Excitation Functions of Reactions of 7- to 24-MeV He^3 Ions with Cu^{63} and Cu^{65}†

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Excitation functions of the (He^3,p), (He^3,n), (He^3,$2p$), (He^3,$p2n$), (He^3,$p3n$), (He^3,α), (He^3,αn), and (He^3,2α) reactions on Cu^{63} and the (He^3,n), (He^3,$2n$), (He^3,$p2n$), (He^3,$3n$), and (He^3,αp) reactions on Cu^{65} have been measured at incident He^3 energies from 7 to 24 MeV. It is shown that the He^3 excitation functions are comparable to those of the analogous He^4 reactions. Computed cross sections based on the compound-nucleus evaporation model are in qualitative agreement with observed values for both He^3 and He^4 reactions.

INTRODUCTION

In the relatively short time since accelerated He^3 nuclei became available on a practical basis, experimental work has tended to exploit the new group of charged particle-producing reactions, with emphasis on stripping and pickup reactions and the properties of individual nuclear levels. Another aspect of reactions with He^3 nuclei, deriving from their high binding energy in target nuclei, is the production of highly excited compound states at relatively low bombarding energies. At incident He^3 energies up to about the Coulomb barrier of the target nucleus only a few units of angular momentum are introduced, but the excitation is sufficient for multiple particle boil-off.

With the aim of exploring reactions of He^3 with target elements of intermediate mass, where reaction mechanisms are usually described in terms of a statistical model, we have measured the cross sections for a number of reactions of 7- to 24-MeV He^3 ions with copper. Copper was selected as the target material because it yields a good variety of measurable product nuclei by reactions that can be distinguished radiochemically, and because there now exists a body of excitation-function data for alpha- and proton-induced reactions on nuclei in this mass range.[1–9]

Although the experimental measurements were the primary concern of this work, the data obtained were also compared with excitation functions calculated from a compound nucleus model. The calculations were carried out with a Monte Carlo program, and included trials of several level density formulations.

EXPERIMENTAL PROCEDURES

The excitation functions were measured by the stacked-foil technique, with chemical separation of the radioactive products. The target foils, consisting of 1.00-in.-diam disks cut from 0.00025-in. electrolytic copper, were individually weighed and stacked in a target holder which served as the Faraday cup and were bombarded in the focused external beam of the Los Alamos variable-energy cyclotron. Collimators in the beam tube limited the exposure area to a 0.5-in. circle in the center of the foils.

After bombardment of duration and intensity appropriate to the half-life and cross-section ranges of interest, the foils were dissolved in the presence of carriers of the individual elements. The chemical separation of the elements involved the following basic steps: extraction of gallium into ether, adsorption of zinc on an anion exchange column, precipitation of copper iodide, precipitation of cobalt and nickel hydroxide, precipitation of potassium cobaltinitrite, and precipitation of nickel dimethylglyoxime. Each element of interest in a particular run was then further purified and mounted for counting. The radioactive species measured were Co^{58}, Ni^{63}, Cu^{61}, Cu^{62}, Cu^{64}, Zn^{62}, Zn^{63}, Zn^{65}, Ga^{65}, Ga^{66}, Ga^{67}, and Ga^{68}. In general, the large differences in counting rates and the time required for processing and preparation of the samples did not permit measurement of all the products from any one bombardment. Chemical procedures for copper and gallium could be performed rapidly enough so that isotopes of these two elements were usually measured in the same experiment. Where good data were wanted on the very short-lived products Cu^{62} and Ga^{65}, two or three of the foils in a stack were selected for fast processing. The three long-lived species, Co^{58}, Ni^{63}, and Zn^{65}, were measured in separate experiments, as were the pair Zn^{62} and Zn^{63}. In the latter case, the procedure allowed time for the radiochemical purification needed to insure complete removal of Ga^{66}, which has a half-life almost identical with that of Zn^{62}.

Routine measurements of the samples were performed with beta proportional counters and with a $1\frac{1}{2}$-in.-diam×1-in.-long NaI(Tl) scintillation counter adjusted to detect gamma and x radiation above 30 keV. The decay components of each sample were established from the counting data by an iterative

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[5] N. T. Porile and D. L. Morrison, Phys. Rev. **116**, 1193 (1959).
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[7] N. T. Porile, Phys. Rev. **115**, 939 (1959).
[8] F. S. Houck and J. M. Miller, Phys. Rev. **123**, 231 (1961).
[9] A summary of excitation function data, published and unpublished, up to mid-1959 is given by I. Dostrovsky, Z. Fraenkel, and G. Friedlander, Phys. Rev. **116**, 683 (1959).

TABLE I. Decay-scheme data and the uncertainties in numbers of product atoms.

Nuclide	Half-life	Standardization based on: Radiation	Energy (MeV)	Radiations: Total dis.	Estimated decay scheme uncertainty (%)	Measurement uncertainty (%)
Co^{58}	71 days	γ	0.81	1.01	2	11
Ni^{63}	125 yr	β^-	0.067	1.00	20	30
Cu^{61}	3.32 h	β^+	1.22	0.600	15	4
			0.94	0.055		
			0.56	0.035		
Cu^{62}	9.91 min	β^+	2.92	0.978	2	14
Cu^{64}	12.74 h	β^+	0.66	0.19	5	5
		β^-	0.57	0.39		
Zn^{62}	9.31 h	β^+	0.66	0.16	7	10
			(2.92)	(0.98)		
Zn^{63}	38.7 min	β^+	2.36	0.856	5	5
			1.40	0.065		
			0.50	0.009		
Zn^{65}	245 days	γ	1.12	0.43	7	8
Ga^{65}	15.1 min	β^+	2.24	0.125	5	10
			2.11	0.466		
			1.39	0.154		
			0.82	0.080		
Ga^{66}	9.28 h	β^+	4.15	0.444	10	4
			0.94	0.04		
			0.77	0.01		
			0.38	0.013		
Ga^{67}	78.0 h	γ	0.092	0.398	15	10
			0.090	0.023		
Ga^{68}	66.9 min	β^+	1.89	0.86	5	6
			0.82	0.015		

least-squares technique on an IBM 704 computer. The computer code took into account decay during count intervals and permitted the fixing of arbitrary combinations of decay constants and zero-time activities.

The decay-scheme information used in determining counting efficiencies was assembled mainly from two reference works[10,11] and is summarized in Table I. As is often the case with neutron-deficient nuclei, the fraction of decays occurring by positron emission is not well known for some of the nuclides of interest. Estimates of the uncertainties in the radiations counted are also listed. Detection efficiencies for Co^{58}, Zn^{65}, and Ga^{67} were established by gamma-spectrum analysis with a scintillation spectrometer employing a calibrated $1\frac{1}{2}$-in.-diam$\times 1\frac{1}{2}$-in.-long NaI(Tl) crystal. Detection efficiencies and sample thickness corrections for the remaining nuclides, which were beta counted, were computed by the method of Bayhurst and Prestwood.[12] The computed detection efficiencies for Zn^{65} and Ga^{65} were cross-checked by counting samples prepared from a strong reference solution of Ga^{65}. An apparent 4% difference in the number of mass-65 atoms as derived by the two methods was compromised by arbitrarily lowering the computed detection efficiency of Zn^{65} by 2% and raising that of the Ga^{65} by an equal amount; the data in Table III correspond to the adjusted values. In the last column are listed the estimated uncertainties associated with actual measurement of the radiations. The sum of the decay scheme and measurement uncertainties indicates the accuracy with which the numbers of product atoms are known.

