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HEAVY ACTINIDE CROSS SECTIONS IN THE $^{238}U + ^{248}Cm$ Reaction

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Over the past three years our group has been interested in the possibility of using damped heavy ion collisions to produce superheavy elements. By studying the production of highly-fissionable, nearby actinides by transfer reactions we had hoped to shed some light on the possibility of forming superheavy elements in the same reaction process. The superheavy elements are expected to be similar to the heavier actinides with respect to the magnitude of their fission barriers. If so, they would survive their birth to about the same extent as the actinides provided the same risks prevailed, i.e. the same excitation energies and angular momenta. In turn, the influence on survival probability of varying these parameters could be roughly evaluated by comparing the yields of the same actinide isotopes produced in bombardments with light, medium, and very heavy ions.

Strong enhancements in the production of Cm, Cf, Es and Fm isotopes were observed[1] when ^{238}U was used to bombard ^{238}U as compared to using ^{136}Xe. The actinide yields for these two projectiles are compared in Fig. 1. An analysis of the $^{238}U + ^{238}U$ cross sections revealed[1] that most of the heavy products that survived were formed in the low energy tails of the energy-loss distributions. Nevertheless, we found that on the average as much as 3-4 neutrons were emitted from the primary fragments implying excitation energies of 30-40 MeV in the heavy fragments that survived birth in $^{238}U + ^{238}U$ collisions. In the $^{136}Xe + ^{238}U$ reaction an equally large mass transfer at the same energy-loss should result in heavy actinide production at considerably lower excitation energies (resulting in much larger survivabilities) because of the much more negative Q_{gg}-values. For example, for Cf-production $Q_{gg} = -33$ MeV for $^{136}Xe + ^{238}U$, whereas the excitation energy is reduced by only $Q_{gg} = -2$ MeV with the ^{238}U projectile. Allthemore, the factors of > 10 increase in actinide production with ^{238}U ions have to be considered as evidence for a much larger primary yield before fission with heavier projectiles like ^{238}U. This was particularly persuasive in leading us to study actinide production in the $^{238}U + ^{248}Cm$ reaction.

The experiment was performed with 7.4 MeV/u ^{238}U ions incident on a thick metallic ^{248}Cm target. Details on the difficult task of safely handling such a highly active target in an intense ^{238}U beam are given elsewhere.[2] Products formed in the bombardment recoiled from the target and were collected on Cu foils placed close behind the target. The actinides were chemically separated into element fractions which were then assayed for alpha- and spontaneous fission activities over a period of several months. The results are shown in Fig. 2. The observed cross sections for Cf, Es, and Fm production are 3-4 orders of magnitude larger than in the $^{238}U + ^{238}U$ reaction. However, a direct comparison of cross sections measured for a given isotope made by different target-projectile combinations is misleading. A more meaningful judgement involves comparison of the yields for the same (xp, yn)-transfer and a proper account of the fact that the fission barrier heights vary considerably from element to element. This comparison also requires knowledge about the primary yield distribution before fission. Therefore, we measured simultaneously the yields of evaporation residues from the much less fissile projectile-like fragments $_{84}Po$ and $_{85}At$. The latter were found to have the same cross sections within the error limits as determined previously in the $^{238}U + ^{238}U$ reaction,[1] indicating that the integral primary yield distribution has nearly the same width in both reactions. Then, if we shift the reconstructed primary distribution of target-like fragments in the $^{238}U + ^{238}_{92}U$ reaction[1] by four charge units to $^{248}_{96}Cm$ and appropriately deplete the primary yields by Γ_n/Γ_f the measured actinide cross sections in the $^{238}U + ^{248}Cm$ reaction can be reproduced, see Fig. 3. These calculations show that an average of 3-4 neutrons are emitted from the primary fragments implying average excitation energies of 30-40 MeV in the heavy fragments that survived birth in the $^{238}U + ^{248}Cm$ reaction. This is entirely consistent with earlier findings for the $^{238}U + ^{238}U$ reaction[1] and implies that the energy- and angular momentum distributions associated with given (xp, yn)-channels are nearly the same in both reactions. On the basis of the phase space available above the minimum of the potential energy surface V(A',Z) and Q_{gg}-values this result is expected, see Fig. 4: Both the dependence of V(A',Z) and Q_{gg}(A',Z) on the charge of the heavy fragment are quite similar in both reactions. The possible drift of the $^{238}U + ^{238}U$ system into the potential energy minimum near Z_ℓ=82, Z_h=102 has been treated theoretically by Schmidt and Wolschin,[3] and by Grossmann.[4] In a qualitative sense a similar drift is not expected for reactions such as $^{48}Ca + ^{238}U$ or $^{136}Xe + ^{238}U$ where, on the contrary, the system finds itself "trapped" in a potential energy minimum near the injection point, see Fig. 4. Despite the much more negative Q_{gg}-values involved in the latter reactions the net production of heavy actinides is significantly less than with the ^{238}U projectile, see again Fig. 1.

