Actinide Production in Collisions of ^{238}U with ^{248}Cm

M. Schädel, W. Brüchle, H. Gäggeler, J. V. Kratz, K. Sümmerer, and G. Wirth
Gesellschaft für Schwerionenforschung, D-6100 Darmstadt, Federal Republic of Germany

and

G. Herrmann, R. Stakemann, G. Tittel, and N. Trautmann
Institut für Kernchemie, Universität Mainz, D-6500 Mainz, Federal Republic of Germany

and

J. M. Nitschke
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

and

E. K. Hulet and R. W. Lougheed
Lawrence Livermore National Laboratory, University of California, Livermore, California 94550

and

R. L. Hahn and R. L. Ferguson
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

(Received 25 January 1982)

Cross sections for the production of heavy actinides in damped collisions of ^{238}U ions with ^{248}Cm targets are reported and compared with similar data for other projectiles. The relatively small differences in the formation rates of a given isotope made by different projectiles indicate a balance between increased mass transfer probability with increasing projectile mass and a concurrent decrease in survivability because of an increase in excitation energy.

PACS numbers: 25.70.Fg, 25.70.Bc

The possibility of using reactions with large mass and energy transfer between two heavy nuclei, damped heavy-ion collisions, to produce superheavy elements depends on the hitherto poorly characterized tails of excitation-energy and angular-momentum distributions associated with large mass transfer. By studying the production of highly fissionable, nearby actinides in transfer reactions with actinide targets, one may hope to shed some light on these rare reaction channels.[1] Strong enhancements in the production of Cf, Es, and Fm isotopes were observed[1] when ^{238}U projectiles were used to bombard ^{238}U as compared to ^{136}Xe projectiles. Substantial additional enhancements were expected if a heavier target than ^{238}U is bombarded with ^{238}U ions.[2] In this Letter we report on actinide production in the $^{238}U + ^{248}Cm$ reaction, which is found to be even larger than theoretically estimated.[2] A comparison of actinide cross sections from $^{238}U + ^{238}U$ and $^{238}U + ^{248}Cm$ collisions reveal great similarities in the reaction mechanisms. We predict the cross section for production of $Z = 114$ in the $^{238}U + ^{248}Cm$ reaction.

The experiments were performed with 10-MeV/u ^{238}U ions at the UNILAC accelerator. The integral particle numbers varied from 1.7×10^{14} to 2.9×10^{15}. Metal targets containing 3.2 and 7.27 mg/cm^2 ^{248}Cm (97% isotopic purity) were produced by evaporation onto Mo foils[3] and were mounted in a target and recoil chamber based on a previous design.[4] Before the beam entered the ^{248}Cm target, windows and cooling gas reduced the energy to 7.4 MeV/u as ascertained by measurements with a surface-barrier detector. The target thicknesses were sufficient to degrade the beam energy E further to near or below the Coulomb barrier B ($1.18 \geq E/B \geq 1.09$ or 0.96). Reaction products emitted within laboratory angles of $\leq 55°$ were stopped in a copper catcher. Chemical fractions of $_{84}Po$, $_{85}At$, and $_{96}Cm$ through $_{102}No$ were separated by gas-phase or high-performance liquid chromatography[5] within about 1 h after irradiation. The fractions were assayed for γ-ray, α-particle, and spontaneous-fission activities over a period of several months. The cross sections deduced from separate experiments were found to be reproducible within the error limits.

The formation cross sections for transcurium

isotopes in the $^{238}U + ^{248}Cm$ reaction are shown in Fig. 1. They are compared with thick-target cross sections for the $^{238}U + ^{238}U$ reaction at 7.5 MeV/u incident energy.[1] This comparison is meaningful because roughly the same energy window was available for dissipation in both experiments and because at these incident energies the whole excitation function[1] is physically integrated inside the thick target. The cross sections for $_{100}Fm$, $_{99}Es$, and $_{98}Cf$ are three to four orders of magnitude higher than in the $^{238}U + ^{238}U$ reaction. These increases are larger than theoretically estimated.[2] For $^{259}_{102}No$ we set an upper cross section limit of 30 nb.