For most of the bombardments, the energies of the He^3 and alpha beams were determined from the range of the particles in 200-μ Ilford C2 emulsions, with energy calibrations taken from Wilkins,[13] and were known to 0.15 MeV. The emulsion plates were exposed to particles scattered out of the beam by a 200-$\mu g/cm^2$ gold foil located near the target. Exposures were usually made before and after each bombardment. In the last He^3 bombardment, at a nominal beam energy of 25 MeV, and in the last alpha bombardment, at 15 MeV, the beam energy was measured also with a solid-state detector system. This system consisted of the detector, its pulse-analyzing equipment, and a Pu^{239} alpha reference source. A set of aluminum slowing foils was used to degrade the energy of the particles scattered out of the beam so as to match the signal of the Pu^{239} source. The energy response of this system was calibrated at the Los Alamos large Van de Graaff accelerator. The beam energies as measured by this system have been found to agree with those derived from the emulsion technique within 0.1 MeV.

The range-energy values used for the aluminum slowing foils and for the target stacks, listed in Table II, were derived from the experimental proton range data of Bichsel *et al.*[14,15] for aluminum and copper, with corrections for proton-alpha differences from the work of Northcliffe *et al.*[16,17] The energy of the particles incident on each foil in a stack was calculated from the beam energy and empirical functions relating range and

TABLE II. Range-energy values used in energy computations.

Alpha energy (MeV)	Range (mg/cm^2) Aluminum	Copper	He^3 energy (MeV)	Range (mg/cm^2) Aluminum	Copper
0	0	0	0	0	0
7.945	12.32	19.17	5.986	9.28	14.44
11.918	22.79	32.88	8.979	17.17	24.77
15.890	36.03	50.12	11.972	27.15	37.76
19.863	51.95	70.60	14.965	39.14	53.19
23.836	70.43	94.16	17.958	53.07	70.94
27.808	91.40	120.67	20.951	68.87	90.92
31.781	114.78	150.17	23.944	86.48	113.14
35.781	140.51	182.45	26.937	105.87	137.46
39.726	168.61	217.51	29.930	127.04	163.88

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

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[13] J. J. Wilkins, U. K. Atomic Energy Research Establishment Report AERE-G/R 664, 1951 (unpublished).

[14] H. Bichsel, R. F. Mozley, and W. A. Aron, Phys. Rev. **105**, 1788 (1957).

[15] H. Bichsel, Phys. Rev. **112**, 1089 (1958).

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[17] P. E. Schambra, A. M. Rauth, and L. C. Northcliffe, Phys. Rev. **120**, 1758 (1960).

TABLE III. Cross sections (in millibarns) for reactions of He^3 with Cu^{63} and Cu^{65}.

He^3 energy Average	(MeV) Span	Target nucleus / Reaction / Product / Reaction Q (MeV)	Cu ($He^3,3n$) +(He^3,n) Ga^{65}	Cu^{63} (He^3,n) Ga^{65} 3.9	Cu^{65} ($He^3,3n$) Ga^{65} −13.9	Cu^{65} ($He^3,2n$) Ga^{66} −4.8	Cu^{65} (He^3,n) Ga^{67} 6.5	Cu^{63} ($He^3,p3n$) Zn^{62} −21.0	Cu^{63} ($He^3,p2n$) +($He^3,3n$) Zn^{63}+Ga^{63} −11.9 −18.0	Cu^{63} (He^3,p) Zn^{65} 8.0	Cu^{65} ($He^3,p2n$) Zn^{65} −9.8	Cu^{63} ($He^3,\alpha n$) Cu^{61} 0.8	Cu^{63} (He^3,α) Cu^{62} 9.7	Cu^{63} ($He^3,2p$) Cu^{64} 0.2	Cu^{63} ($He^3,2\alpha$) Co^{58} 4.3	Cu^{65} ($He^3,\alpha p$) Ni^{63} 3.5
6.7	2.3		...	...	...	1.0	...	...	...	...	...	0.03	...	0.41	...	...
7.0	2.2		...	...	...	...	...	...	...	4.63	...	...	...	...	...	...
8.4	2.1		...	...	...	18.9	4.70	...	...	...	...	1.56	...	4.75	...	...
8.7	2.1		2.5	3.6	...	21.3	5.20	...	...	...	...	1.46	5.44	5.04	...	...
9.3	1.9		...	...	...	...	...	...	0.019	...	...	...	...	...	...	...
9.5	1.8		...	...	...	...	...	...	...	25.0	...	...	...	...	...	...
10.3	1.7		...	...	...	...	...	...	...	...	...	9.70	...	16.8	...	...
10.8	1.7		5.8	8.4	...	121	12.0	...	0.258	...	...	14.0	10.6	26.1	...	...
10.9	1.7		5.9	8.5	...	117	12.2	...	...	...	...	11.9	13.1	25.9	...	...
11.0	1.7		5.3	7.7	...	115	12.4	...	...	...	...	12.4	...	23.1	...	...
11.1	1.7		...	...	...	...	...	...	0.390	...	...	...	...	...	...	...
11.2	1.7		...	...	...	...	...	...	...	40.7	...	...	...	...	...	...
11.7	1.6		...	...	...	...	...	...	...	...	...	...	...	...	...	2.0
11.9	1.6		...	...	...	171	12.5	...	...	...	...	23.4	...	40.4	...	...
12.7	1.4		6.4	9.3	...	...	...	...	0.75	...	...	30.0	19.0	46.3	...	...
12.8	1.5		...	...	...	...	...	...	...	41.6	6	...	...	...	...	...
13.2	1.5		...	...	...	...	...	...	...	...	...	...	...	...	...	3.4
13.4	1.4		...	...	...	233	11.8	...	...	...	...	41.7	...	62.6	...	...
13.8	1.4		...	...	...	...	...	...	2.17	...	...	...	...	...	...	...
13.9	1.2		...	...	...	...	...	...	...	38.3	...	...	...	66.0	...	...
14.6	1.3		...	...	...	...	...	...	...	...	...	...	...	...	...	3.9
14.8	1.3		...	...	...	268	10.3	...	...	...	...	54.3	...	76.1	...	...
16.1	1.2		...	...	...	281	9.50	...	...	...	...	69.4	...	93.9	...	...
16.3	1.3		5.5	6.8	2.6	284	...	...	...	32.9	110	67.1	17.0	89.0	3.01	4.9
16.5	1.3		...	...	...	...	...	0.008	13.1	...	...	...	...	...	...	...
17.3	1.2		...	...	...	265	8.46	...	...	...	...	73.8	...	101	...	...
18.7	1.2		...	...	...	...	...	...	...	26.8	285	...	...	...	4.67	...
18.8	1.2		9.0	5.9	16	242	...	...	...	...	...	76.1	20.6	114	...	...
19.0	1.2		...	...	...	...	...	0.05	51.1	...	...	...	...	...	...	8.8
19.2	1.1		...	...	...	...	...	...	...	25.6	...	...	...	114	...	...
19.6	1.1		...	...	...	209	7.00	...	...	...	...	82.2	...	129	...	...
19.9	1.1		...	...	...	...	...	...	...	24.5	380	...	...	...	5.24	10.1
20.3	1.1		12.4	5.4	28	217	...	...	...	...	...	80.2	30.2	114	...	...
21.2	1.1		...	...	...	...	...	0.19	119	...	...	...	...	...	...	12.2
21.4	1.0		17.9	5.0	47	191	...	...	...	...	...	77.2	...	117	...	...
21.7	1.0		...	...	...	168	6.44	...	...	...	...	77.4	...	126	...	...
22.1	1.0		...	...	...	...	...	...	...	22.9	536	...	...	...	6.65	11.4
22.2	1.0		...	...	...	...	...	...	...	...	...	...	...	...	...	11.7
22.4	1.0		23.4	4.7	65	156	...	...	...	...	...	73.7	42.7	118	...	...
23.4	1.0		...	...	...	...	...	0.39	189	...	...	...	...	...	...	...
23.6	1.0		23.9	4.2	67	...	...	...	...	...	...	69.3	35.3	122	...	...
23.7	1.0		...	...	...	118	5.29	...	...	...	...	...	...	119	...	...
24.1	1.0		...	...	...	...	...	...	...	19.1	690	67.5	...	...	6.48	13.8
24.6	0.8		...	...	...	...	...	...	...	18.5	...	...	...	117	...	...

