Excitation functions for production of heavy actinides from interactions of ^{18}O with ^{248}Cm and ^{249}Cf

Diana Lee, Kenton J. Moody, Matti J. Nurmia, and Glenn T. Seaborg
Nuclear Science Division, Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

Hans R. von Gunten
Eidgenössisches Institut für Reaktorforschung, Würenlingen, Switzerland and Anorganisch-Chemisches Institut, University of Bern, Bern, Switzerland

Darleane C. Hoffman
Isotope and Nuclear Chemistry Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545

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Excitation functions have been measured for the production of isotopes of Bk through Fm in bombardments of ^{248}Cm with 97- to 122-MeV ^{18}O ions and of isotopes of Bk through No in bombardments of ^{249}Cf with 91- to 150-MeV ^{18}O ions. The cross sections and widths of the mass distributions for the actinides produced in these reactions are very similar for transfer of the same numbers of nucleons. A semiquantitative comparison of the experimental results with calculations based on a simple model shows that calculations of this type are helpful in selection of projectile-target systems and optimum energies for production of specific actinide isotopes and for synthesis of as yet unknown heavy isotopes and elements. Comparisons of experimental results with calculations show that, in general, about half of the kinetic energy of the projectile is transferred to the actinide product.

[NUCLEAR REACTIONS $^{248}Cm(^{18}O,X)$, $E(^{18}O)=97$, 104, 113, 122 MeV; $^{249}Cf(^{18}O,X)$, $E(^{18}O)=91$, 97, 104, 113, 122, 150 MeV; measured σ and isotopic distributions for $Z=97-102$.]

I. INTRODUCTION

In a previous publication[1] we reported on the formation of neutron-rich heavy actinides in interactions of ^{16}O, ^{18}O, ^{20}Ne, and ^{22}Ne ions with ^{248}Cm at energies close to the calculated Coulomb barriers of the interacting systems. In these transfer-type reactions many product nuclei are formed with low excitation and are, therefore, relatively stable toward prompt fission and/or particle emission. The production cross sections decrease with increasing Z of the products and range from a few mb for Bk and Cf isotopes to a few μb for the formation of Es and Fm isotopes. ^{256}Md and ^{259}No were also observed, but the yields are still smaller, only of the order of nb.

Calculations of the Coulomb barrier energies using nuclear radii of $\approx 1.4\times A^{1/3}$ fm can only be considered as an approximation since heavy actinides are deformed in the ground state. Therefore, these transfer reactions often proceed well below the estimated Coulomb barriers,[2] but the cross sections at these bombarding energies may be considerably smaller than at higher energies. In addition, the shapes of the excitation functions are expected to be different for different transfer reactions, depending on the ground-state Q values for the specific reactions. In order to help determine the optimum projectile energies for the production of neutron-rich actinides in transfer-type reactions, we have measured excitation functions for the formation of isotopes of Bk through Fm in reactions of ^{18}O with ^{248}Cm and of isotopes of Bk through No in reactions of ^{18}O with ^{249}Cf. From the measured excitation functions it should be possible to estimate the heights of the Coulomb barriers and deduce information about fission and particle emission. Furthermore, systematic investigations of this type should enable us to predict the optimum conditions for the synthesis of as yet unknown neutron-rich heavy actinides and possible superheavy elements by transfer-type reactions. This systematic approach

TABLE I. Cross sections for heavy actinides from bombardment of ^{248}Cm with ^{18}O of different energies.

Nuclide	97 MeV Cross section (μb)	s^a (%)	104 MeV Cross section (μb)	s^a (%)	113 MeV Cross section (μb)	s^a (%)	122 MeV Cross section (μb)	s^a (%)	Decay mode	Measured radiation Energy (MeV)	Abundance
Bk 245	0.3	20	2.0	10	5.8	5	8.7	20	EC,γ	0.253	0.31
246	5.9	10	15	5	50	6	56	5	EC,γ	0.799	0.61
248*m*	137	6	360	5	690	6	586	10	β^-,γ	0.551	0.05
250	1080	8	1970	2	1700	5	546	3	β^-,γ	0.989	0.45
251	≥ 180	13	≥ 420	15	≥ 125	21	≥ 65	14	β^-,γ	0.177	b
Cf 246	0.05	14	0.1	20	0.5	14	0.85	24	α	6.76	1.00
248	54	22	93	3	210	20	152	13	α	6.26[c]	1.00
250	930	7	1300	27	900	25	713	41	α	6.03[c]	0.96
252	287	20	337	5	310	30	186	5	α	6.12	0.97
253	49	27	40	5	37	22	13	4	$\beta^-\rightarrow\alpha$	6.63[d]	1.00
254	3.3	21	2.5	20	1.2	50	0.4	13	SF		1.00
Es 252	5.9	25	20	8	37	10	26	16	α	6.63	0.73
253	11.6	3	28.8	3	23	4	9.6	7	α	6.63[e]	0.98
254*m*	6.5	3	9.2	2	4.1	2	0.9	11	$\beta^-\rightarrow\alpha$	7.19[d]	1.00
255	0.25	28	0.31	23	0.2	38	0.08	38	$\beta^-\rightarrow\alpha$	7.01[d]	0.99
Fm 252	1.1	27	1.2	17	1.2	17	0.4	30	$\alpha\rightarrow\alpha$	6.26[d]	1.00
253	1.9	21	1.9	21	1.5	47	0.9	22	EC$\rightarrow\alpha$	6.63[d]	0.86
254	2.4	4	3.1	6	2.0	5	0.6	5	α	7.06–7.19[f]	1.00
255	1.1	20	1.1	14	0.5	38	0.2	43	α	6.89–7.02[g]	0.99
256	0.3	15	0.33	23	0.16	16	0.04	33	SF		0.92