The measured cross sections for the much less fissile projectilelike fragments $_{84}Po$ and $_{85}At$ are about the same in the $^{238}U + ^{248}Cm$ and $^{238}U + ^{238}U$ reactions, indicating that the integral, primary yield distribution is nearly the same in both reactions. This suggests that also the primary actinide yields before fission are the same for a given $(\Delta Z, \Delta N)$ transfer in both systems. The experimental observation of different cross sections for the evaporation residues of targetlike fragments from these same $(\Delta Z, \Delta N)$ channels could therefore either indicate differences in the reaction mechanism, or simply reflect the different fission probabilities of the then different product nuclei. In order to test the latter hypothesis, we assume that for the same $(\Delta Z, \Delta N)$ channels excitation energies and angular momenta are the same. Then, it is reasonable to approximate the ratios of cross sections $\sigma(U+U)/\sigma(U+Cm)$ for a given channel by the ratio of relative neutron decay widths,

$$\prod_{i=1}^{x} \langle \Gamma_n/\Gamma_{tot}\rangle_{i(U+U)} / \prod_{i=1}^{x} \langle \Gamma_n/\Gamma_{tot}\rangle_{i(U+Cm)},$$

using angular-momentum–independent, effective values of Γ_n/Γ_f averaged over x deexcitation steps, such as the empirical values of Sikkeland *et al.*[6] Inherent in this approach is the assumption that modifications of the fission probabilities by excitation energy and angular momentum cancel to a good approximation. Starting from the measured yields for $_{95}Am$ $(\Delta Z = 3)$ through $_{97}Bk$ $(\Delta Z = 5)$ in the $^{238}U + ^{238}U$ reaction[1] we calculated cross sections for $_{99}Es$ $(\Delta Z = 3)$ through $_{101}Md$ $(\Delta Z = 5)$ in the $^{238}U + ^{248}Cm$ reaction for given values of x. The results (Fig. 2) show that an average of $x = 3$ to 4 evaporated neutrons is consistent with the data for the heavier actinides implying average excitation energies of about 30 MeV in the surviving heavy fragments. This is also consistent with the difference between the observed mass numbers $\langle A\rangle$ associated with the peak cross section for a given element (Fig. 1) and the primary mass numbers $\langle A'\rangle$ calculated by minimization of the potential energy[7] for two

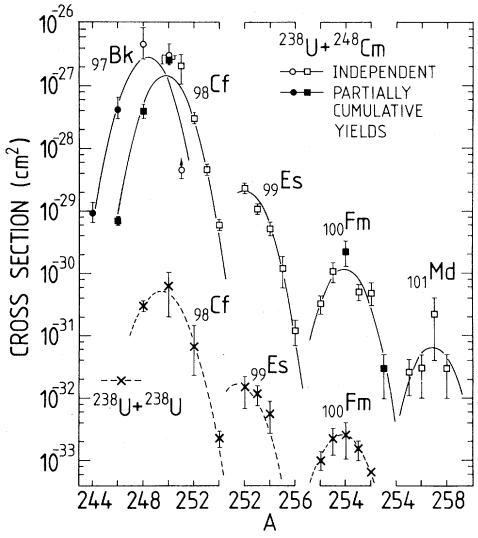

FIG. 1. Cross sections for the formation of transcurium isotopes in the $^{238}U + ^{248}Cm$ reaction at 7.4 MeV/u incident energy. For comparison, data for the $^{238}U + ^{238}U$ reaction at ≤ 7.5 MeV/u from Ref. 1 are shown. The curves are drawn to guide the eye. The lower limit for the yield of ^{251}Bk is based on γ-ray intensities of $\leq 70\%$ and $\leq 30\%$ for the 177 and 153 keV transitions, respectively.