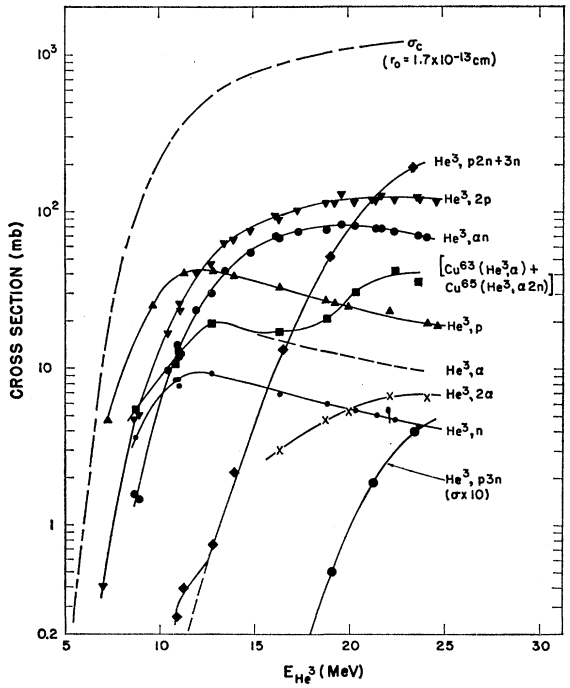

FIG. 1. Excitation functions for reactions of He^3 with Cu^{63}. The portion of the (He^3,α) curve above 15 MeV is an estimate. The dash-dot curve is the total reaction cross section based on the calculations of Shapiro, with the interaction distance taken as $(1.7A^{1/3}+1.21)\times10^{-13}$ cm.

energy for each material encountered. In general, the functions used were eighth-degree polynomials fitted to the data in Table II, and the computations were performed on an IBM 704 computer.

The intensity and integrated current of the He^3 and He^4 beams were measured and recorded by standard techniques.[18] Error in integrated current was estimated to be 1%.

EXPERIMENTAL RESULTS

Ten He^3 bombardments were performed with stacks of natural copper foils, at nominal beam energy settings of 12, 15, and 24 MeV. In addition, two 25-MeV bombardments were carried out on stacks containing enriched Cu^{63} foils[19]; in the first, the Cu^{63} foils were spaced at positions intended to correspond to energies of about 24, 19, and 14 MeV, and in the second the nominal energy positions were 24 and 16 MeV. Seven of the stacks contained single aluminum foils for measurement of recoil losses.

The cross-section data are summarized in Table III. Beam energy at each foil is described in terms of the average of incident and exit energies; the difference is listed as energy span. The reactions are listed according to standard usage, in terms of neutrons, protons, and alphas as the light reaction products and without specification as to the order of emission. The Q values were computed from the table of mass data of König *et al.*[20] and apply to the reactions as written. Five of the heavy reaction products measured, Ni^{63}, Cu^{62}, Cu^{64}, Zn^{65}, and Ga^{65}, could have been produced in significant amounts from both Cu^{63} and Cu^{65}. The contributions of the Cu^{63} reactions to the Ni^{63}, Cu^{64}, and Zn^{65} were established experimentally from the bombardment of the enriched Cu^{63} foils. The excitation function for the production of Ga^{65} was estimated by assigning the entire reaction cross section at low energies to Cu^{63}(He^3,n)Ga^{65} and then extrapolating to high energies with an energy dependence derived from the Cu^{65}(He^3,n)Ga^{67} excitation function, which was unambiguous. At He^3 energies up to about 15 MeV, the Cu^{62} may be assigned to the (He^3,α) reaction on Cu^{63}; at higher energies, the (He^3,$\alpha 2n$) reaction on Cu^{65} is probably a strong contributor, but for convenience in listing the entire excitation function is reported in Table III as the reaction on Cu^{63}. The measured Zn^{63} included that part produced via Cu^{63}(He^3,$3n$)Ga^{63} and subsequent decay of the Ga^{63}; from consideration of the high reaction threshold ($\approx$19 MeV) and of the corresponding excitation function for Cu^{65}, this contribution is believed to

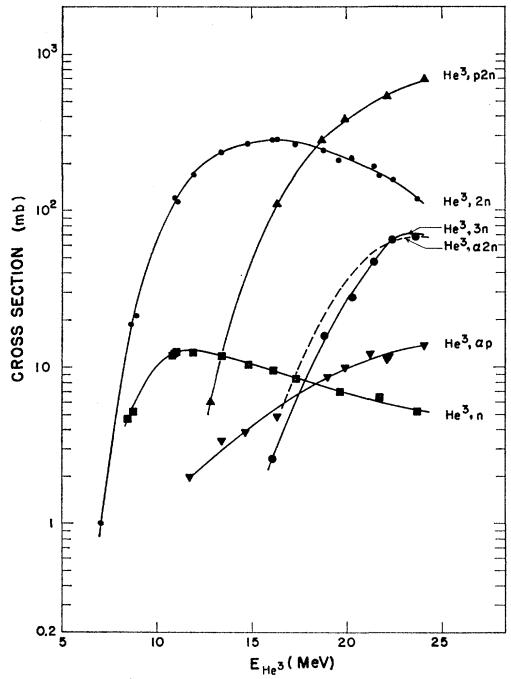

FIG. 2. Excitation functions for reactions of He^3 with Cu^{65}. The dashed (He^3,$\alpha 2n$) curve represents the difference between the estimated (He^3,α) curve of Fig. 1 and the total observed cross section for production of Cu^{62}, corrected to correspond to the isotopic abundance of Cu^{65}.

[18] R. J. Helmer and A. Hemmendinger, Rev. Sci. Instr. **28**, 649 (1957).

[19] This material, enriched to 99.87% in Cu^{63}, was obtained from Union Carbide Nuclear Company, Oak Ridge, Tennessee.

[20] L. A. König, J. H. E. Mattauch, and A. H. Wapstra, Nucl. Phys. **31**, 18 (1962).

TABLE IV. Cross sections (in mb) for reactions of He^4 with Cu^{63} and Cu^{65}.

