Absolute Cross Sections and Excitation Functions for (d,p) and $(d,2n)$ Reactions on Mn^{55}, Cu^{63}, Cu^{65}, Zn^{66}, and Zn^{68} Between 3 and 11.6 MeV

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Absolute cross sections and excitation functions for some (d,p) and $(d,2n)$ reactions have been measured by activation and stacked-foil techniques. The cross sections for (d,p) reactions seem to indicate a direct mechanism, although there seems to be some compound nucleus admixture above the Coulomb barrier. A striking result is the great difference (a factor 3.5) between the (d,p) cross sections on the two Cu isotopes. This result is unexplained and requires confirmation. The $(d,2n)$ reaction proceeds via compound-nucleus formation but the theoretical excitation functions, calculated on the basis of compound-nucleus formation followed by evaporation of particles, are not in agreement with the experimental ones. The isomeric ratio of the Zn^{69} isomers is also discussed.

INTRODUCTION

At a time when deuterons are used widely as a tool in nuclear spectroscopy, little is known about the absolute cross sections and excitation functions for the reactions they induce. For this reason, we undertook some measurements, hoping to get some information about reaction mechanisms. The experiments were repeated several times to pursue the consistency of the results.

Deuterons of low and medium energy can give rise to (d,p), (d,n), $(d,2n)$, $(d,2p)$, (d,t), and (d,α) reactions. For the elements studied and in the range of energies available to us (3 to 12 MeV), only the (d,p) and $(d,2n)$ reactions induce appreciable activities. This was shown by following the decay curves in each experiment. The reactions thus observed were

$_{25}Mn^{55}(d,p)_{25}Mn^{56}$	2.58	h
$_{29}Cu^{63}(d,p)_{29}Cu^{64}$	12.8	h
$_{29}Cu^{65}(d,p)_{29}Cu^{66}$	5.1	min
$_{29}Cu^{63}(d,2n)_{29}Zn^{63}$	38.3	min
$_{30}Zn^{68}(d,p)_{30}Zn^{69m}$	13.8	min
$_{30}Zn^{68}(d,p)_{30}Zn^{69}$	57	min
$_{30}Zn^{68}(d,2n)_{31}Ga^{68}$	68	min
$_{30}Zn^{66}(d,2n)_{31}Ga^{66}$	9.45	h.

It must be noted that, because we irradiated natural elements, the cross sections for the various reactions on Cu and the one on Zn are obtained together from the same sample. Consequently, these cross sections all involve the same errors.

The excitation functions were measured by the stacked-foil technique and the absolute cross sections were calculated from the measured induced activities.

IRRADIATIONS

The irradiations were carried out in the extracted beam of the Louvain University cyclotron. The energy of the deuterons was measured by magnetic analysis to be 11.6±0.2 MeV.

The incident beam current was determined by means of a Faraday cup connected to a leakproof capacitor. The voltage across the capacitor was measured and recorded with a precision voltmeter. This voltmeter was calibrated with a known variable voltage and was found to be linear.

The time constant of the apparatus was long compared with the irradiation time. This minimized the error due to possible charge leakage during irradiation. For the same reason, the irradiation time was always kept short with respect to the half-life of the induced activity. This reduced the influence of intensity variations during irradiation. The irradiation time was about 2 min on the average.

For calculation of the cross section, we took only the shortest irradiations (0.5–1.5 min), during which the beam was constant.

TARGET PREPARATION

The targets were prepared by evaporating the natural element onto aluminum backings 2.7 mg/cm² thick and 19 mm in diameter. On the average, the targets were roughly 0.5 mg/cm² thick and 11 mm in diameter. The beam collimator was only 9 mm in diameter to reduce errors in positioning the samples.

Each target was separated from the following one by a 2.7-mg/cm² aluminum degrader. There was, thus, a known weight of aluminum between each pair of targets. This allowed the deuteron energy at the front surface of each target to be calculated accurately from the Berkeley[1] dE/dx curves.