[a]The standard deviation associated with the quoted absolute cross sections is estimated to be ±12%, in addition to the statistical standard deviation s given in the tables, which is based on the decay analysis.
[b]No absolute gamma-ray intensity data are available for the 0.177-MeV photon which we measured, but the 0.177-MeV level in ^{251}Cf (Ref. 3) is deexcited by a 0.177-MeV γ transition (72.5%) and a 0.153-MeV γ transition (27.5%). The total conversion coefficient for the 0.177 γ transition was estimated to be ≈ 8 based on a measured α_K of 6.0 (Ref. 3) and an estimated $(\alpha_L+\alpha_M)$ of 1.7 for an $M1$ (+E2) transition. The decay of ^{251}Bk is assumed to primarily populate the 0.177-MeV level. If there is appreciable feeding of the ground state or other levels which do not deexcite via the 0.177-MeV transition, our quoted cross sections will be correspondingly too low.
[c]Corrected for contribution from the Bk parent.
[d]Radiation from daughter activity was measured.
[e]Corrected for contribution from decay of the Cf parent.
[f]Corrected for contribution from decay of the Es parent.
[g]Corrected for contribution from 7.04-MeV alpha group of ^{252}Fm.

should also increase the chances for unambiguous identification of new isotopes and possibly superheavy elements.

II. EXPERIMENTAL

The target arrangement and the ^{248}Cm targets were similar to those described in our previous work.[1] The ^{249}Cf target contained 0.52 mg/cm^2 of ^{249}Cf ($\approx 100\%$ ^{249}Cf) in the form of CfF_3 deposited with a diameter of 6.5 mm on 2.13 mg/cm^2 Be foil. The ^{248}Cm and ^{249}Cf targets were irradiated at the Lawrence Berkeley Laboratory 88-inch cyclotron with 97-, 104-, 113-, and 122-MeV ^{18}O ions. In addition, the ^{249}Cf was irradiated with 91- and 150-MeV ^{18}O ions. (All quoted energies have been corrected for the total energy loss of about 15 MeV in the Havar window, cooling gas, and Be target backing. No corrections were made for the energy losses of 1 to 2 MeV in the targets.) The chemical separations, measurements of radioactivity, and data processing were performed as described earlier.[1]

III. RESULTS AND DISCUSSIONS

The results of the experiments for ^{18}O reactions with ^{248}Cm and ^{249}Cf are summarized in Tables I and II and are plotted in Figs. 1–8. The results for

TABLE II. Cross sections for heavy actinides from bombardment of ^{249}Cf with ^{18}O of different energies.

Nuclide	91 MeV Cross section (μb)	91 MeV s[a] (%)	97 MeV Cross section (μb)	97 MeV s[a] (%)	104 MeV Cross section (μb)	104 MeV s[a] (%)	113 MeV Cross section (μb)	113 MeV s[a] (%)	122 MeV Cross section (μb)	122 MeV s[a] (%)	150 MeV Cross section (μb)	150 MeV s[a] (%)
Bk 245			6.7	39								
246			83	17								
248*m*			104	32								
250			10.5	20								
Cf 246	0.4	21	35	4	129	2	270	1	260	1	141	2
248	2840	1	10 800	9	17 500	1	22 900	1	19 200	1	9150	1
250	24 500	2	38 700	2	34 100	3	38 700	10	37 800	2	40 700	3
Es 249	2	50	103	4	480	13	1175	6	1030	8	650	10
250[b]	430	13	3850	22	6730	9	8330	17	4320	13	1960	6
251	334	11	1775	5	3900	5	2865	2	2150	5	730	10
252	263	11	1100	4	1350	6	817	3	325	16	127	49
253	6.1	28	27	7	29	18	32	7	15	20	4.9	20
254*m*[c]	≤0.02		0.05	20	0.12	5	0.25	4	0.29	3	0.09	6
Fm 250	≤0.02		10.4	2	68	1	131	3	157	1	43	5
252[c]	610	18	1910	19	2400	20	1600	13	620	17	89	17
253[c]	286	13	477	4	526	3	324	8	160	31	19	10
254	12.3	4	80	1	103	1	56	2	24.5	3	2.2	13
255[d]	2.5	28	40	43	55	44	19	40	6.0	42	0.8	50
256	0.11	10	1.2	3	1.5	7	0.9	22	0.5	20	0.02	20
Md 256[c]	0.07	20	0.69	20	0.19	19	0.33	9	0.11	19	0.006	38
258*m*[c]			≤0.7				≤0.24					
No 259			≤0.006				0.035	30	0.006	70		

[a]The standard deviation associated with the quoted absolute cross sections is estimated to be ±12%, in addition to the statistical standard deviation s given in the tables, which is based on the decay analysis. The same radiations and abundances were used as in our previous paper, Ref. 1. (Also see Table I.)