He^4 energy (MeV) Average	Span	Target nucleus / Reaction / Product / Threshold (MeV)	Cu^{63} (α,n) Ga^{66} 8.0	Cu^{65} $(\alpha,2n)$ Ga^{67} 15.0	Cu^{65} (α,n) Ga^{68} 6.2
7.8	2.5		17		38
10.2	2.2		189		269
11.0	2.0		293		407
11.3	2.0		332	1.84	450
12.2	1.9		428		557
12.5	1.8			2.38	
12.9	1.8		501		652
14.0	1.7		589		735
14.6	1.7			15.1	
15.0	1.7		644	12.1	820
16.1	1.5			34.4	
16.2	1.5		698	88.4	882
17.6	1.5		637	175	
17.7	1.5			222	
18.0	1.4		623	237	726
19.0	1.4			309	
19.2	1.4		568	363	669
20.4	1.3		448	507	
20.7	1.3		407	557	456
21.7	1.3			675	
22.9	1.3		263	820	248
23.0	1.3		252	789	251
23.3	1.2		225	801	231
24.2	1.2			902	
25.3	1.2		135	952	130
25.6	1.1		121	920	122
26.4	1.1			973	
26.5	1.1			967	

be less than 10% of the total Zn^{63} production even at 24 MeV.

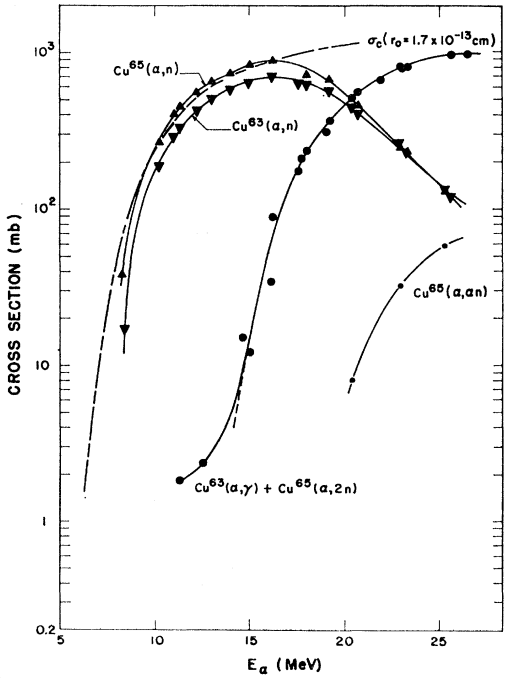

FIG. 3. Excitation functions for the reactions of alpha particles with copper. The dash-dot curve is the total reaction cross section based on the calculations of Shapiro, with the interaction distance taken as $(1.7A^{1/3}+1.21)\times10^{-13}$ cm.

The cross-section data for He^3 on Cu^{63} and Cu^{65} are plotted in Figs. 1 and 2. The cross-section points in Fig. 1 indicating the production of Cu^{62} appear to represent the sum of at least two reactions. The excitation function for the (He^3,α) reaction on Cu^{63}, which should be responsible for all the Cu^{62} production below about 15 MeV, was extrapolated to higher energies with an energy dependence similar to those for the (He^3,p) and (He^3,n) reactions; the remaining Cu^{62} in the region of extrapolation was attributed to the $(He^3,\alpha 2n)$ reaction on Cu^{65} and appears as the dashed curve in Fig. 2.

Since average energies are not appropriate when the cross section does not vary linearly with depth in a foil, the plotted energy values in Figs. 1 and 2 have been adjusted to approximate the centroids of the activity of interest. Another effect, the net downstream recoil movement of the heavy reaction products, tends to

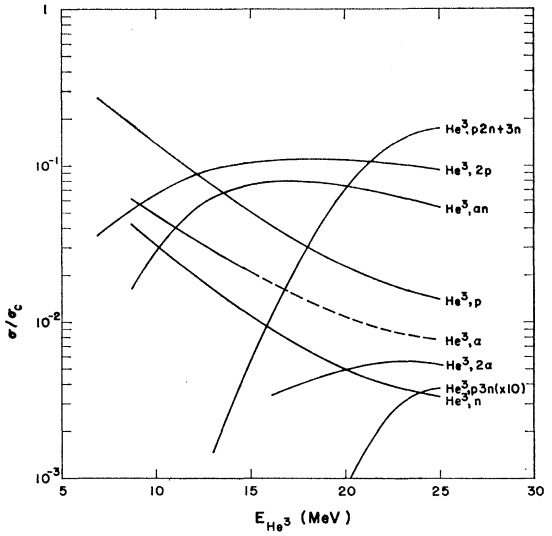

FIG. 4. Excitation functions for the reactions of He^3 with Cu^{63}, expressed as fractions of the total reaction cross section.

displace the excitation function curves toward lower energies. Since the magnitude of the effect lay well within the uncertainty of the energies, corrections for recoil effects (about 1% at 10 MeV, 3% at 24 MeV) were limited to the first copper foil and to the copper foil immediately following an aluminum foil in a stack. For such foils there is no influx of recoil products to compensate for recoil losses. In general, the data points from bombardments with the 12-MeV beam agreed with the low-energy points from the 24-MeV bombardments, and should have uncertainties no greater than 0.25 MeV.

In the course of this investigation it appeared appropriate to repeat the measurement of some of the previously reported excitation functions for He^4 reactions on copper. Our results are summarized in Table IV and Fig. 3. The plotted energy values have been

corrected to activity centroids as above. In this case also, the data from the high-energy bombardments agreed with those from the 15-MeV bombardment, and the energy uncertainties should be no greater than 0.25 MeV. These excitation functions show generally good agreement in shape with the excitation functions reported by Porile and Morrison,[5] but differ significantly in energy scale. The fact that the latter excitation functions appear to lie 2 to 3 MeV higher in energy than ours may be due, in part, to the use of a different range-energy relation.

The binding energies of He^3 in Ga^{66} and Ga^{68} are 13.1 and 14.7 MeV, and thus even at He^3 energies where Coulomb barrier penetration is very small a wide variety of reactions is energetically possible. Because the thresholds for comparable He^4 reactions are of the

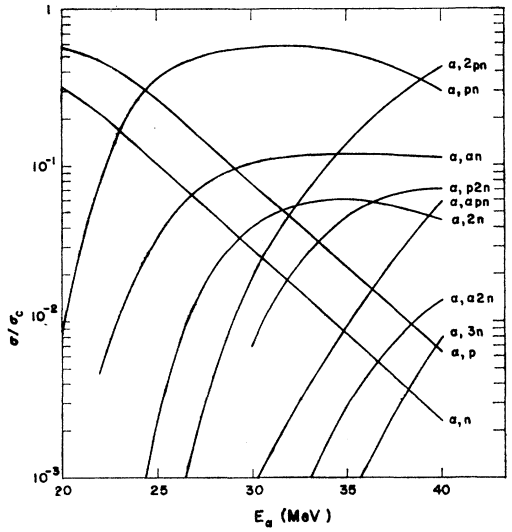

FIG. 5. Excitation functions for the reactions of alpha particles with Zn^{64}, expressed as fractions of the total reaction cross section based on $r_0=1.6\times10^{-13}$ cm. Data taken from Porile (reference 7).

order of 10 to 15 MeV higher, He^3 and He^4 excitation functions are best compared when individual cross sections are expressed as fractions of total reaction cross sections. The total reaction cross sections, σ_c, indicated in Figs. 1 and 3, are based on the compound-nucleus cross sections calculated by Shapiro,[21] with the interaction distance for both He^3 and He^4 reactions taken to be $(1.7A^{1/3}+1.21)\times10^{-13}$ cm. The choice of 1.7×10^{-13} cm as the r_0, though somewhat larger than commonly used, was necessary to fit our data for the $Cu^{65}(\alpha,n)Ga^{68}$ reaction, and is more nearly in accord with the optical-model calculations by Igo.[22] It is of interest that the larger r_0 value has been used by Tanaka[1] and by Houck and Miller[8] to fit their data for alpha reactions on isotopes of nickel and iron.