TREATMENT OF THE SAMPLES

It has been experimentally verified that the only activities induced in aluminum were the 2.3-min Al^{28} activity from $Al^{27}(d,p)Al^{28}$ and the 9.45-min Mg^{27} activity from $Al^{27}(d,2p)Mg^{27}$. Thus, there was no

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[1] W. A. Aron, B. G. Hoffman, and F. C. Williams, University of California Radiation Laboratory Report UCRL-121, 1948 (unpublished).

significant activity due to aluminum 2 h after the end of irradiation.

The Mn^{55} samples needed no treatment after irradiation since the half-life of Mn^{56} can be measured after the aluminum activity has decayed.

The irradiated copper targets, which contained Zn^{63} from the $(d,2n)$ reaction and Cu^{64} and Cu^{66} from the (d,p) reactions, were dissolved in a HNO_3 solution containing Cu and Zn as carriers. The zinc and copper were then precipitated as $ZnHg(SCN)_4$ and $CuHg(SCN)_4$, and the precipitate was filtered off and thoroughly washed before counting. The chemical yield was the same for all samples. The above quantities have been chosen to give a minimum amount of precipitate so that the correction for self-absorption is negligible.

The half-lives of the Ga^{66} and Ga^{68} produced by $(d,2n)$ reactions in the zinc targets are roughly equal to those of the Zn^{69m} and Zn^{69} from (d,p) reactions. But fortunately, the beta end-point energies of zinc (1 MeV) and gallium (4 MeV) are very different. The procedure then was to irradiate a stack of target foil with no aluminum degraders between them. The odd-numbered targets were used to measure the zinc activities, the even-numbered ones for the gallium activities. The decay curve verified that the zinc and gallium were completely separated when the zinc was precipitated by the procedure used for the copper targets. The gallium activity was measured with the even-numbered targets covered with a 400 mg/cm² aluminum foil that completely stopped the β rays from the zinc.

EVALUATION OF THE CROSS SECTIONS

The activity in a sample is

$$A = N\sigma\phi(1-e^{-\lambda T}),$$

where A is the activity in disintegrations/min, N is the number of target atoms per cm², σ is the cross section in cm² ($=10^{24}$ b), ϕ is the incident flux in particles/min, λ is the radioactive decay constant in min^{-1}, and T is the length of irradiation in min.

Activities were measured by means of thin-windowed G.M. counters. The latter were calibrated with standard sources of different energies; so geometric arrangement, absorption, and back scattering were taken into account One of the standard sources was a Sr^{90}/Y^{90} source in decay equilibrium. This source, which was prepared and calibrated by the Centre d'Etudes Nucléaires in Mol, gives an equal number of 0.545- and 2.3-MeV beta rays. Another standard source was a Tl^{204} source furnished by the Picker X Rays and Electronics Co. which gives beta rays with a maximum energy of 0.76 MeV.

Activities were corrected for background and counting losses. These corrections were no greater than 10%.

The decay schemes for the reduction of the data were those given by Strominger *et al.*[2] and the *Nuclear Data Sheets*. There do not seem to be any ambiguities in the decay schemes involved here.

The gallium activity, which was attenuated by the aluminum used to stop the zinc betas, was corrected by integrating the beta-ray spectrum of gallium,[3,4] and taking account of the losses in the aluminum absorber. This could lead to some error, but we think it is included in the experimental one.

The activities at time 0 after irradiation were calculated by the integral method.[5] The number of target atoms was calculated from the target weight and was corrected for isotopic abundance and effective target area. The actual area of the target was slightly greater than the beam area to reduce the effect of small errors in the position of the samples.

TABLE I. Comparison between the experimentally measured cross sections and the cross sections calculated for compound-nucleus formation at 11 MeV.

Reactions	Cross section (E_d=11 MeV) (in mb) Experimental	Theoretical
$Mn^{55}(d,p)Mn^{56}$	154±20	26
$Cu^{63}(d,p)Cu^{64}$	210±21	96
$Cu^{63}(d,2n)Zn^{63}$	202±17	690
$Cu^{65}(d,p)Cu^{66}$	726±64	63
$Zn^{66}(d,2n)Ga^{66}$	368±34	600
$Zn^{68}(d,p)Zn^{69}$	506±34	61
$Zn^{68}(d,p)Zn^{69m}$	313±39	61
$Zn^{68}(d,2n)Ga^{68}$	504±39	700