[b]In order to calculate the total cross section for ^{250}Es when both isomers were not measured, the ratio of the cross section of the 6^+ (8.6 h) to the sum of the cross sections of the 6^+ and 1^- (2.1 h) isomers was taken to be 0.17±0.17 for the 91- and 97-MeV bombardments, consistent with our measured values of 0.17±0.05 at 104 MeV, 0.32±0.16 at 122 MeV, and 0.43±0.13 at 150 MeV. An interpolated value of 0.25±0.17 for 113 MeV was used. These errors are included in the quoted standard deviations.

[c]Radiation from daughter activity was measured.

[d]Corrected for contribution from 7.04-MeV alpha group of ^{252}Fm.

97-MeV ^{18}O on ^{248}Cm agree with our earlier measurements[1] within the quoted errors. Corrections were made for the contribution to the measured activities of ^{248}Cf and ^{250}Cf from decay of ^{248}Bk, ^{250}Bk, and ^{250}Es, for contributions to ^{253}Es from decay of ^{253}Cf, and to ^{254}Fm from decay of ^{254}Es during bombardment and prior to chemical separation.

Maxima in the experimental excitation functions, E_M, obtained by inspection of Figs. 1–6, are listed in Tables III and IV together with the calculated[4] excitation energies, E_X, for binary reactions. These calculations are based on ground-state Q values for the reactions and the Coulomb barriers. The total reaction yield should increase with energy proportionally to the increase in the square of the maximum impact parameter for Rutherford trajectories which can result in collisions. The interaction time decreases as $E^{-1/2}$ and tends to reduce the total reaction yield. If fission and/or particle emission did not occur, then the measured yields should decrease no faster than $E^{-1/2}$, where $E = E_{\text{proj}} - E_{\text{Coul}}$. However, in most cases, the experimental excitation functions drop off much more rapidly than this and the observed maxima probably indicate the onset of fission and/or neutron emission.

A separate discussion of the excitation functions

TABLE III. Comparison of maxima, E_M, estimated from experimental excitation functions for $^{248}Cm+^{18}O$ with calculated excitation energies (Ref. 4), E_X, and fraction of energy transferred, F_T, to ^{248}Cm target. [$F_T=(E_{f,n}-E_X)/(E_M-E_B)$, where $E_{f,n}$ is either the energy of the fission barrier or the neutron binding energy, whichever is smaller. $E_B\approx 94$ MeV in the laboratory system].

Product mass	ΔN[a]	Bk E_M (MeV)	Bk E_X (MeV)	Bk F_T	Cf E_M (MeV)	Cf E_X (MeV)	Cf F_T	Es E_M (MeV)	Es E_X (MeV)	Es F_T	Fm E_M (MeV)	Fm E_X (MeV)	Fm F_T
245	−3	≥122	−11.1	≤0.6									
246	−2	113−122	−9.3	0.8−0.5	≥122								
248	0		−4.8		114	−5.4	0.6						
248*m*	0	116	−4.8[b]	0.5									
250	2	106	−2.5	0.6	104	1.8	0.4						
251	3	104	1.2	0.5									
252	4				97−113	6.9	c	114	−4.1	0.5	≤97−113	−11.6	≥0.9
253	5				97−113	3.2	0.5−0.1	107	1.0	0.35	≤97−113	−8.2	≥0.7
254	6				≤97	3.9	≥0.7		0.8		104	0.4	0.5
254*m*	6							103	0.8[b]	0.5			
255	7							104	3.2	0.2	≤97−104	2.3	1−0.3
256	8										≤97−113	8.2	c

[a]Number of nucleons transferred from projectile to target.
[b]E_X for ground state was used for calculation of F_T.
[c]$(E_{f,n}-E_X)$ is negative.

for the individual isotopes of each element is given in the following subsections. The results are also compared to excitation energies calculated[4] for the actinide products.

A. $^{248}Cm+^{18}O$ reactions

The calculated Coulomb barrier, E_B, for this reaction is about 94 MeV in the laboratory system.

1. *Excitation functions for Bk isotopes*

The excitation functions for the Bk isotopes 245, 246, 248*m*, 250, and 251 produced in reactions of ^{18}O with ^{248}Cm are plotted in Fig. 1. In general, the cross sections at each energy increase considerably from ^{245}Bk to ^{250}Bk, but decrease between ^{250}Bk and ^{251}Bk. All of the cross sections increase above the lowest projectile energy of 97 MeV with maxima at

TABLE IV. Comparison of maxima, E_M, estimated from experimental excitation functions for $^{249}Cf+^{18}O$ with calculated excitation energies (Ref. 4), E_X, and fraction of energy transferred, F_T, to ^{249}Cf target. [$F_T=(E_{f,n}-E_X)/(E_M-E_B)$, where $E_{f,n}$ is either the energy of the fission barrier or the neutron-binding energy, whichever is smaller. $E_B\approx 96$ MeV in the laboratory system.]

Product mass	ΔN[a]	Es E_M (MeV)	Es E_X (MeV)	Es F_T	Fm E_M (MeV)	Fm E_X (MeV)	Fm F_T
249	0	115	−5.0	0.6			
250	1	111	−2.0	0.5	122	−5.4	0.4
251	2	105	−1.5	0.6			
252	3	102	0.9	0.75	104	2.4	0.45
253	4	104−113	−4.0	1−0.6	103	6.4	c
254	5		9.9		103	4.3	0.1
254*m*	5	113−122	−9.9[b]	0.9−0.6			
255	6				103	4.2	0.1
256	7				103	−8.6	d

[a]Number of nucleons transferred from projectile to target.
[b]E_X for ground state was used for calculation of F_T.
[c]$(E_{f,n}-E_X)$ is negative.
[d]Calculated $F_T>1$.