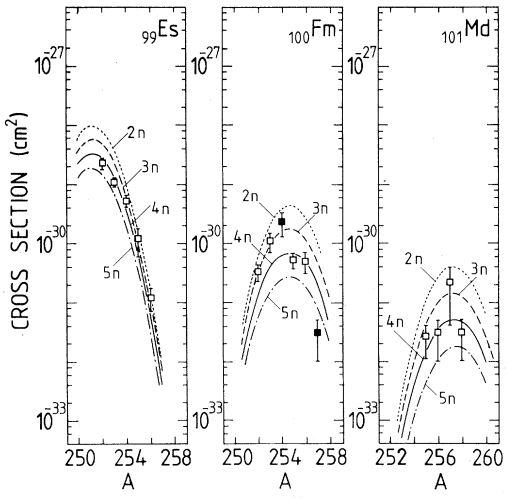

FIG. 2. Comparison of measured (symbols) and calculated (curves) isotope populations in the $^{238}U + ^{248}Cm$ reaction. The calculations for $2n-5n$ deexcitation channels are outlined in the text.

touching spherical liquid drops, where $\langle A' \rangle - \langle A \rangle = x$. Earlier, we had found the same values of $x = 3$ to 4 for the $^{238}U + ^{238}U$ reaction[1] which, in turn, confirms that the reaction mechanism is very nearly the same in both these reactions. Assuming $x = 4$ for the production of Md and No in the $^{238}U + ^{248}Cm$ reaction we calculate cross sections of about 10 nb for ^{260}Md, 2 nb for ^{261}Md, and 1 nb for $^{259}_{102}No$ and $^{260}_{102}No$.[8]

A similar analysis of the primary and residual masses, $\langle A' \rangle - \langle A \rangle$, applied to the systems $^{136}Xe + ^{238}U$ (Ref. 1) and $^{136}Xe + ^{248}Cm$ (Ref. 9) gives the best fit to the observed mass yields when it is assumed that on the average $x = 2$ to 3 neutrons are emitted from the primary targetlike fragment. The available energies (in the absence of angular momentum and fragment deformation), the ground-state Q values, Q_{gg}, and the resulting ranges of excitation energies in the heavy fragment are summarized in Table I for $\Delta Z = 4$. Table I also contains data for several light-ion reactions, where the residual mass numbers[10,11] and the corresponding excitation energies are consistent with the emission of $x \simeq 1 \pm 1$ neutron. The inclusion of these latter reactions in Table I may, however, be problematic because (i) no excitation functions are available so that the possible contributions of higher xn channels to the cross sections at energies comparable to the ^{136}Xe and ^{238}U studies are unknown, (ii) the bombbombarding energies[11] were so close to the interaction barrier that transfer of protons was energetically only possible *from the projectile to the target*, and (iii) breakup of the projectile and subsequent incomplete fusion may contribute to the observed cross sections. Nevertheless, a common picture seems to be emerging from Table I: If we assume that each evaporated neutron carries away ~8 MeV of excitation energy, then the number of evaporated neutrons together with the value of Q_{gg} gives an estimate of 40–50 MeV for the range of kinetic energy losses (TKEL) associated with the dominant cross section for surviving actinides in all cases considered.

With respect to the cross sections for producing *nearby* actinides on ^{248}Cm targets, it is surprising to see that, apart from the expected shifts in the centroids $\langle A \rangle$ of the individual isotope distributions, the peak yields[1,9-11] for all projectiles are of the same order of magnitude (with some tendency for the ^{136}Xe and ^{48}Ca cross sections to be the lower and for ^{18}O and ^{238}U to represent the upper extremes).

Thus, the *major* differences associated with actinide production in all these reactions are the different values of x ranging from 1 to 4. Because Γ_n/Γ_f is of the order of 0.1 (Fm), yield losses due to prompt fission vary over 1 to 4 orders of magnitude. Then, in order for the same residual cross sections to be observed, the same bin of TKEL $\simeq$ 40–50 MeV must be populated with probabilities differing by up to three orders of magnitude for these different projectiles. Thus, the huge gain in primary cross section for the

TABLE I. Comparison of the energetics and the dominant deexcitation channels for actinide production in transfer reactions with $\Delta Z = 4$.