EXPERIMENTAL RESULTS

Each result given here is the average of at least 7 to 10 experiments. The errors are thus experimental ones obtained from the average of the results. Chauvenet's criterion[6] has been applied to discard the too divergent results. Enough counts were accumulated in each case to make the statistical errors smaller than the experimental ones. The experimental points show the average ratio of the activities at different energies to the activity at 11.6 MeV. The experimental points are shown together with theoretical excitation functions. These have been obtained from the probability of compound nucleus formation calculated from the tables of Shapiro.[7] The evaporation of nucleons is then calculated following Blatt and Weisskopf[8] with a nuclear temperature depending on excitation energy and taking account of the pairing effects. The latest data of Erba[9] have been used. Since the absolute theoretical cross sections

[2] D. Strominger, I. M. Hollander, and G. T. Seaborg, Rev. Mod. Phys. **30**, 585 (1958).

[3] L. M. Langer and R. B. Moffat, Phys. Rev. **80**, 651 (1950).

[4] A. Mukerji and P. Preisswerk, Helv. Phys. Acta **23**, 516 (1950).

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[8] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, Inc., New York, 1952), p. 379.

[9] E. Erba, Nuovo Cimento **22**, 1237 (1961).

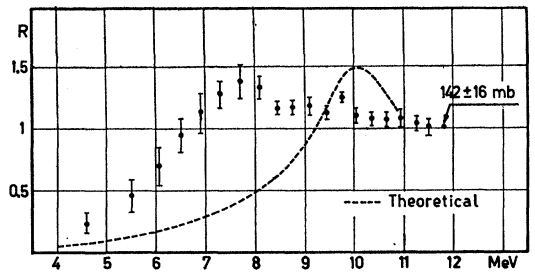

FIG. 1. Excitation function for $_{25}Mn^{55}(d,p)_{25}Mn^{56}$. (Average of 10 runs.) R is the ratio of the activity at a given deuteron energy to the activity at 11.6 MeV. The dashed curve is the theoretical excitation function for compound-nucleus formation, arbitrarily normalized to the experimental one at 11 MeV.

always differ widely from the experimental ones, *the theoretical curve has been arbitrarily normalized to the experimental one at 11 MeV*. The absolute theoretical and experimental cross sections are given in Table I.

One can see that the experimental (d,p) cross sections are always much larger than the theoretical ones. This is not the case for $(d,2n)$ reactions, for which the experimental cross sections are lower than the theoretically expected ones. This suggests that the (d,p) reactions proceed mainly through a stripping mechanism, and the excitation functions confirm this. The low values of the experimental cross sections for $(d,2n)$ reactions might be due to inadequacy in the parameters of the evaporation theory or might result from competition between (d,p) and $(d,2n)$ reactions in the same nuclides.

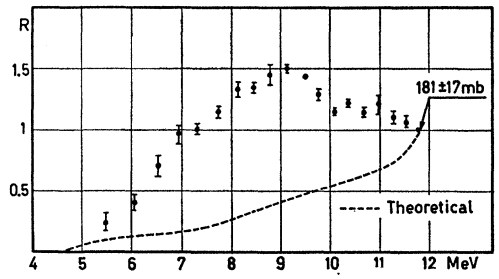

FIG. 2. Excitation function for $Cu^{63}(d,p)Cu^{64}$. (Average of 10 runs.)

$_{25}Mn^{55}(d,p)_{25}Mn^{56}$ and $_{29}Cu^{63}(d,p)_{29}Cu^{64}$

The experimental results are given in Figs. 1 and 2. The experimental excitation function has the shape characteristic of a direct-reaction mechanism because of the slow decrease of the cross section with energy above its maximum.[10] The absolute value for Mn is in reasonably good agreement with the value of 77 mb at 18 MeV given by Cohen.[11] It seems, however, that the decrease after the maximum is too slow to be explained by one reaction mechanism only. Some admixture of compound-nucleus formation above the Coulomb barrier might be possible.

Another fact which points towards a direct-reaction mechanism is that the experimental cross section is an order of magnitude larger than the cross section for compound-nucleus formation.