If the probability for large mass transfer together with little excitation energy is indeed related to the shape of the potential energy surface we can make some qualitative predictions for reactions of the same projectiles with the $^{248}_{96}Cm$ target on the basis of Fig. 4. Even though local minima in the potential energy occur again for ^{48}Ca and ^{136}Xe, the absolute values of V(A',Z) in the Z-region accessible to the experiment are the same as for ^{238}U within a few MeV. Only for $Z \geq 100$ should we expect increasingly significant differences in the net actinide production in favor of the ^{238}U + ^{248}Cm system.

Also shown in Fig. 2 are actinide yields from the ^{48}Ca + ^{248}Cm reaction[5] at a comparable ratio E/B ≈ 1.1 which allows a meaningful comparison with the ^{238}U + ^{248}Cm data. Similarly, ^{136}Xe + ^{248}Cm actinide cross sections were measured recently by a Livermore-Berkeley collaboration[6] and were found to be very close to the ^{48}Ca + ^{248}Cm yields. In qualitative agreement with the potential energy considerations we find that the enhancement in the yield of Cm and Cf-isotopes found in ^{238}U + ^{238}U vs. ^{136}Xe + ^{238}U had almost disappeared when ^{248}Cm was bombarded with these same projectiles. Then, for $_{100}Fm$ the yields in the ^{48}Ca + ^{248}Cm and ^{136}Xe + ^{248}Cm reactions were again reduced significantly relative to ^{238}U + ^{248}Cm, and $_{101}Md$ could not be detected any more with the ^{48}Ca and ^{136}Xe projectiles. Apparently, for very large mass transfer, reactions with the ^{238}U projectile are better suited due to an increased mass transfer probability which is, however partially balanced by the concurrent decrease in survivability because of an increase in excitation energies.

In summary, we have found some evidence for the influence of the potential energy surface on the probability for large mass transfer at modest excitation energies. The effect of washing-out of ground-state shell effects on both the primary mass flow and on the absolute values of Γ_n/Γ_f is still an open question which deserves further study.

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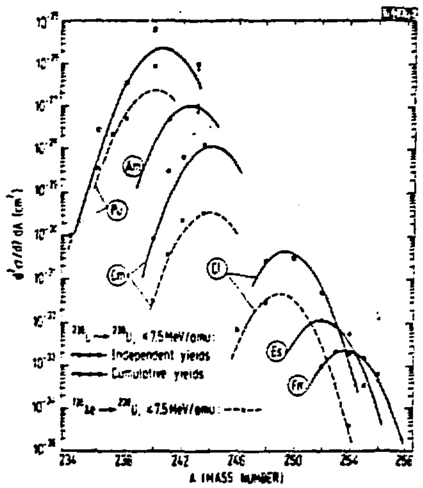
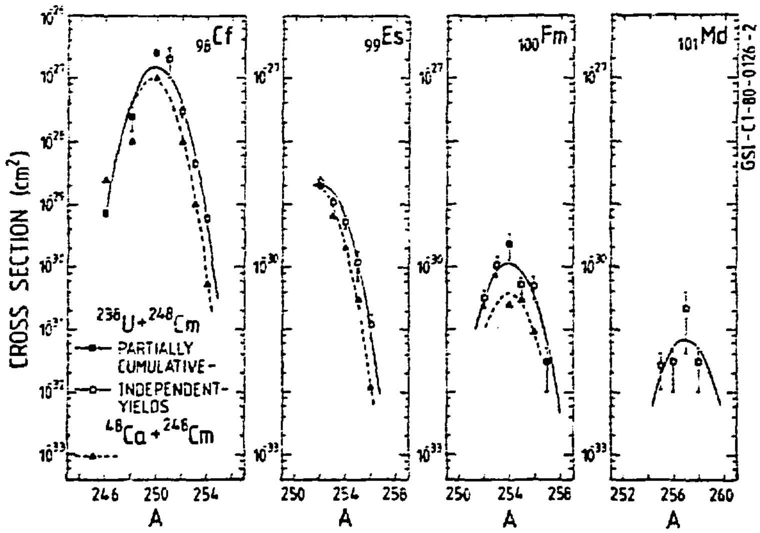


Fig.1 Cross sections for the formation of heavy actinides in the reactions of 7.5 MeV/u ^{136}Xe and ^{238}U-projectiles with ^{238}U-targets (Ref.1).