Figure 4 shows the measured excitation functions for

[21] M. M. Shapiro, Phys. Rev. **90**, 171 (1953).
[22] G. Igo, Phys. Rev. **115**, 1665 (1959).

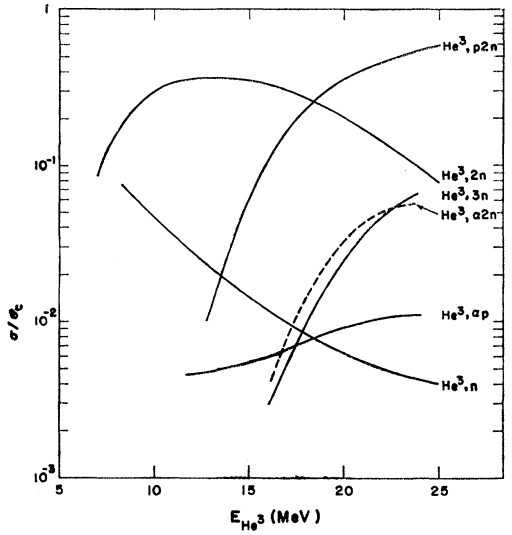

FIG. 6. Excitation functions for the reactions of He^3 with Cu^{65}, expressed as fractions of the total reaction cross section.

He^3 on Cu^{63} with cross sections represented as fractions of the calculated total reaction cross section, and Fig. 5 shows the excitation functions, similarly represented, from the data of Porile[7] for He^4 on Zn^{64}. In the latter, Porile's choice of total reaction cross section (based on $r_0=1.6\times10^{-13}$ cm) has been retained; in the high-energy portion of the alpha-reaction data, to which the comparison has been applied, the shapes of the curves are relatively insensitive to the choice of r_0. The measured He^3 and He^4 excitation functions for reactions which yield the same light products, i.e., n, p, αn, and $p2n$, are seen to be similar in shape and magnitude.

The excitation functions for the reactions of He^3 with Cu^{65} are plotted in terms of fractions of calculated total cross section in Fig. 6. As expected from the difference in balance of proton and neutron binding energies, the (He^3,n) and $He^3,p2n)$ reaction cross sections are larger for Cu^{65} than for Cu^{63}.

Although the lower binding energy of the nucleons in He^3 should be reflected in an increased probability for stripping reactions, relative to He^4, this difference does not show up conspicuously in the excitation functions measured. In particular, the cross-section curve for the $(He^3,2p)$ reaction on Cu^{63} bears a close resemblance to that estimated by Porile[7] for the $(\alpha,2p)$ reaction on Zn^{64}, when plotted in terms of fraction of total reaction

TABLE V. Inverse cross-section parameters for Zn^{65}.

Particle	A_j (b)	B_j (MeV^{-1})	ϵ_0 (MeV)	F_j (b)	ϵ_j (MeV)
H^1	0.985	0.045	2.05	1.615	4.21
H^2	1.23	0.055	2.31	2.31	4.55
H^3	1.17	0.065	2.70	2.22	4.60
He^3	0.99	0.0235	5.95	2.28	9.64
He^4	0.98	0.0235	6.28	2.23	9.80

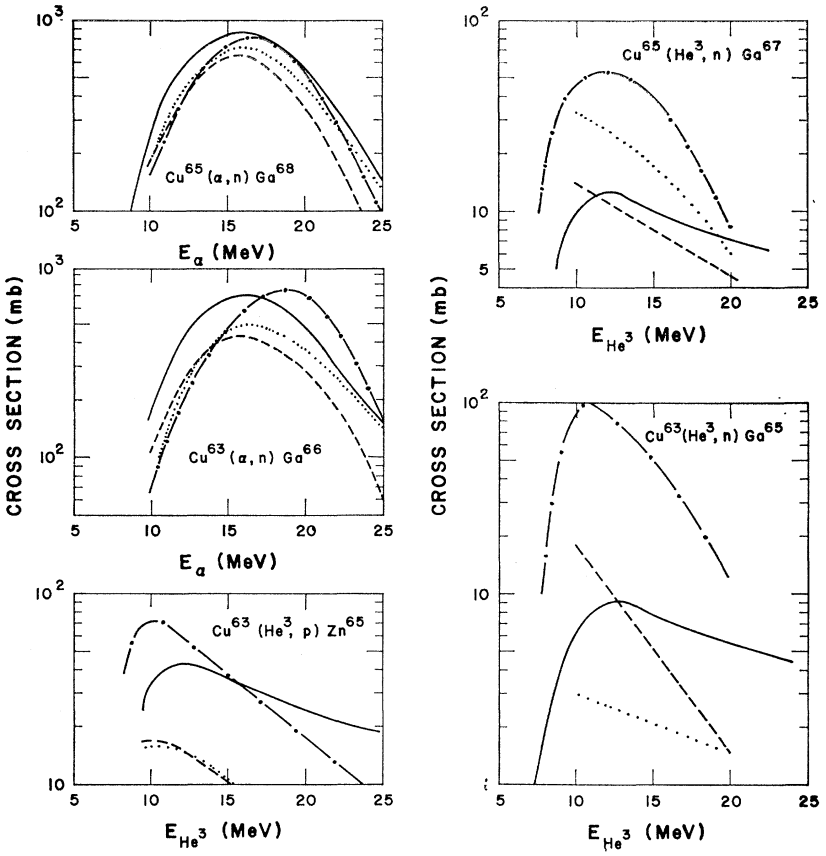

FIG. 7. Excitation functions for emission of a single nucleon. Solid curves: experimental. Dotted curves: calculated, level density expression (3a). Dashed curves: calculated, level density expression (3b). Dash-dot curves: calculated, level density expression (3c).

cross section. Direct evidence that $(\alpha,2p)$ reactions with target nuclei in this mass region proceed via compound-nucleus formation has been reported by Bodansky *et al.*,[23] who measured the proton-proton angular correlation for the reaction $Ni^{58}(\alpha,2p)Ni^{60}$ at an alpha energy of 32 MeV.

COMPOUND-NUCLEUS CALCULATIONS

Evaporation-model computations were undertaken to provide a basis for recognition of possible direct interaction contributions to the reaction cross sections of 10- to 25-MeV He^3 particles with copper nuclei. The objective was to choose a set of parameters to give a fit to the excitation function data for He^4 reactions with copper nuclei and then to apply the same parameters to the computation of the He^3 excitation functions.