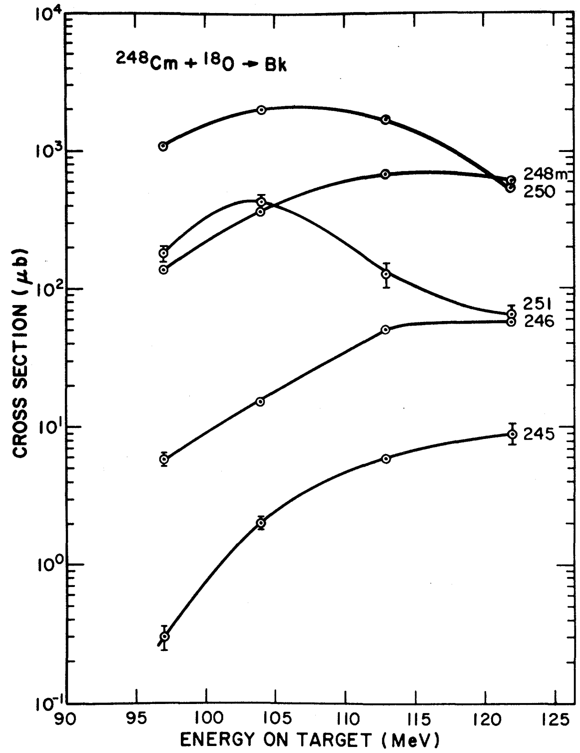

FIG. 1. Excitation functions for Bk isotopes produced in the bombardment of ^{248}Cm with ^{18}O. Points are connected only as a visual aid.

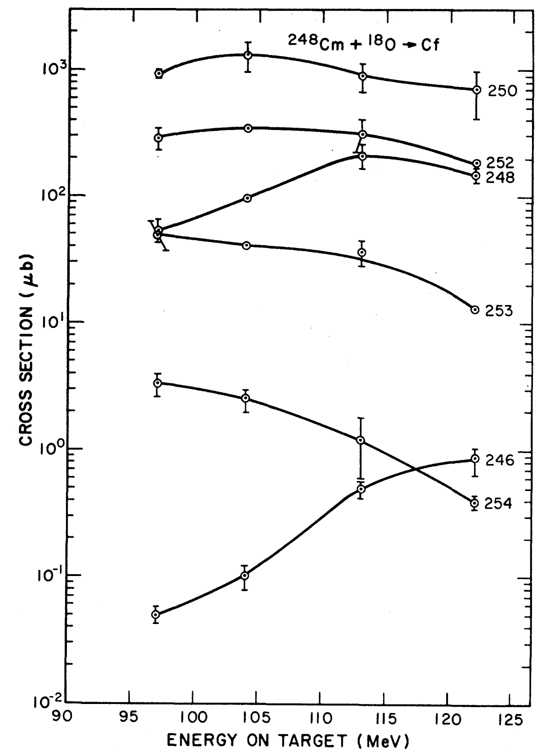

FIG. 2. Excitation functions for Cf isotopes produced in the bombardment of ^{248}Cm with ^{18}O. Points are connected only as a visual aid.

the energies given in Table III. In general, the isotopes with lower calculated[4] excitation energies reach their maximum yields at a higher projectile energy, indicating that more projectile energy is required before prompt fission or particle emission begins to deplete the yield.

2. Excitation functions for Cf isotopes

The excitation functions for the Cf isotopes 246, 248, 250, 252, 253, and 254 produced in reactions of ^{18}O with ^{248}Cm are shown in Fig. 2. The cross sections at all measured energies increase from ^{246}Cf to ^{250}Cf, and decrease afterwards with increasing mass of the isotope. Again, the maxima of the excitation functions tend to be at higher energies for those isotopes with lower calculated excitation energies. (See Table III.) The cross sections for ^{253}Cf and ^{254}Cf decrease monotonically with increasing energy within the investigated energy range. This can be explained on the basis of the excitation energies, which are positive. The excitation energy for ^{252}Cf is already 7 MeV at the Coulomb barrier. Its cross section might, therefore, also be expected to monotonically decrease with increasing projectile energy due to depletion by fission, but it is rather constant in this energy region. It is possible that ^{252}Cf might be pro-

