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Dynamical hindrance to neutron-rich-projectile-induced fusion

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We show that the inclusion of the dynamics after contact in a heavy-ion collision can completely modify the predictions of superheavy element production through fusion induced by neutron-rich-projectile nuclei.

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Since the advent of heavy-ion accelerators it has been possible to synthesize new elements [1] exploiting the fusion process. The resulting neutron numbers, however, tend to be lower than those corresponding to the stability line. Neutron-rich projectiles are thus expected to favor the formation of nuclei closer to the valley of β stability. Besides leading to more stable products, these exotic projectiles present several other desirable characteristics. They are expected to possess large halos of loosely bound neutrons which reduce significantly the height of the Coulomb barrier. Also, in these nuclei one expects to find soft giant dipole resonances in which the nuclear core oscillates inside the neutron halo [2]. It has been shown that these resonances increase markedly the probability of nuclear contact at low energies [3] and should consequently enhance the fusion cross section.

Recently this effect was discussed in regard to the synthesis of superheavy elements, and it was speculated that it constituted a viable route for their production [4]. In that work, however, the dynamics of the nuclear system after contact was not taken into account. It is important to realize that for such heavy systems the strong Coulomb forces and energy dissipation conspire to hinder the fusion process. These effects have been widely discussed in the literature [5,6] and recently studied specifically for the case of neutron-rich projectiles [7]. In this work we discuss their relevance and consequences for the formation of very heavy elements. To this end we calculate the fusion probability for a head-on collision in two stages, as we indicate below.

The approach and contact phase of the process is described using the same procedure as in Ref. [3]. The coordinates that characterize the motion are the distance between the centers of mass of the two nuclei, r, and the amplitude of the oscillation of the neutron skin with respect to the core, α. The evolution of the system is then described by a Hamiltonian of the form

$$H(r,p,\alpha,\Pi)=\frac{p^2}{2m}+\frac{\Pi^2}{2D}+\frac{C}{2}\alpha^2+V_{\text{coup}}(r,\alpha)\,, \qquad (1)$$

where m is the reduced mass, p and Π are the momenta canonically conjugated to r and α, and C and D are the restoring force and mass parameters of the collective vibration. These last two quantities are related to the energy $\hbar\omega$ and deformation parameter β of the mode. The coupling term between relative motion and intrinsic variables, V_{coup}, includes both the Coulomb and the surface-surface nuclear interactions. To incorporate quantal effects associated with the excitation of the harmonic degree of freedom we consider an ensemble of initial conditions in the $\alpha\Pi$ plane that are consistent with the ground-state distribution of the dipole mode and study its time evolution by solving the equations of motion derived from Eq. (1). A trajectory of this ensemble reaches the contact configuration when the radial distance r becomes less than the radius of the Coulomb barrier r_B. A neck joining the two nuclei begins to form [8] and at this point one has to take into account this degree of freedom as well as the strong dissipation that sets in.

For this second stage of the collision process we use a schematic dynamical model due to Swiatecki [5], which incorporates as its main ingredients the conservative

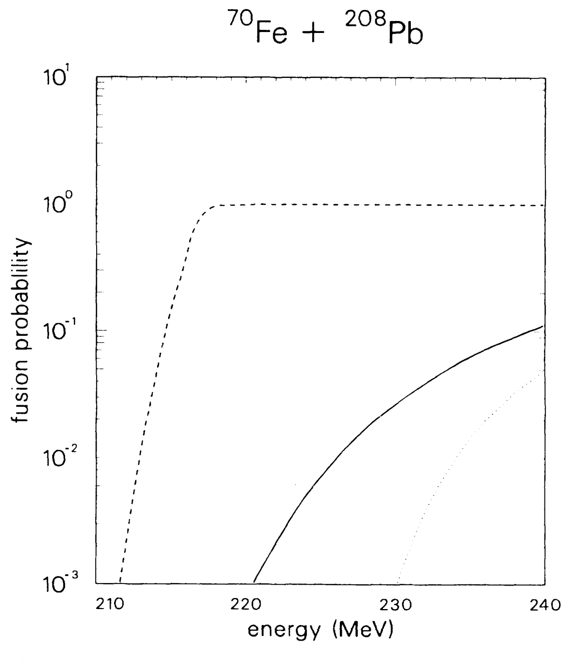

FIG. 1. Fusion probability in the head-on collision of a ^{70}Fe projectile on ^{208}Pb. The meanings of the different curves are given in the text.

forces given by the liquid-drop model and one-body dissipation. Fluctuations arise because of the random forces associated to the energy dissipation, and are included via the Langevin equation [9]. As initial conditions for this stage we take, for each trajectory of the ensemble that reaches the contact configuration, a radial distance $r \approx r_B$, a zero neck size and a radial kinetic energy equal to the one remaining when the system goes over the Coulomb barrier. The subsequent evolution is not deterministic due to the presence of the random forces and, as a consequence, one needs to perform a Monte Carlo calculation to extract the fusion probability. The results of this procedure reveal a strong dependence on the bombarding energy, especially for the highly charged systems associated with superheavy element formation.

In Fig. 1 we show the calculated fusion probability for the head-on collision of ^{70}Fe on ^{208}Pb discussed in Ref. [4]. The dashed line shows the results when the possibility of reseparation after contact is ignored— as it was done in that work. When the dynamics after contact is taken into account the fusion probability is considerably reduced, as indicated by the solid line. In both calculations the enhancement effects of the soft dipole modes were included by assuming the Steinwedel-Jensen hydrodynamical estimate for its energy, $\hbar\omega = 7.5$ MeV. A deformation parameter value $\beta = 0.1$ was used, derived from a 20% value of the energy weighted sum rule for this mode. If the soft dipole vibration were not taken into consideration, the results of the second calculation would be those shown by the dotted curve. We should remark at this point that these reseparation effects can be disregarded for lighter or more asymmetric systems, such as those considered in Ref. [3]. In fact, the reseparation probability can be neglected in the case of a central collision of a heavy-ion system having a product of their atomic numbers not in excess of 1600.

The inclusion of the dynamics after contact shows that there is actually very little possibility of forming a cold compound nucleus using the $^{70}\text{Fe}+{}^{208}\text{Pb}$ system. Because of its effect on the liquid-drop model energy contours, the asymmetry in the entrance channel is expected to be a most important consideration in the study of very-heavy-ion fusion. A careful theoretical analysis of the most appropriate systems for the production of superheavy elements should incorporate, besides the effects discussed here, those arising from the static deformation of one or both collision partners [10] and other structural details of the two nuclei.

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