Sub-barrier quasifission in heavy element formation reactions with deformed actinide target nuclei

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Background: The formation of superheavy elements (SHEs) by fusion of two massive nuclei is severely inhibited by the competing quasifission process. Low excitation energies favor SHE survival against fusion-fission competition. In "cold" fusion with spherical target nuclei near ^{208}Pb, SHE yields are largest at beam energies significantly below the average capture barrier. In "hot" fusion with statically deformed actinide nuclei, this is not the case. Here the elongated deformation-aligned configurations in sub-barrier capture reactions inhibits fusion (formation of a compact compound nucleus), instead favoring rapid reseparation through quasifission.
Purpose: To determine the probabilities of fast and slow quasifission in reactions with prolate statically deformed actinide nuclei, through measurement and quantitative analysis of the dependence of quasifission characteristics at beam energies spanning the average capture barrier energy.
Methods: The Australian National University Heavy Ion Accelerator Facility and CUBE fission spectrometer have been used to measure fission and quasifission mass and angle distributions for reactions with projectiles from C to S, bombarding Th and U target nuclei.
Results: Mass-asymmetric quasifission occurring on a fast time scale, associated with collisions with the tips of the prolate actinide nuclei, shows a rapid increase in probability with increasing projectile charge, the transition being centered around projectile atomic number $Z_P = 14$. For mass-symmetric fission events, deviations of angular anisotropies from expectations for fusion fission, indicating a component of slower quasifission, suggest a similar transition, but centered around $Z_P \sim 8$.
Conclusions: Collisions with the tips of statically deformed prolate actinide nuclei show evidence for two distinct quasifission processes of different time scales. Their probabilities both increase rapidly with the projectile charge. The probability of fusion can be severely suppressed by these two quasifission processes, since the sub-barrier heavy element yield is likely to be determined by the *product* of the probabilities of surviving each quasifission process.

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I. INTRODUCTION

Superheavy nuclei—isotopes of elements with atomic number $Z \geqslant 104$—are created in the laboratory by fusion of two heavy nuclei. There are three sequential processes involved in superheavy element (SHE) synthesis by fusion followed by neutron evaporation. The fastest is capture, where the two nuclear surfaces "stick" together. This is followed by shape evolution to form a compact compound nucleus, and finally survival as an evaporation residue (ER) against statistical fission decay. Because of the different typical time scales of each process, the cross section for heavy element formation is written as the product of factors related to the three stages of formation:

$$\sigma_{ER} = \sum_{J=0}^{\infty} \sigma_J(E_{c.m.},J)P_{\rm CN}(E_x,J)W_{\rm sur}(E_x,J). \qquad (1)$$

Here $\sigma_J(E_{c.m.},J)$ is the capture cross section as a function of center-of-mass energy $E_{c.m.}$ and angular momentum $J\hbar$. It is the fastest process, occurring in $\sim 10^{-21}$ s. $P_{\rm CN}(E_x,J)$ is the probability that the system reaches the compact compound nucleus equilibrium configuration, expressed as a function of the excitation energy E_x and J. $P_{\rm CN}$ can reduce SHE cross sections by several orders of magnitude, through the separation of the system formed after capture into two fissionlike fragments (quasifission) on a time scale of $\sim 10^{-20}$ s [1–4]. For fusion reactions forming much lighter nuclei, $P_{\rm CN} = 1$, and thus capture and fusion need not be distinguished. $W_{\rm sur}(E_x,J)$ is the probability that the system survives statistical fission decay through sequential particle evaporation, thus eventually

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