Ref.	Reaction[a]	$E_{c.m.}$ (MeV)[b]	E_{ex} (MeV)[c]	Q_{gg} (MeV)[d]	E_h^* (MeV)[e]	Channel[f]
1	$^{238}U(^{238}U, ^{228}Ra)^{248}Cm$	893–730	729	− 2	85–0	$(3-4)n$
This work	$^{248}Cm(^{238}U, ^{228}Ra)^{258}Fm$	899–757	755	− 5	74–0	$(3-4)n$
1	$^{238}U(^{136}Xe, ^{128}Sn)^{246}Cm$	649–462	448	−18	120–0	$(2-3)n$
9	$^{248}Cm(^{136}Xe, ^{128}Sn)^{256}Fm$	559–513	464	−17	52–22	$(2-3)n$
10	$^{248}Cm(^{48}Ca, ^{41}S)^{255}Fm$	224–204	168	−40	13–0	$1n$
11	$^{248}Cm(^{22}Ne, ^{15}C)^{255}Fm$	109–104	69	−34	6–0	$1n$
11	$^{248}Cm(^{20}Ne, ^{15}C)^{253}Fm$	109–104	69	−29	11–5	$1n$
11	$^{248}Cm(^{18}O, ^{10}Be)^{256}Fm$	89–84	47	−32	10–5	$1n$
11	$^{248}Cm(^{16}O, ^{10}Be)^{254}Fm$	95–89	47	−31	16–11	$1n$

[a] The considered exit channel represents the most probable mass split predicted by the minimum potential energy of two touching spherical liquid drops.

[b] Bombarding energy as calculated from the incident energy and the effective target thickness.

[c] Exit channel barrier for spherical fragments at $R_{ex} = 1.16\ (A_1^{1/3} + A_2^{1/3} + 2)$ fm.

[d] Calculated from experimental ground-state masses.

[e] Heavy-fragment excitation energy if one assumes partition of the total excitation energy proportional to the fragment masses.

[f] Dominant xn channel (see text); the uncertainties in x are about ± 1.

heavier projectiles is largely compensated by the concurrent decrease in survivability because of the much less favorable Q_{gg} values.

The noted small differences in the residual cross sections (factors 5–10 at most for $\Delta Z = 4$) for nearby actinides formed in collisions of different projectiles with ^{248}Cm targets seem to become more significant for larger values of ΔZ as is indicated by the data for ^{48}Ca (Ref. 12), ^{136}Xe (Ref. 1), and ^{238}U (Ref. 1) bombardments of ^{238}U targets where transfers with $\Delta Z \leq 8$ could be observed. These finer details may be associated with the single-particle structure of the colliding nuclei[13]; however further analysis has to await more detailed experimental information, in particular on excitation functions which, at present, is available only for the ^{238}U + ^{238}U reaction.[1]

In summary, the gross trends in the yield curves for actinide production seem to indicate a balance between increasing mass transfer probability with increasing mass of the projectile and a concurrent decrease in survivability because of an increase in excitation energy. This makes the use of ^{238}U projectiles not notably more favorable for the production of new neutron-rich heavy actinides than, e.g., ^{18}O. However, for the production of superheavy elements the advantage of ^{238}U projectiles would be the very large mass transfer probability and the high neutron-to-proton ratio which makes it possible to reach neutron-rich areas in the "island of stability" inaccessible to transfer or fusion reactions with lighter projectiles. The areas in these reactions lie on the neutron-deficient side of the island where fission barriers are expected to be decreasing rapidly. We have also seen that great similarities exist in the reaction mechanisms of ^{238}U + ^{238}U and ^{238}U + ^{248}Cm collisions. This gives some confidence in using the experimental data[7] on Z and TKEL distributions for the ^{238}U + ^{238}U reaction to predict cross sections for $Z = 114$ in the ^{238}U + ^{248}Cm reaction. For excitation energies of 25–35 MeV (which are possible due to the large negative Q_{gg}) we estimate a cross section of 10^{-32} cm^2 which is a factor of 30 higher than the estimate for the ^{238}U + ^{238}U reaction.

We wish to thank B. Haefner, E. Schimpf, W. Schorstein, and W. Weber for their cooperation. We wish to thank the U. S. Department of Energy for supporting this research and the U. S. Office of Basic Energy Science and the Oak Ridge National Laboratory for the production and isolation of the ^{248}Cm used as the target isotope. This work was supported by a grant from the Bundesministerium für Forschung und Technologie, Federal Republic of Germany.

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