The computations were made with a Monte Carlo program and were based on Weisskopf's expression[24] for the probability per unit time of emission of particle j with kinetic energy between ϵ and $\epsilon+d\epsilon$:

$$P_j(\epsilon)d\epsilon = (\text{constant})M(2I+1)\sigma\epsilon(W_f/W_i)d\epsilon. \quad (1)$$

In this expression, M and I are the mass and spin of particle j, σ is the cross section for the inverse reaction, and W_i and W_f are the level densities of the initial and final nuclei at their respective excitation energies. Since only relative probabilities for emission of the particles were required, the formula was simplified by dropping the constant and W_i terms. The states of the nuclei were specified in terms of excitation energy only; angular momentum effects were neglected.

Values of σ for neutrons were taken from Dostrovsky *et al.*,[9] who give the expressions

$$\sigma=\pi R^2\alpha(1+\beta/\epsilon),$$
$$\alpha=0.76+1.93A^{-1/3},$$
$$\beta=(1.66A^{-2/3}-0.050)/\alpha,$$

for

$$R=1.7\times10^{-13}\,A^{1/3}\text{ cm}.$$

Values of σ for charged particles were expressed by empirical functions of the form

$$\sigma_j=A_j\{1-\exp[-B_j(\epsilon-\epsilon_0)^2]\} \quad (2a)$$

for proton, deuteron, or triton energies below 10 MeV and for He^3 or alpha energies below 15 MeV, and by

$$\sigma_j=F_j(1-\epsilon_j/\epsilon), \quad (2b)$$

[23] D. Bodansky, R. K. Cole, W. G. Cross, C. R. Gruhn, and I. Halpern, Phys. Rev. **126**, 1082 (1962).
[24] V. F. Weisskopf, Phys. Rev. **52**, 295 (1937).

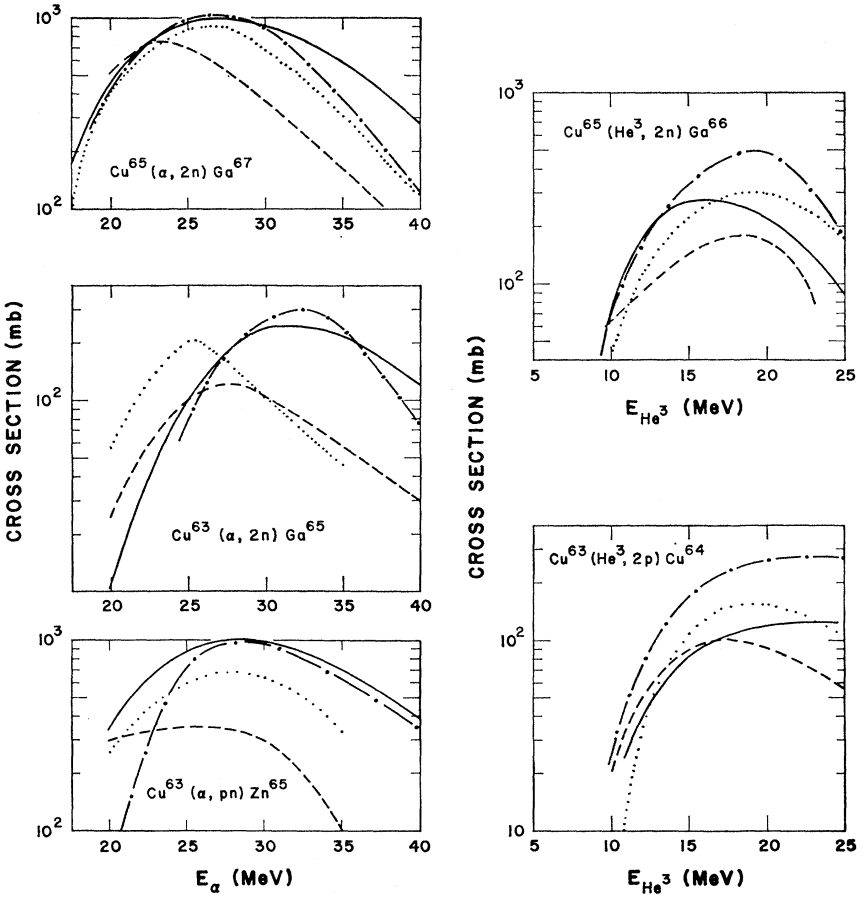

FIG. 8. Excitation functions for emission of two nucleons. Curve designations as in Fig. 7.

for higher energies. With proper choice of parameters, these functions were found to give good fits to the compound-nucleus formation cross sections calculated for $r_0=1.7\times10^{-13}$ cm from the tables of Shapiro.[21] As an illustration of the application of expressions (2a) and (2b), the parameters used for Zn^{65} are listed in Table V.

Three different expressions were tried for the level density of the product nuclei, W_f:

$$W_f=\exp[2(a_1E^*)^{1/2}], \tag{3a}$$

$$W_f=K_{N,Z}(E^*+3T/2)^{-2}\exp[2(a_2E^*)^{1/2}], \tag{3b}$$

$$W_f=A^{-2}(E^*+T)^{-2}\exp[2(a_3E^*)^{1/2}]. \tag{3c}$$

In these three expressions, E^* is the excitation energy above a reference state ($\delta_{N,Z}$ above the real ground state) of the nucleus, and a is the "level density parameter." The meaning of a_1 differs from the meaning of a_2 and a_3 in the sense that if the logarithmic derivative dW_f/W_fdE^* is to be the same for the three expressions, then a_1 must be about half as large as a_2 or a_3. Expression (3a) has been widely used in previous calculations of excitation functions (see, for example, references 7, 8, and 9). Expression (3b), in which

$$(K_{N,Z})^{-1}=(2j_Z+1)^{1/2}(2j_N+1)^{1/2}A^{5/3},$$

and j_Z and j_N are empirical numbers, represents the form of the level density expression given by Newton.[25] Expression (3c) was taken from Lang and LeCouteur.[26] The parameter T in expressions (3b) and (3c) is defined by

$$T=(2a)^{-1}[1+(1+4aE^*)^{1/2}].$$

De-excitation by gamma-ray emission was included in the computations, with the emission probability per unit time (assuming only dipole transitions) given by the expression $P_\gamma(\epsilon)d\epsilon=k\epsilon^3W_fd\epsilon$. The k was treated as an adjustable parameter, and the W_i was dropped as it was in the application of expression (1).

Because of the large number of adjustable parameters (a,δ,k), it appeared to be impractical to attempt to choose the one set which would result in the best fit to the experimental data. Accordingly, the choice of values for the δ's was limited to those suggested by

[25] T. D. Newton, Can. J. Phys. **34**, 804 (1956).
[26] J. M. B. Lang and K. J. LeCouteur, Proc. Phys. Soc. (London) **A67**, 586 (1954).