It must be pointed out that in no case does the experimental excitation function agree with the calculations of Peaslee,[12] which involved rather crude approximations. The result for Cu^{63} is in reasonable agreement with the one obtained previously by Irvine.[13]

$_{29}Cu^{63}(d,2n)_{30}Zn^{63}$

The excitation function in this case (Fig. 3) has the normal shape of a compound-nucleus reaction (thresh-

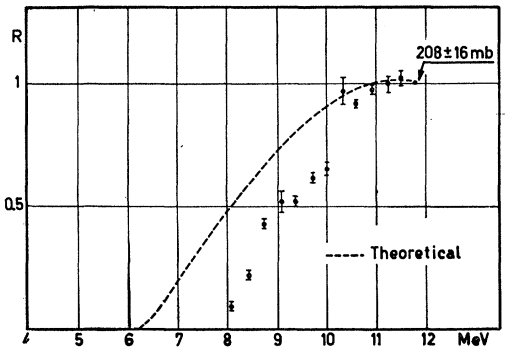

FIG. 3. Excitation function for $Cu^{63}(d,2n)Zn^{63}$. (Average of 10 runs.)

old and fast rise) although the experimental and theoretical excitation functions do not agree very well. The experimental cross section is lower than the theoretical one by a factor of four. This, as has been said, might be ascribed to inadequacy in the parameters of the evaporation theory or to competition from (d,p) reactions. Similar situations have been observed in other

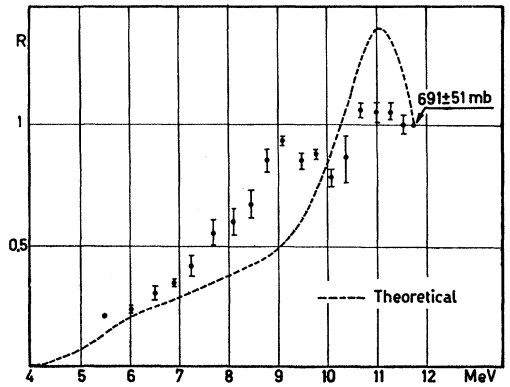

FIG. 4. Excitation function for $Cu^{65}(d,p)Cu^{66}$. (Average of 10 runs.)

[10] M. Gusakov, thesis, Série A, N° Orsay, N° d'ordre 3, Université de Paris, Paris, 1961.
[11] B. L. Cohen (private communication).
[12] R. Peaslee, Phys. Rev. **74**, 1001 (1948).
[13] J. W. Irvine, Jr., J. Am. Chem. Soc. **5**, 356 (1949).

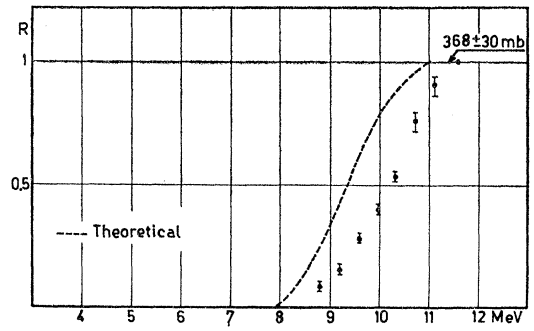

FIG. 5. Excitation function for $Zn^{66}(d,2n)Ga^{66}$. (Average of 7 runs.)

types of reactions.[14] The experimental threshold is in good agreement with the calculated value. The cross section and excitation function are in good agreement with the ones obtained by Irvine.[13]

$$_{29}Cu^{65}(d,p)_{29}Cu^{66}$$

The excitation function (Fig. 4) shows a strong admixture of compound-nucleus formation on the high-energy side. But most of the cross section seems to come from a direct-reaction mechanism.

The striking fact is that the (d,p) cross section on Cu^{65} is three to four times as large as the one on Cu^{63}. This is hard to explain for a stripping mechanism alone

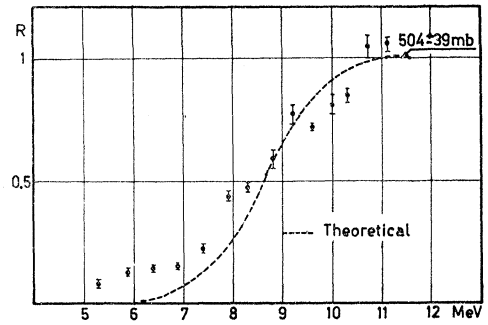

FIG. 6. Excitation function for $Zn^{68}(d,2n)Ga^{68}$. (Average of 7 runs.)

since the angular momenta involved are the same for both isotopes.

