (1958).
[12] D. W. Lang, Nucl. Phys. **26**, 434 (1961).
[13] N. T. Porile, Phys. Rev. **115**, 939 (1959).
[14] J. R. Grover, Phys. Rev. **123**, 267 (1961).
[15] F. S. Houck and J. M. Miller, Phys. Rev. **123**, 231 (1961).
[16] B. W. Shore, N. S. Wall, and J. W. Irvine, Jr., Phys. Rev. **123**, 276 (1961).
[17] M. M. Shapiro, Phys. Rev. **90**, 171 (1953).
[18] J. M. C. Scott, Phil. Mag. **45**, 441 (1954).
[19] J. A. Evans, Proc. Phys. Soc. (London) **73**, 33 (1959).

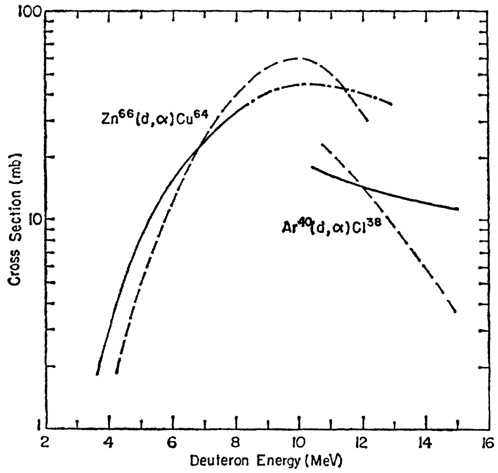

FIG. 10. Comparison of the $Ar^{40}(d,\alpha)Cl^{38}$ and $Zn^{66}(d,\alpha)Cu^{64}$ excitation functions with the predictions of the statistical model. Solid curves are experimental and broken curves are theoretical. The experimental $Zn^{66}(d,\alpha)Cu^{64}$ curve is an extrapolation above 8.4 MeV.

$Zn^{64}(d,\alpha n)Cu^{61}$ reaction, and may compete more effectively than the calculation indicates, since the sharp cutoffs in the formulas used virtually eliminate it.

The $Zn^{64}(d,\alpha n)Cu^{61}$ excitation function exhibits a low-energy tail, easily observable at deuteron energies of 7.5 MeV. This indicates that some of the alpha particles must be emitted with center-of-mass energies considerably less than the classical barrier height (10.5 MeV), since the reaction Q value is -0.83 MeV. A statistical model calculation was carried out for this energy, using the continuum-theory inverse cross sections of Shapiro[17] and performing the necessary integration graphically. The results indicate that barrier tunneling is ample to account for the observed tail, with no need to postulate direct processes.

(d,α) Reactions

The predicted and experimentally observed excitation functions of the reactions $Ar^{40}(d,\alpha)Cl^{38}$ and $Zn^{66}(d,\alpha)$-Cu^{64} are shown in Fig. 10. The experimental curve for the latter is, of course, only an extrapolation above 8.4 MeV.

Theory reproduces the increase of the $Zn^{66}(d,\alpha)Cu^{64}$ cross section with increasing deuteron energy quite well. Differences are probably within the limitations of the calculation.

The $Ar^{40}(d,\alpha)Cl^{38}$ excitation function falls much more slowly with increasing deuteron energy than theory predicts. Indeed, the experimental data (Fig. 1) are consistent with a cross section almost constant with increasing energy above 13 MeV. In part, these differences may be due to the calculation's overestimating the number of alpha emissions that are followed by further particle emission, even if only compound nucleus processes are involved. It is also quite possible that some alpha particles are emitted at high energies in direct processes that leave insufficient energy in the residual nucleus for further particle emission. Mead and Cohen[20] have studied the angular distribution and energy spectrum of alpha particles emitted during 15-MeV deuteron bombardment of a wide range of target nuclides, and found strong evidence that both compound nucleus processes and direct processes contribute significantly.

$(d,2p)$ Reactions

The Monte Carlo program described by DFF was unsuitable for calculation of low cross sections, since excessive computer time would be required to accumulate adequate statistics. A modified form of this program[21] is now available at MIT, in which it is possible to "force" the evaporation chain to proceed along a selected path, such as evaporation of two protons. Only the energies of the emitted particles are selected by a random number process. This modification greatly reduces the statistical uncertainty of the calculation. The same formulas are still used to calculate the relative emission widths for different particles and the spectra of the emitted particles, and the inherent limitations of these formulas remain.