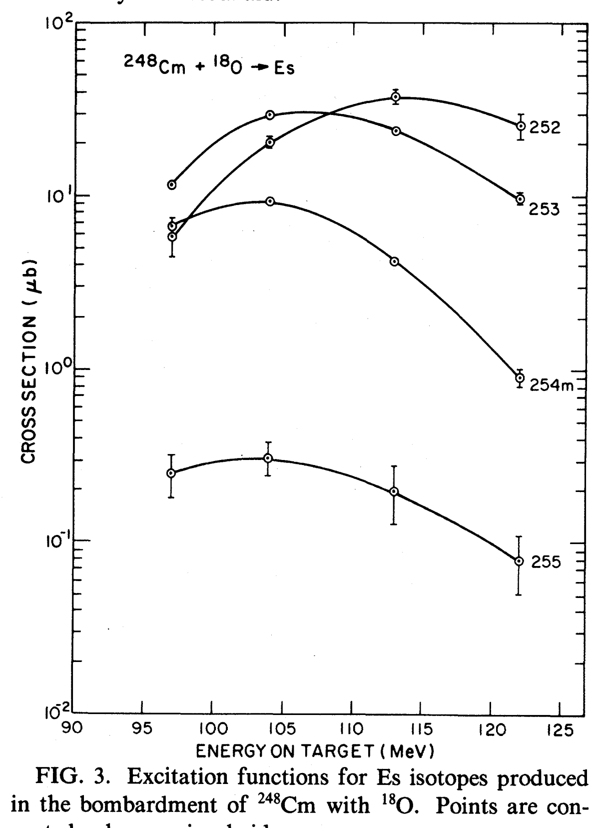

FIG. 3. Excitation functions for Es isotopes produced in the bombardment of ^{248}Cm with ^{18}O. Points are connected only as a visual aid.

duced at the higher energies by neutron emission from ^{253}Cf because the neutron binding energy[5] in ^{253}Cf is only 4.8 MeV, less than its fission barrier[6] of 5.3 MeV. (The neutron-binding energy[5] in ^{252}Cf is 6.2 MeV.)

3. Excitation functions for Es isotopes

The excitation functions for the Es isotopes 252, 253, 254*m*, and 255 are presented in Fig. 3. The cross sections for ^{252}Es and ^{253}Es are of similar magnitude and in the range of a few tens of μb. The maxima of the excitation functions are again in qualitative agreement with the calculated product excitation energies. (See Table III).

4. Excitation functions for Fm isotopes

The excitation functions for the Fm isotopes 252, 253, 254, 255, and 256 are shown in Fig. 4. The cross sections increase from mass 252 to 254 and are of the order of a few μb, but decrease for heavier isotopes. The maxima of the excitation functions are not well defined and, except for masses 255 and 256, are rather flat up to 114 MeV. However, the cross sections for 252 do not decrease until nearly 20 MeV above the Coulomb barrier, consistent with its very negative excitation energy. (See Table III.) The excitation function for 255 begins to decrease 10 MeV above the barrier, consistent with its positive excitation energy. However, the excitation function for 256 is similar to that for 255 even though its excitation energy is higher; its yield may be augmented by neutron emission from 255 whose neutron-binding energy[5] is only 5.2 MeV, less than its measured fission barrier[7] of 5.7 MeV.

B. $^{18}O+^{249}Cf$ reactions

The calculated Coulomb barrier, E_B, for this reaction is about 96 MeV in the laboratory system.

1. Excitation functions for Bk isotopes

Cross sections for the Bk isotopes 245, 246, 248*m*, and 250 were measured only at 97 MeV. (See Table II.) The peak cross section of 104 μb was observed at mass 248. With this limited information excitation functions cannot be constructed, but it appears that cross sections for formation of products with one proton less than the target are much smaller than those for isotopes of the target element and up to two protons larger.

2. Excitation functions for Cf isotopes

Excitation functions were measured for production of Cf isotopes of masses 246, 248, and 250. (See Table II.) Yields are high (tens of mb) for ^{250}Cf and ^{248}Cf which can be produced by neutron capture

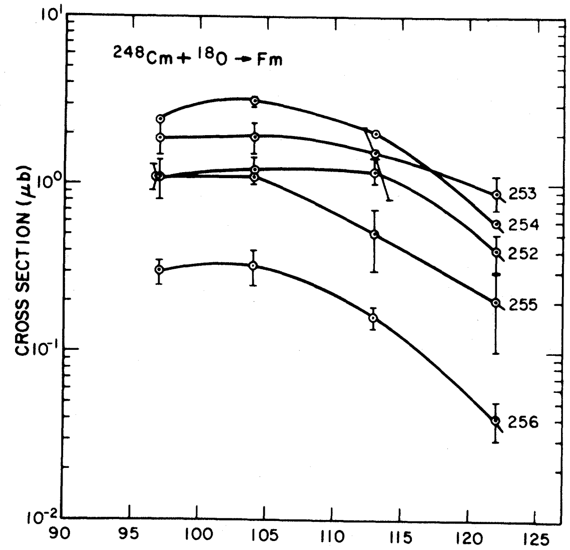

FIG. 4. Excitation functions for Fm isotopes produced in the bombardment of ^{248}Cm with ^{18}O. Points are connected only as a visual aid.

and $(n,2n)$ reactions, respectively. There is also considerable yield of ^{246}Cf. Although small amounts of ^{252}Cf and ^{253}Cf were observed, these data were not used because of the undetermined corrections re-

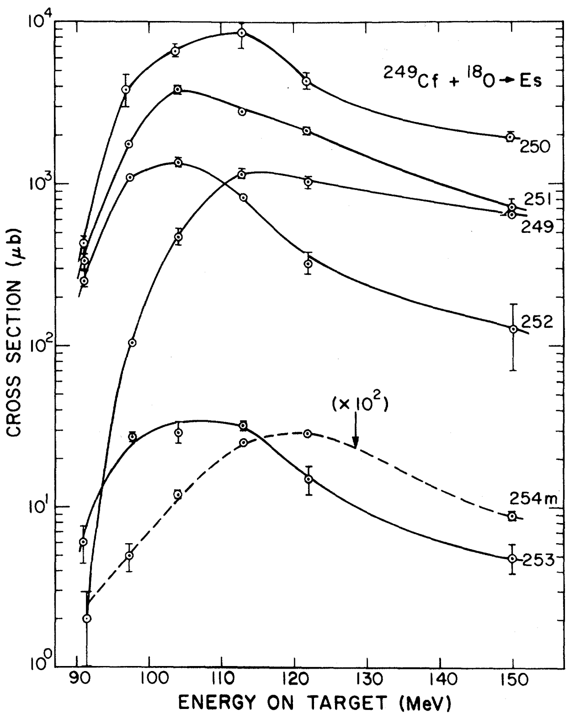

FIG. 5. Excitation functions for Es isotopes produced in the bombardment of ^{249}Cf with ^{18}O. Points are connected only as a visual aid.

