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Capture cross sections for the synthesis of new heavy nuclei using radioactive beams

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We have measured the capture-fission excitation functions for the reaction of stable ^{39}K and radioactive ^{46}K with ^{181}Ta using the ReA3 facility at the National Superconducting Cyclotron Laboratory. In addition the capture-fission excitation function for the $^{39}\text{K} + {}^{181}$Ta reaction was measured at Australian National University . The capture cross sections for the $^{46}\text{K} + {}^{181}$Ta reaction are larger than those for the ^{39}K induced reactions in the near barrier region although the reduced excitation functions for the two reactions do not indicate any fundamental differences between the reactions. The results of the measurements are compared to modern phenomenological models and microscopic time-dependent Hartree-Fock calculations. The implications of these measurements for the synthesis of heavy nuclei at radioactive beam facilities are discussed.

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Formally, the cross section for producing a heavy evaporation residue σ_{EVR} in a fusion reaction can be written as

$$\sigma_{\text{EVR}}(E) = \frac{\pi h^2}{2\mu E}\sum_{\ell=0}^{\infty}(2\ell+1)T(E,\ell)P_{\text{CN}}(E,\ell)W_{\text{sur}}(E,\ell), \quad (1)$$

where E is the center of mass energy, μ is the reduced mass, ℓ is the orbital angular momentum, and T is the probability of the colliding nuclei to overcome the potential barrier in the entrance channel and reach the contact point where the initial kinetic energy was dissipated. P_{CN} is the probability that the projectile-target system will evolve from the contact point to the compound nucleus. W_{sur} is the probability that the compound nucleus will decay to produce an evaporation residue rather than fissioning. To understand the synthesis of new heavy nuclei, one must understand each of the terms in this equation.

The capture cross section is, in the language of coupled channel calculations, the "barrier crossing" cross section. It is the sum of the quasifission, fast fission, fusion-fission, and fusion-evaporation residue cross sections. The barriers involved are the interaction barriers and not the fusion barriers. The subject of capture and fusion cross sections is the subject of a recent comprehensive review article [1]. There are several models for capture cross sections [2–6]. Each of these models was calibrated by fitting a set of fusion-capture data. In general, these models have been shown to predict the magnitudes of these capture cross sections within 50% and the values of the interaction barriers within 20% [7].

However, when the predictions of these models are compared with measured data for capture cross sections for reactions involving neutron-rich projectiles, such as $^{31}\text{Al} + {}^{197}\text{Au}$, $^{26}\text{Mg} + {}^{248}\text{Cm}$, $^{48}\text{Ca} + {}^{154}\text{Sm}$, ^{238}U, ^{248}Cm, and $^{64}\text{Ni} + {}^{238}$U, the agreement between prediction and data is much worse. For example, in Fig. 1, one notes that the agreement between models and data gets worse as the Z of the completely fused system increases and the agreement is also worse at lower energies. While the capture cross section is not the least well known of the three factors affecting heavy element synthesis, it is vexing that this simple quantity is not better described. This work described in this paper addresses this issue.

A number of authors have tried to assess the possibility of using neutron-rich projectiles, especially those available at radioactive beam facilities, to synthesize new neutron-rich heavy nuclei [8–13]. (It should be noted that all the known isotopes of elements 100–118 are neutron deficient relative to β stability.) The problem is that to make new superheavy ($Z > 118$) nuclei, the production cross sections are at the sub-picobarn level, and radioactive beam facilities do not have the requisite beam intensities of $>10^{12}$ pps.

Does that mean that radioactive beams have no role in the synthesis of neutron-rich heavy nuclei? Loveland [20,21] and Hong, Adamian, and Antonenko [22] have pointed out

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