In Cu^{63} and Cu^{65}, the levels which are filled by (d,p) reactions are $p_{3/2}$, $f_{5/2}$, $p_{1/2}$, $g_{9/2}$, and higher. Small differences could arise from the facts that the lower levels are differently occupied in the two isotopes and that the highest levels which participate in the (d,p) reaction are differently occupied when the competition from the (d,pn) reaction starts. But these differences can not account for the factor of 3 to 4 between the two cross sections. It has indeed been shown, for instance by Cohen *et al.*,[15] that in other instances the (d,p) cross sections on different isotopes of one element agree well with each other. The only possible explanation is that the compound-nucleus contribution is more important than expected. In any case, this difference between the cross sections of the two isotopes of copper should be further investigated by other methods (for instance, by actual counting of the protons from the reaction).

It is perhaps worth mentioning that Irvine[13] finds that the cross section for the $Cu^{63}(d,2n)Zn^{63}$ reaction (180 mb at 1 MeV) is much smaller than the cross section for the $Cu^{65}(d,2n)Zn^{65}$ reaction (450 mb at 11 MeV). This is found also by Weigold and Glover[16]

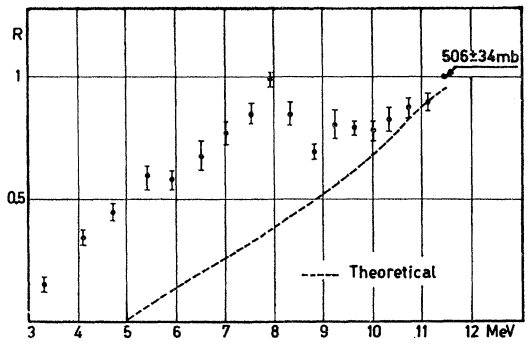

FIG. 7. Excitation function for $Zn^{68}(d,p)Zn^{69}$. (Average of 10 runs.)

for the $(n,2n)$ reaction. Further clarification is needed in this field.

$$_{30}Zn^{66}(d,2n)_{31}Ga^{66}$$

The excitation function (Fig. 5) is again characteristic of a compound-nucleus mechanism. The agreement with the theoretical one is reasonable. The experimental threshold agrees with the one calculated from the masses.[17] This result is in excellent agreement with the one obtained by Irvine.[18]

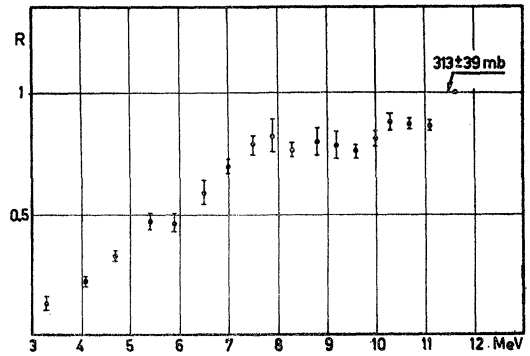

FIG. 8. Excitation function for $Zn^{68}(d,p)Zn^{69m}$. (Average of 10 runs.)

[14] B. L. Cohen and E. Newman, Phys. Rev. **99**, 718 (1955).
[15] B. L. Cohen, R. M. Fulmer, and A. L. McCarthy, Phys. Rev. **126**, 698 (1962).
[16] E. Weigold and R. N. Glover (private communication).
[17] B. S. Dzhelepov and L. K. Peker, *Decay Schemes of Radioactive Nuclei* (Pergamon Press, Inc., New York, 1961).
[18] I. W. Irvine, Jr., and D. C. Williams (private communication).