quired due to the $\approx 10^{-3}$wt. % of ^{252}Cf in the target. Corrections for formation from alpha decay of Fm isotopes are small for ^{248}Cf and ^{250}Cf, but may be significant for ^{246}Cf, which can be formed by alpha decay of ^{250}Fm as well as by removal of three neutrons from the target. The excitation functions for production of the Cf isotopes show a different energy dependence and decrease much more slowly with increasing energy than those for the isotopes of Es, Fm, and Md which are described in the following subsections. Production of ^{250}Cf is essentially independent of projectile energy between 100 and 150 MeV, as might be expected for a neutron-capture reaction. Neutron capture in the target may lead to a nearly isotropic recoil pattern, and therefore, these yields may be low by a factor of 2 or more because products recoiling into the target will not be collected in the catcher foil.

3. *Excitation functions for Es isotopes*

The excitation functions for the Es isotopes 249, 250, 251, 252, 253, and 254*m* produced in reactions of ^{18}O with ^{249}Cf are shown in Fig. 5. The cross sections at each energy are highest for ^{250}Es and reach tens of mb. The excitation functions increase sharply above 91 MeV until the maxima (see Table IV) are reached, and fall off more gradually on the high-energy side. The curves for ^{250}Es, ^{251}Es, ^{252}Es, and ^{253}Es peak at considerably lower energies than those for ^{249}Es and ^{254}Es^{m}; this result is again in qualitative agreement with the calculations.[4] The excitation function for ^{249}Es decreases much less steeply, perhaps because this is a neutron-proton exchange rather than a net transfer of mass from the projectile to the target.

4. *Excitation functions for Fm isotopes*

The excitation functions for the Fm isotopes 250, 252, 253, 254, 255, and 256 are presented in Fig. 6. They increase steeply above 91 MeV; those for masses 252 through 256 all peak around 103 to 104 MeV and show a similar decrease with increasing projectile energy. The excitation function for ^{250}Fm shows a maximum around 122 MeV. (Also see Table IV.)

5. *Excitation functions for Md and No isotopes*

The excitation function for ^{256}Md peaks around 97 MeV and then decreases rapidly. (See Table II.) The peak cross section of 0.69 μb is much lower than for the lighter Fm isotopes, but is about half of that for ^{256}Fm. Upper limits were obtained for ^{258}Md at only two projectile energies. Since no other Md isotopes were measured, we were not able to

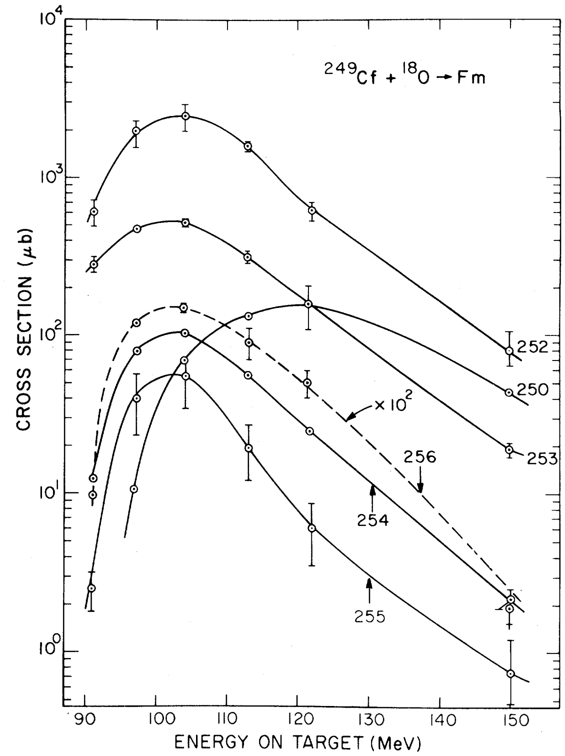

FIG. 6. Excitation functions for Fm isotopes produced in the bombardment of ^{249}Cf with ^{18}O. Points are connected only as a visual aid.

determine the peak of the mass-yield curve for the Md isotopes. ^{259}No was detected in the 113- and 122-MeV bombardments but with still smaller cross sections.

C. Comparison of excitation functions with calculations

We tried (see Tables III and IV) to estimate the fraction, F_T, of projectile kinetic energy transformed into product excitation energy according to the following formula:

$$F_T = \frac{E_{f,n} - E_X}{E_M - E_B} ,$$

where $E_{f,n}$ is either the energy of the fission barrier[6,7] or the neutron-binding energy,[5] whichever is smaller. No obvious trend can be seen, and the F_T values are generally about 0.5 for these transfers of zero to eight nucleons. If the energy is apportioned according to the fraction of projectile mass transferred, F_T should be 0.44 for a transfer of eight nucleons. Recently, Karp *et al.*[8] found that for one- or two-nucleon transfers, about one-half of the incident kinetic energy above the Coulomb barrier results in internal energy, while for transfer of six or seven nucleons most of the energy is transferred.