This modified DFF program was used to calculate

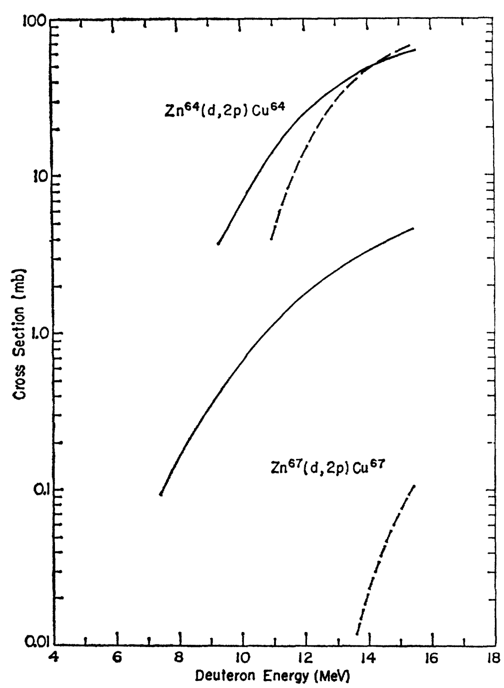

FIG. 11. Comparison of the $Zn^{64}(d,2p)Cu^{64}$ and $Zn^{67}(d,2p)Cu^{67}$ excitation functions with the predictions of the statistical model. Solid curves are experimental and broken curves are theoretical.

[20] J. B. Mead and B. L. Cohen, Phys. Rev. 125, 947 (1962).
[21] P. C. Rogers (private communication, June, 1962).

the theoretical $Zn^{67}(d,2p)Cu^{67}$ excitation function, and the result is compared with experiment in Fig. 11. The experimental cross section exceeds the theoretical by a factor of about 50 at 15.4 MeV. At this energy, excitation energies of a few MeV should be available to the $(d,2p)$ reaction product without requiring a large degree of barrier penetration by the emitted protons. The approximations used in the calculation should be reasonably valid in such a case, and the calculation should be reliable to within an order of magnitude. It appears that compound nucleus processes do not make a significant contribution to the $Zn^{67}(d,2p)Cu^{67}$ reaction.

It is also unlikely that (d,p) stripping followed by evaporation of a proton is important, as stripping events leave less excitation energy in the residual nucleus than do evaporation events. This reduces still further the probability that any second emitted particle will be a proton. It is probable, then, that the $Zn^{67}(d,2p)Cu^{67}$ reaction takes place by a purely direct process. The most obvious possibility is a (d,p) stripping event combined with an (n,p) knock-on process. Zinc has two protons lying outside the $Z=28$ closed shell, and one of these could be ejected relatively simply in such a process.

In contrast, the $Zn^{64}(d,2p)Cu^{64}$ excitation function is reproduced rather well by theory (Fig. 11), even though the measured cross section is over ten times the $Zn^{67}(d,2p)Cu^{67}$ cross section. It is interesting to note that the theory can match experiment only when the large value of the nuclear radius ($r_0=1.7$ F) is assumed. With $r_0=1.5$ F, the theoretical $Zn^{64}(d,2p)Cu^{64}$ cross section was much too small for any reasonable choice of the other parameters. The closest approach was obtained by using $a=A/20$ and the special "adjusted" δ set given by DFF, and even this gave only 25% of the measured cross section.

It could be argued that this reaction does not proceed by a compound nucleus mechanism, and that agreement with theory for $r_0=1.7$ F does not, then, represent evidence for this choice. However, it is difficult to explain this reaction by other mechanisms. A direct process, such as described above, probably contributes to a small degree, but it is very difficult to see why such a process should be over ten times as probable here as in the Zn^{67} case. Level-density considerations, which dominate evaporation processes, are not particularly relevant to the direct interactions. Q values might have some effect, but the Q's of these reactions are nearly identical (Table I). Direct processes are often sensitive to the structural details of the target nucleus, but the most significant structural feature, two protons outside a closed shell, is the same in both cases.

The $Zn^{64}(d,2p)Cu^{64}$ excitation function, then, fits the statistical model for $r_0=1.7$ F, but is very difficult to explain by any mechanism if a smaller value of the nuclear radius parameter, such as 1.5 F, is assumed. These data provide some additional support for the use of the larger value of the nuclear radius parameter to describe charged particle emission.

ACKNOWLEDGMENTS

The authors wish to acknowledge the assistance of Earl White, Frank Fay, and William Carrasco of the MIT Cyclotron staff in carrying out the deuteron bombardments. One of the authors (D. C. W.) wishes to acknowledge the financial assistance of the National Science Foundation.