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A new framework to investigate the systematics of fusion probabilities in heavy element formation: Application to Th isotopes

D.J. Hinde, M. Dasgupta

Department of Nuclear Physics, Research School of Physical Sciences and Engineering, Australian National University, Canberra, ACT 0200, Australia

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Abstract

A new framework for comparing fusion probabilities in reactions forming heavy elements is presented, which eliminates both theoretical and experimental uncertainties, and gives new insights into systematic behavior. For the first time, it can be seen that in reactions forming neutron-deficient isotopes of Th, the probabilities of forming a compact compound nucleus after capture follow a simple universal trend at energies above the capture barriers, with the nuclear structure of the colliding nuclei having a smaller influence than the mass-asymmetry. Surprisingly, the yields of specific Th isotopes appear to have little dependence on the number of neutrons evaporated, contrary to general expectations from statistical decay.

Keywords: Nuclear fusion; Quasi-fission; Heavy element formation

The fusion process leading to the formation of heavy elements is divided conceptually into two stages. The first is capture of the two nuclei due to the nuclear attraction between their surfaces. Then the elongated dinucleus formed at contact must explore the potential energy surface (PES), and find with probability P_{CN} the compact compound nucleus (CN) shape at the potential minimum. If the CN survives subsequent statistical fission decay, with probability W_{ER} (by means of particle evaporation to an excitation energy E^* below the fission threshold), then an evaporation residue (ER) results, and a heavy element has been formed. Conceptually, the ER cross-section can be written as the product of the capture cross section σ_{cap} and angular momentum weighted fusion and survival probabilities P_{CN} and W_{ER}:

$$\sigma_{ER} = \sigma_{cap} P_{CN} W_{ER}. \tag{1}$$

E-mail address: david.hinde@anu.edu.au (D.J. Hinde).

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In fusion reactions forming lighter elements [1] essentially all capture leads to formation of a CN, i.e., $P_{CN} = 1$. However, for heavier elements $P_{CN} < 1$, since after capture many nuclei fail to reach the compact CN shape, instead undergoing fission from a more elongated shape. This process is called quasi-fission (QF) [2,3], and result in a distribution of fission events having different characteristics from fusion–fission (FF) following formation of a compact CN. Quasi-fission competition can suppress the cross sections for very heavy element formation by many orders of magnitude. It is very important to understand quantitatively the quasi-fission process, in order to optimize heavy element production. However, because of its complexity, it is difficult to model in a realistic way.

The variables influencing P_{CN} can be studied experimentally by measuring cross sections for a range of reactions of different projectile and target nuclei, forming the same dinucleus, and later compound nucleus. Because of the difficulty of separating fusion–fission from quasi-fission (since their properties have considerable overlap), the most reliable indication of formation of a compact CN is the observation of ERs. At above-barrier energies, where the partial waves giving ERs are fully populated, W_{ER} is the same for each reaction, thus the ratios of ER yields for different reactions give directly the corresponding ratios of P_{CN} [7], without any direct measurement of the competing quasi-fission (or deep-inelastic) reaction process.

Nuclear shell structure can affect P_{CN}, as it causes local maxima and minima in the PES over which the system must move to reach the CN shape. Significant features are the so-called "cold valleys", corresponding to magic numbers of neutrons and/or protons in the two parts of the dinucleus. Fusion through the cold valleys is advantageous, as it allows formation of a CN at low E^*, giving a larger W_{ER}. Shell structure may also result in reduced friction in the cold valleys (due to fewer single-particle level crossings [4]) thus assisting fusion. This is, however, a complex dynamical situation. The colliding nuclei are initially cold, thus the temperature (energy dissipated) at a later time is determined by the strength of the friction experienced. However, the friction should in turn depend on the temperature, through the washing out of the effect of shell gaps by single-particle excitations. Thus the quantitative nature of this effect, and its dependence on kinetic energy, is uncertain. Another effect of nuclear structure is the effect on P_{CN} of the orientation of statically deformed nuclei at capture. Based on measurements of quasi-fission properties, it was suggested [5] that collisions with the tips of prolate deformed nuclei favour quasi-fission, thus reducing P_{CN}. Measured ER yields [6] have supported this picture. A better understanding of the effects of shell structure on P_{CN} is essential to allow the development of realistic models of heavy element formation, where shell structure surely plays a crucial role.

To investigate the role of shell structure in determining heavy element yields, comparisons of yields for reactions of nuclei with different shell structure should be performed in a systematic way. The aim of this Letter is to present a new general framework allowing model-independent investigation of the dependence of ER yields, and thus fusion probabilities, on shell structure, and on any other variables that they may be sensitive to. This new approach eliminates experimental and theoretical uncertainties, and allows for the first time systematic comparisons of an unlimited range of data.

To be sensitive to differences in P_{CN}, heavy nuclei should be formed, having $P_{CN} \ll 1$, but not so heavy that ER yields are too small to allow systematic measurements. Many suitable measurements of ER cross sections for reactions forming different Th compound nuclei have been made, at various laboratories, in the last 20 years. Analyses [8] within the framework of the extra-push model assumed P_{CN} approaches unity for *all* reactions at sufficiently high beam energy, whilst evidence of the effects of shell structure has been claimed [9] at low energies. Recently, measurements of ER cross sections for $^{16}O + ^{204}Pb$, forming ^{220}Th, showed [10] that for projectiles of ^{40}Ar and heavier forming the same CN, the values of P_{CN} even at the highest beam energies are only ~ 0.1, with some dependence on entrance-channel mass-asymmetry. All these reactions forming Th compound nuclei, now known to satisfy the criterion $P_{CN} \ll 1$, are simultaneously interpreted for the first time, using our new framework.

The emission of charged particles during the dynamical transition from contact to the compact CN can dramatically increase the ER yield in reactions forming fissile nuclei. However, interpretation of the total ER yield requires a reliable model framework which explicitly includes the couplings between charged