Their measurements show a large spread in the energy of projectilelike products. Because the actinides we measured will fission or emit neutrons if more than about 5 to 6 MeV is transferred, our measurements will tend to be biased toward detection of the products to which a smaller fraction of projectile energy was transferred.

D. Comparison of different reactions

The present work allows comparison of cross sections for production of isotopes of Bk through Fm from reactions of ^{248}Cm and ^{249}Cf with ^{18}O ions at different projectile energies. For example, comparisons of the mass-yield curves for Es and Fm isotopes produced in the bombardment of ^{248}Cm and ^{249}Cf with ^{18}O ions at 97 MeV, i.e., near the calculated Coulomb barriers, are shown in Figs. 7 and 8. The shapes of the mass-yield curves for these systems look rather similar.

However, from Fig. 7 it can be seen that the cross sections for the formation of light Es isotopes ($A \leq 252$) are orders of magnitude higher for ^{18}O reactions with ^{249}Cf than with ^{248}Cm. In the former reactions only a single proton must be transferred, whereas in the latter case three protons must be added to the target nucleus. On the other hand, the cross sections are of comparable magnitude for mass 253 for both systems, but are higher for $A \geq 254$ for the ^{248}Cm+^{18}O reactions. The peak of the mass-yield curve for Es occurs around mass 250 to 251 for the ^{249}Cf target, while it is around mass 253 for ^{248}Cm. This can be explained by the higher neutron-to-proton ratio in the ^{248}Cm+^{18}O system, which favors the production of neutron-rich products.

The mass-yield curves for Fm isotopes produced from ^{248}Cm+^{18}O and ^{249}Cf+^{18}O at 97 MeV given in Fig. 8 show maximum yields at masses 253 to 254 for the ^{248}Cm target and at mass 252 for the ^{249}Cf target. These maxima represent the transfer of the fewest nucleons to the target for products whose excitation (See Tables III and IV) is positive but not higher than the fission barrier or neutron-binding energy. At the peak of the mass-yield curve the cross section is about a factor of 1000 greater for ^{249}Cf than for ^{248}Cm. The yields for Fm from ^{18}O reactions with ^{249}Cf then drop rapidly with increasing mass until at mass 256 the yield is only a factor of 4 higher for the ^{249}Cf than for the ^{248}Cm target. It appears that for masses ≥ 257 the yields will probably be higher for the ^{248}Cm target and, indeed, a yield of 15 nb has been measured[9] for ^{259}Fm, again reflecting the influence of the neutron-rich ^{248}Cm.

The results of this and our earlier investigation[1] can also be compared with results of Schädel *et al.*[10]

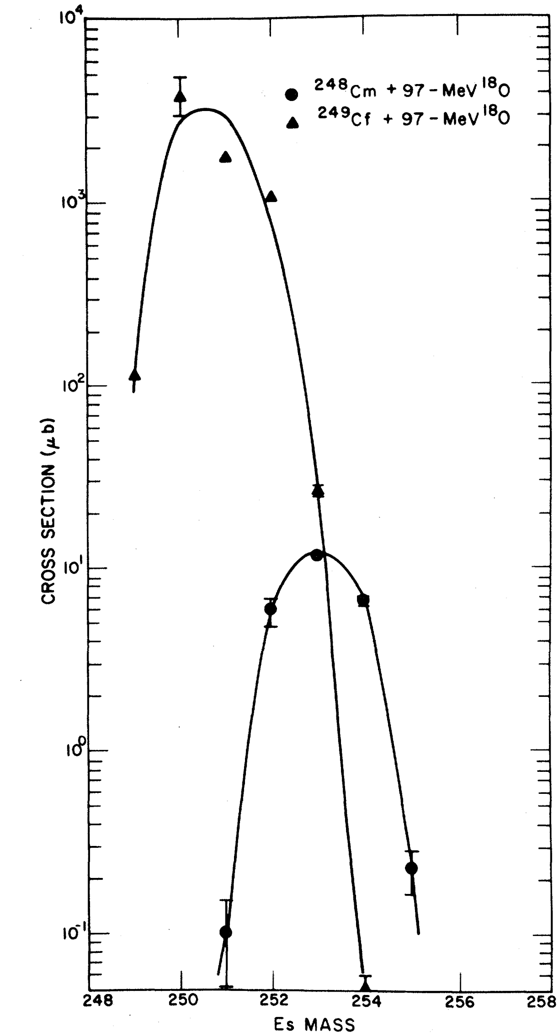

FIG. 7. Comparison of the mass distributions for Es isotopes from the bombardment of ^{248}Cm and ^{249}Cf with 97-MeV ^{18}O. Data for ^{248}Cm are averages from this work and Ref. 1. Points are connected only as a visual aid.

for bombardment of ^{248}Cm with 10 MeV/μ ^{238}U ions. Our yields for Cf, Es, Fm, and Md isotopes obtained from bombardment of ^{248}Cm with ^{18}O and ^{22}Ne at energies close to the calculated Coulomb barriers compare very favorably with those produced in the much more complex reactions of the ^{248}Cm+^{238}U system. In addition to the cross sections being of similar magnitude, the centroids of the mass distributions are also at roughly the same masses for these very different reaction systems. The results with neutron-rich lighter ions (e.g., ^{18}O and ^{22}Ne) appear even more favorable for the production of neutron-rich actinides when the cross sections at the maxima of the excitation functions are used in the comparison. Furthermore, much higher intensities are available for the lighter projectiles.