$_{30}Zn^{68}(d,2n)_{31}Ga^{68}$

The theoretical and experimental excitation functions (Fig. 6) are in better agreement here, but the experimental curve is not perfectly smooth. This irregularity is hard to explain in view of the very high excitation (25 MeV) of the compound nucleus. This could perhaps be due to interferences between different reaction mechanisms. One might also suspect that some activity might come from the (d,n) reaction on Zn^{67}. However, this reaction has no threshold and the $(d,2n)$ reaction has a threshold around 6 MeV. We see experimentally that there is almost no activity below 6 MeV. The contribution from the (d,n) reaction is thus negligible.

$_{30}Zn^{68}(d,p)_{30}Zn^{69}$ and $_{30}Zn^{68}(d,p)_{30}Zn^{69m}$

The excitation functions (Figs. 7 and 8) for both states of the isomeric pair again show a direct mechanism with evident admixture of compound-nucleus formation on the high-energy side. Most of the cross section is due to stripping. The cross section here is much larger than the value of 37 mb at 18 MeV given by Cohen.[19] One could object here that some of the measured 13.8-h activity could be mixed with the 12.8-h activity of $Zn^{66}(d,\alpha)Cu^{64}$. But the cross section measured by Irvine[20] for the (d,α) reaction is only 12 mb at 11 MeV against 320 mb for the (d,p) reaction on Zn^{68}.

Isomeric Ratio $\sigma(Zn^{69})/\sigma(Zn^{69m})$

Two noticeable facts appear from Fig. 9.

(1) The isomeric ratio is greater than unity. This means that the ground state $(I=\frac{1}{2})$ is favored over the metastable state $(I=\frac{9}{2})$. This implies that the spin of the capturing state is closer to that of the ground state than to that of the metastable state.[21] A similar effect had been reported for the isomers of bromine, selenium, and zinc.[22]

(2) The variation of the isomeric ratio with deuteron energy is smooth and slow. This can be indicative of a stripping-reaction mechanism since in many cases the isomeric ratio from (n,γ) reactions shows a fast variation with neutron energy.[20] This is also observed in (p,pn) reactions.[23]

[19] B. L. Cohen (private communication).
[20] J. W. Irvine, Jr. (private communication).
[21] L. Katz, L. Pease, and H. Moody, Can. J. Phys. **30**, 484 (1952).
[22] P. C. Capron and E. Crèvecoeur, XXII Congrès des Industries Chimiques, Bruxelles, 1954; Bull. Acad. Belg. **40**, 1214 (1954).
[23] B. Linder and R. A. James, Phys. Rev. **114**, 322 (1959).

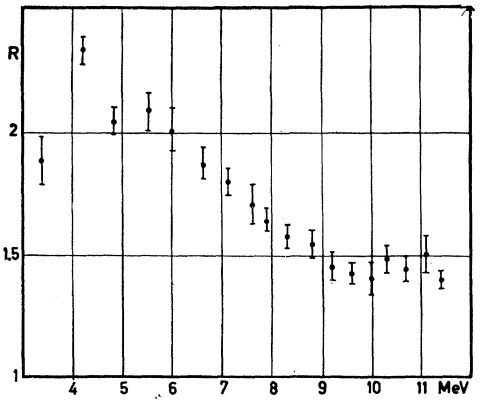

FIG. 9. Isomeric ratio $R=\sigma(Zn^{69})/\sigma(Zn^{69m})$ for $Zn^{68}(d,p)Zn^{69}$.

CONCLUSIONS

The excitation functions for the $(d,2n)$-induced reactions have the normal shape of compound-nucleus reactions. They do not agree very well in shape or in magnitude with the theoretical curves.

The (d,p) excitation functions, which in the case of zinc and copper were obtained simultaneously with the $(d,2n)$ ones, show the predominance of a stripping-reaction mechanism. There seems to be an admixture of compound-nucleus reaction above the Coulomb barrier. That this is not an isolated case can be seen, for instance, in Ref. 24. The big difference between the (d,p) cross sections on Cu^{63} and Cu^{65} cannot be explained by stripping.

The humps seen in some of the (d,p) curves are difficult to explain. They do not appear to result from interfering reactions on different isotopes. We followed the decay curves carefully in each case and never noticed any interference. One should thus proceed further by measuring the angular distributions of the reaction products of incident deuteron energy.

ACKNOWLEDGMENTS

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[24] L. Colli and F. Tonolini, Phys. Letters **3**, 149 (1962).