Fig.2 Cross sections for the production of Cf, Es, Fm, and Md isotopes in the reaction of 7.4 MeV/u ^{238}U-ions with ^{248}Cm targets. Shown for comparison are similar results for $^{48}Ca+^{248}Cm$ (Ref.5).



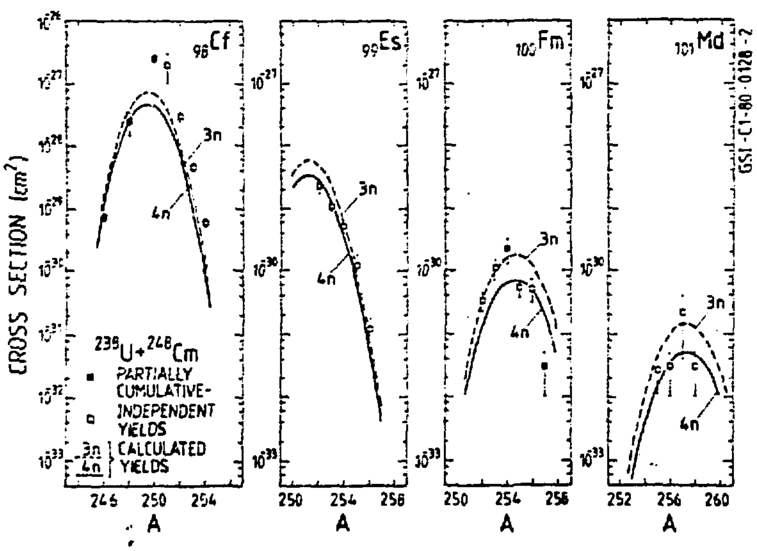


Fig.3

$^{238}U+^{248}Cm$ cross sections from Fig.2 and calculated cross sections for the 3n and 4n channels based on the primary yield distribution and empirical values of Γ_n/Γ_f in the $^{238}U+^{238}U$ reaction. The yield distribution was shifted from $^{238}_{92}U$ to $^{248}_{96}Cm$ and the higher fissility of the resulting (xp,yn)-products was appropriately taken into account.

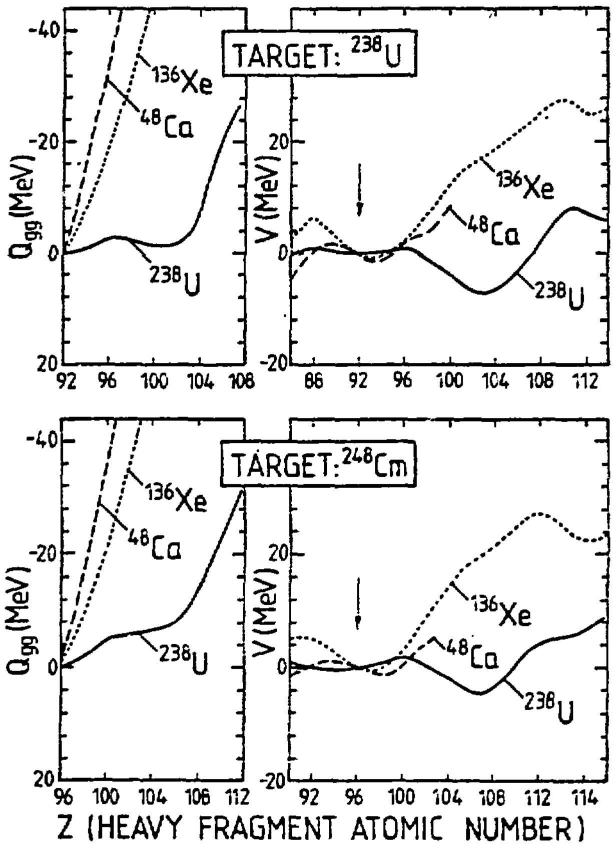


Fig.4 Left hand side: Ground-state Q-values, Q_{gg}, associated with the formation of heavy fragments in transfer reactions of various projectiles with ^{238}U- and ^{248}Cm-targets.
Right hand side: Minimum of the potential energy surface vs. charge number Z of the heavy fragment in transfer reactions of various projectiles with ^{238}U- and ^{248}Cm-targets. The potential V is normalized to the entrance channel. Q_{gg} is calculated for shell-corrected ground-state liquid drop masses. The differences in the coulomb potential and in the nuclear potential (proximity potential) between entrance and exit channel are added to the ground-state Q-value, the difference in the centrifugal potential is neglected (ℓ=0). The potentials are calculated for a nuclear distance equal to the sum of the half-density radii. The injection point is indicated by the arrow.