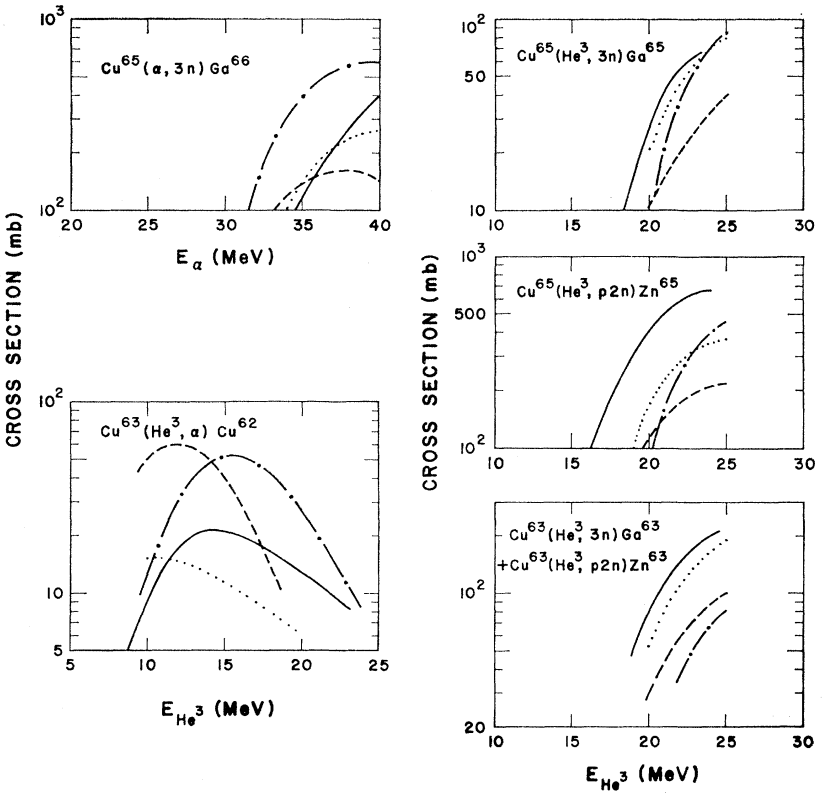

FIG. 9. Excitation functions for emission of three nucleons and for emission of an alpha. Curve designations as in Fig. 7.

Stolovy and Harvey[27] or to the sum of pairing and shell corrections derived by Cameron[28] from the fit of an empirical mass formulation to experimental atomic masses. The Stolovy δ's are defined by

$$\delta_{ee}=3.36(1-A/400),$$
$$\delta_{eo}=\delta_{oe}=1.68(1-A/400),$$
$$\delta_{oo}=0,$$

and are quite similar in value to the pairing energy δ's given by Cameron.[29] Cameron's "pairing plus shell correction" δ's for the isotopes of Zn were adjusted by 0.5 MeV in the direction which puts the reference state at a higher energy above the real ground state. This was done because there seemed to be a constant error in Cameron's values for the Zn masses and because the change gave a better fit to the excitation function data.

The computer program was written in IBM 7090 Fortran language. For each nucleus in an evaporation chain the following sequence of computations was performed. The total emission probability for each particle j was computed. In some cases j was allowed to be any one of the particles n, H^1, H^2, H^3, He^3, He^4, or gamma rays. However, since the emission of H^2, H^3, and He^3 was found to be relatively rare and did not appreciably affect the excitation functions of interest, most calculations were restricted to emission of n, H^1, He^4, and gammas. The particle to be emitted was chosen by means of a random number $N1$ ($0\leqslant N1\leqslant\sum_j \mathrm{TEP}_j$) on the basis of the relative values of the total emission probabilities (TEP). The total emission probabilities,

$$\mathrm{TEP}_j=\int_{\epsilon\min}^{\epsilon\max} P_j(\epsilon)d\epsilon,$$

were computed by Simpson's rule integration. Thus, it was possible to keep in memory the values of

$$Q_j(\epsilon_i)=\int_{\epsilon\min}^{\epsilon_i} P_j(\epsilon)d\epsilon$$

for a series of ϵ_i between $\epsilon_{\min}$ and $\epsilon_{\max}$. The choice of an energy ϵ_j for the emitted particle, from the distribution indicated by Eq. (1), was made on the basis of another random number $N2$ ($0\leqslant N2\leqslant \mathrm{TEP}_j$) by interpolation between the appropriate pair of $Q_j(\epsilon_i)$'s, that is, $Q_j(\epsilon_k)\leqslant N2\leqslant Q_j(\epsilon_l)$ and $\epsilon_k\leqslant\epsilon_j\leqslant\epsilon_l$, where ϵ_j is the energy chosen.

The output of the program included the number of events terminating at each product nucleus, and cross-section values based on the relative numbers of product nuclei and the expressions, (2a) and (2b), used for charged-particle compound-nucleus formation cross sections.

[27] A. Stolovy and J. A. Harvey, Phys. Rev. **108**, 353 (1957).
[28] A. G. W. Cameron, Can. J. Phys. **35**, 1021 (1957).
[29] A. G. W. Cameron, Can. J. Phys. **36**, 1040 (1958).

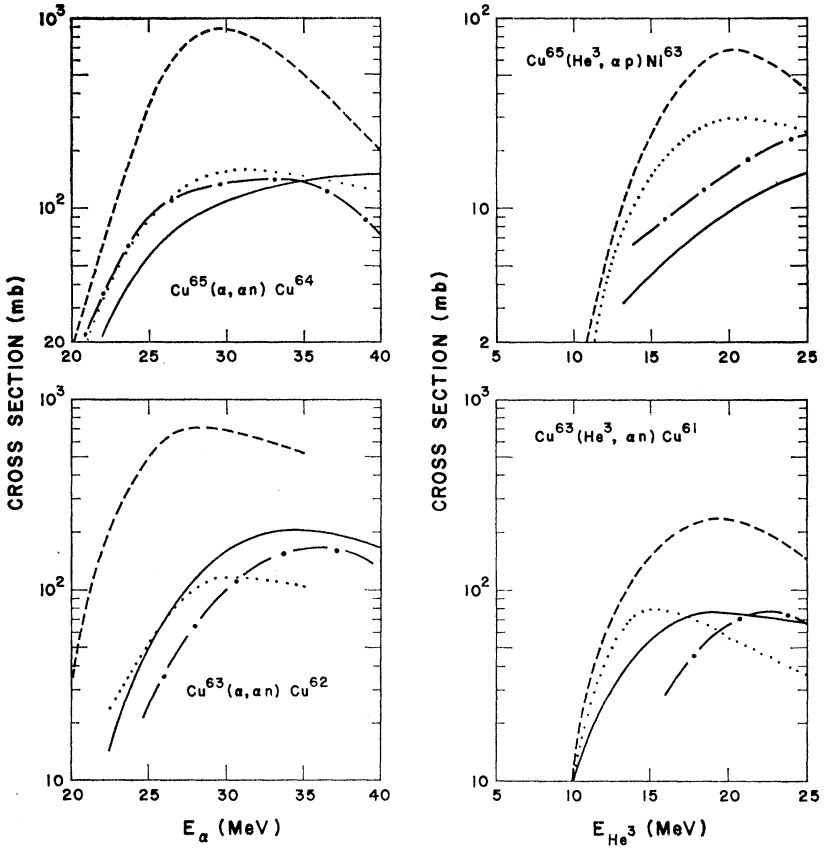

FIG. 10. Excitation functions for emission of an alpha plus a nucleon. Curve designations as in Fig. 7.