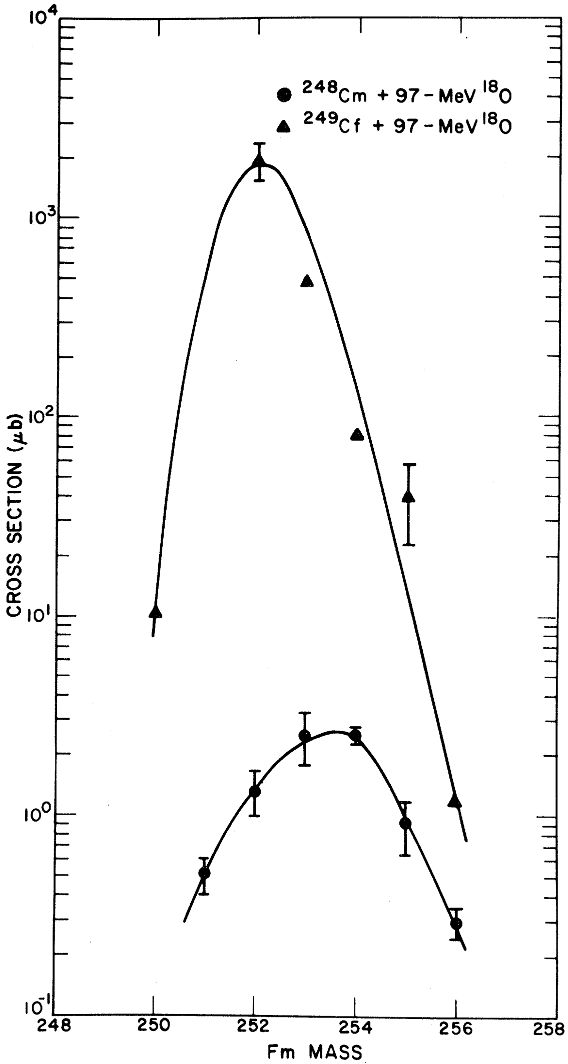

FIG. 8. Comparison of the mass distribution for Fm isotopes from the bombardment of ^{248}Cm and ^{249}Cf with 97-MeV ^{18}O. Data for ^{248}Cm are averages from this work and Ref. 1. Points are connected only as a visual aid.

However, the full width at half maximum (FWHM) for the mass distributions is $\approx 3.4\,\mu$ for the reactions with ^{238}U ions while it is only $\approx 2\,\mu$ for reactions with ^{18}O and ^{22}Ne ions. This might tend to favor the production of very neutron-rich products in the ^{238}U reactions.

A comparison of the $(1p,xn)$ and $(2p,xn)$ transfers in reactions of ^{248}Cm, ^{249}Cf, and ^{254}Es (Ref. 11) with ^{18}O ions near the Coulomb barrier shows that the cross sections and the widths of the mass distributions are very similar for transfer of the same nucleons.

In summary, comparison of the maxima of the measured excitation functions with calculated[4] product excitation energies indicates that, in general, products with lower excitation energy reach their maximum cross sections at higher energies. This is because fission and/or neutron evaporation does not occur until the product excitation energy exceeds 5–6 MeV. Even if quantitative agreement with experiment is not achieved, such simple calculations based on ground-state Q values for the binary reactions allow a useful prediction of the optimum reaction system and projectile energy for production of neutron-rich actinides in high yields with a minimum of interference from lighter isotopes. Predictions of this kind should also be helpful in selecting the best reactions and projectile energies for the synthesis of as yet unknown isotopes and perhaps even superheavy elements.

IV. SUMMARY

The following conclusions are based both on the results of the present paper and our previous publication.[1]

(a) Cross sections are largest for transfer of a few nucleons and decrease rapidly as the number of transferred nucleons increases.

(b) Neutron-rich projectiles (e.g., ^{18}O, ^{22}Ne) and targets (e.g., ^{248}Cm) enhance formation of neutron-rich actinide isotopes.

(c) Cross sections and widths of the mass distributions for products from transfer of the same numbers of nucleons are very similar for ^{18}O reactions with ^{248}Cm, ^{249}Cf, and ^{254}Es (Ref. 11).

(d) Reactions using lighter heavy ions (e.g., ^{18}O) lead to production cross sections for actinide isotopes which are at least as large as those obtained using the heaviest projectiles so far available, e.g., ^{238}U, but the widths of the mass distributions are about one mass unit narrower for the lighter projectiles.

(e) The production of heavy actinides is appreciable, even near the calculated Coulomb barrier.

(f) Simple calculations based on reaction Q values and Coulomb barriers are useful for selection of optimum target-projectile systems and energies for the production of new transcurium isotopes and elements.

(g) For the measured actinide products (i.e., those surviving fission or particle emission), about half of the projectile kinetic energy appears to be transferred to the product. From our limited data no correlation between the number of nucleons transferred and the energy transferred can be inferred.

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