Computed excitation functions for reactions of He^3 and He^4 with Cu^{63} and Cu^{65} are shown in Figs. 7–10, together with experimentally determined excitation functions for comparison. The experimental values were taken from the present work, from Houck and Miller,[8] and from Porile and Morrison.[5] The three sets of computed excitation functions were obtained with the three level density expressions (3a), (3b), and (3c). The set associated with expression (3a) is only one of many such sets for which various values of a_1, k, and $\delta_{N,Z}$ were used; the set shown in the figures was computed with $a_1=A/25$, $k=3\times10^{-6}$, and Cameron's shell plus pairing energy δ's (with the Zn δ's adjusted). The set of excitation functions computed with expression (3b) incorporated Lang's[30] recommendation of $a_2=0.0748\times(j_Z+j_N+1)A^{2/3}$, $k=0$ (no gamma emission), and Stolovy's[27] δ's. The set of excitation functions associated with expression (3c) were computed using $a_3=A/8$, $k=4\times10^{-6}$, and Cameron's[28] shell plus pairing δ's (again with the Zn δ's adjusted).

Excitation functions for reactions involving emission of a single neutron or proton are shown in Fig. 7. The agreement between computed and experimental functions for the alpha-particle bombardments is reasonably good for all three level density formulations. The agreement for the He^3 reactions is poor, as might have been expected since the range of compound-nucleus excitation energies for 10- to 20-MeV incident He^3 energy corresponds to the high-energy tail of the single-particle evaporation excitation function. The corresponding range of excitation energies for alpha reactions occurs at incident energies between 20 and 30 MeV. All the experimental data shown in Fig. 7 are taken from the present work.

Excitation functions for reactions in which two neutrons, a neutron and a proton, or two protons are emitted are shown in Fig. 8. All show qualitative agreement between computed and experimental values. The experimental data for the $Cu^{63}(\alpha,2n)Ga^{65}$ reaction were taken from Porile and Morrison,[5] with energy values adjusted to agree with the present work. The experimental data for the $Cu^{63}(\alpha,pn)Zn^{65}$ reaction were obtained by subtracting the excitation function for the $Cu^{63}(\alpha,2n)Ga^{65}$ reaction from Houck and Miller's[8] values for the sum of the cross sections for the $Cu^{63}\times(\alpha,2n)Ga^{65}$ and $Cu^{63}(\alpha,pn)Zn^{65}$ reactions.

Excitation functions for emission of three nucleons are shown in Fig. 9. Again, there is qualitative agreement between computed and experimental values. The experimental data for the $Cu^{65}(\alpha,3n)Ga^{66}$ reaction were taken from Porile and Morrison.[5] Also shown in Fig. 9 are excitation functions for $Cu^{63}(He^3,\alpha)Cu^{62}$.

[30] D. W. Lang, Nucl. Phys. **26**, 434 (1961).

In Fig. 10 are shown excitation functions for reactions involving emission of an alpha particle and a neutron or a proton. The computed cross sections based on expression (3b) are consistently too large. This can be interpreted as indicating that Newton's[25] choice of values for j_Z and j_N for Ni and Cu isotopes is not consistent with his values for Zn and Ga. The agreement between experimental and computed values based on expressions (3a) and (3c) is qualitatively satisfactory. The experimental data for the alpha reactions were taken from Porile and Morrison[5] with adjusted energy scale.

In summary, it appears that there is little basis for a choice between formula (3a) and (3c) for level density. Formula (3b) is essentially of the same form as formula (3c); however, the specific recommendations of values for j_N and j_Z and the resulting values of a do not provide a qualitatively good fit for reactions involving emission of alpha particles. The incorporation of gamma de-excitation generally shifted the peak values in the excitation functions to a higher energy and the fit to experimental values could generally be improved by a proper choice of k. The fit obtained with both (3a) and (3b) suggests that the reactions of 10- to 25-MeV He^3 particles with copper targets are similar in mechanism to the reactions of 15- to 40-MeV alpha particles. Although a number of "improvements" were incorporated in the computations, the agreement of theory with experiment must be regarded as no better than qualitative. Indeed, it is doubtful that excitation function data alone can provide an adequate basis for quantitative conclusions as to reaction mechanism. The degree of fit does suggest, however, that the computations employed here are useful in predicting approximate reaction cross sections.

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(p,n) Cross Sections at 6.75 MeV*

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The (p,n) partial reaction cross sections at 6.75 MeV have been measured for the isotopes Sc^{45}, V^{51}, Mn^{55}, Cu^{63}, Cu^{65}, Ga^{69}, Ga^{71}, and Br^{79}. The results of the measurements in millibarns are 179 ± 9, 480 ± 31, 440 ± 40, 239 ± 13, 566 ± 37, 981 ± 98, 649 ± 69, and 86 ± 5, respectively. The purpose of the experiment is to provide information on reaction cross sections for comparison with optical-model computations. A preliminary comparison of the variation of the cross sections with mass number is made with the partial wave penetrabilities computed from an optical-model potential.

INTRODUCTION

THE optical model has been successfully used in fitting the general features of neutron total elastic cross sections, proton elastic cross sections, and polarizations. The parameters obtained for the potential are relatively insensitive to mass number, although there appears to be a Z dependence for proton scattering. However, there are a number of areas of disagreement between model prediction and experiment. The optical-model parameters are not unique for a given set of data, and some of the parameters may vary widely and still be consistent with a single set of data. Furthermore, the model parameters deduced from proton elastic scattering and polarization data have led to predicted reaction cross sections which are smaller than measured reaction cross sections. As an example, the comparison between experimental and calculated proton-reaction cross sections at 10 MeV as reported by Meyer and Hintz[1] shows the discrepancy to be about 100 mb for the copper and zinc isotopes.

A number of experiments have been reported in the literature[2] on studies of proton-induced reactions which can be compared with optical-model computations. These experiments have measured angular distributions of elastically scattered protons, the polarization of the scattered proton beam, and total reaction cross sections. These quantities have been studied on the isotopes of copper, Cu^{63} and Cu^{65} by a number of groups at proton energies of from 6 to 18 MeV. The data at a proton energy of 10 MeV has been analyzed by Nodvik and Saxon[3] and a set of consistent parameters published. The discrepancy between the experimental reaction cross sections and the reaction cross sections calculated from a set of optical-model parameters consistent with the elastic scattering and polarization data appears to be the most serious from the standpoint of obtaining a

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† Taken in part from a thesis submitted by R. M. Humes to the Graduate School of The Ohio State University in partial fulfillment of the requirements for the degree Master of Science.
[1] V. Meyer and N. Hintz, Phys. Rev. Letters **5**, 207 (1960).
[2] As examples: H. Taketani and W. P. Alford, Phys. Rev. **125**, 291 (1962); R. D. Albert and L. F. Hansen, *ibid.* **123**, 1749 (1961); B. W. Shore, N. S. Wall, and J. W. Irvine, Jr., *ibid.* **123**, 276 (1961); R. D. Albert, *ibid.* **115**, 925 (1959); C. A. Preskitt, Jr., and W. P. Alford, *ibid.* **115**, 389 (1959); H. A. Howe, *ibid.* **109**, 2083 (1958); N. M. Hintz, *ibid.* **106**, 1201 (1957); G. W. Greenlees, L. G. Kuo, and M. Petravic, Proc. Roy. Soc. (London) **A243**, 206 (1957); J. P. Blaser, F. Boehm, P. Marmier, and P. Scherrer, Helv. Phys. Acta **24**, 441 (1954).
[3] J. S. Nodvik and D. S. Saxon, Phys. Rev. **117**, 1539 (1960).