Deformability as a Critical Factor in Initiating Fusion between Very Heavy Ions

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Fusion reactions are initiated by capture of two incident nuclei to form a quasistable dinuclear complex. Excitation functions for such capture reactions have been measured in bombardments with ^{208}Pb on targets of ^{26}Mg, ^{27}Al, ^{48}Ca, ^{50}Ti, ^{52}Cr, and ^{58}Fe. Compared with standard fusion models, based on the interaction of rigid spheres, the experiments show major deviations. These are explained by a dynamical model that takes deformations induced upon contact into account.

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The standard description of fusion reaction cross sections is based on the radial potential of two *rigid spheres* interacting through nuclear, Coulomb, and centrifugal forces. When such a potential exhibits a pocket, fusion is believed to take place through capture into the pocket, the trapping being due to friction forces. A sharp cutoff of the incident angular momenta contributing to fusion follows from this description. For fusion reactions between lighter nuclei with values of $Z_1Z_2 < 1600$ good agreement with data has been found recently by Birkelund *et al.*[1] with use of a standard proximity potential. This analysis also shows that tangential friction during contact reduces the angular momentum in the relative motion to about $\frac{5}{7}$ of the total l value (i.e., rolling). Fusion cross sections derived from such a model will saturate approximately at the l value where, after angular momentum dissipation, the pocket disappears.

Thus, the general experimental situation, as summarized for example in Ref. 1, appears to be consistent with the idea that capture and fusion reaction cross sections can be understood on the basis of a one-dimensional, radial potential acting between two spheres in the entrance channel. The magnitudes of the fusion cross sections appear to be completely insensitive to what happens later to the two spheres; how they evolve dynamically towards fusion through shape changes and mass motion on a large scale. The evidence presented in this Letter shows that this is not always true. For heavy systems, the capture cross sections turn out to be influenced in a major way by dynamical deformation effects subsequent to the initial approach phase.

Capture is usually measured through the yield of compound-nucleus residues, with a correction added in those cases where the compound nucleus can undergo fission. For very heavy systems, however, fission is the main decay channel for the compound nucleus formed, and the yield of compound-nucleus residues is negligible. In this case the reaction products generally fall into two groups: (i) a group of target- and projectile-like fragments representing the scattering and deep-inelastic reaction cross sections and (ii) a group of products with nearly half the mass of the total system resulting from symmetric fission and representing the capture cross section. In order to test fusion, or more correctly, capture models, it is sufficient to be able to distinguish these two groups of reaction products. This can be accomplished by choosing asymmetric target-projectile systems.

At the Unilac accelerator of the Gesellschaft für Schwerionenforschung, we have used a ^{208}Pb beam to bombard thin targets of ^{26}Mg, ^{27}Al, ^{48}Ca, ^{50}Ti, ^{52}Cr, and ^{58}Fe at energies from 1.0 to 1.8 times the interaction barrier.[2] The resulting two-body decay products, all moving into a forward cone, are recorded in coincidence in a large circular position-sensitive detector placed downstream from the target.[3] The detector acceptance

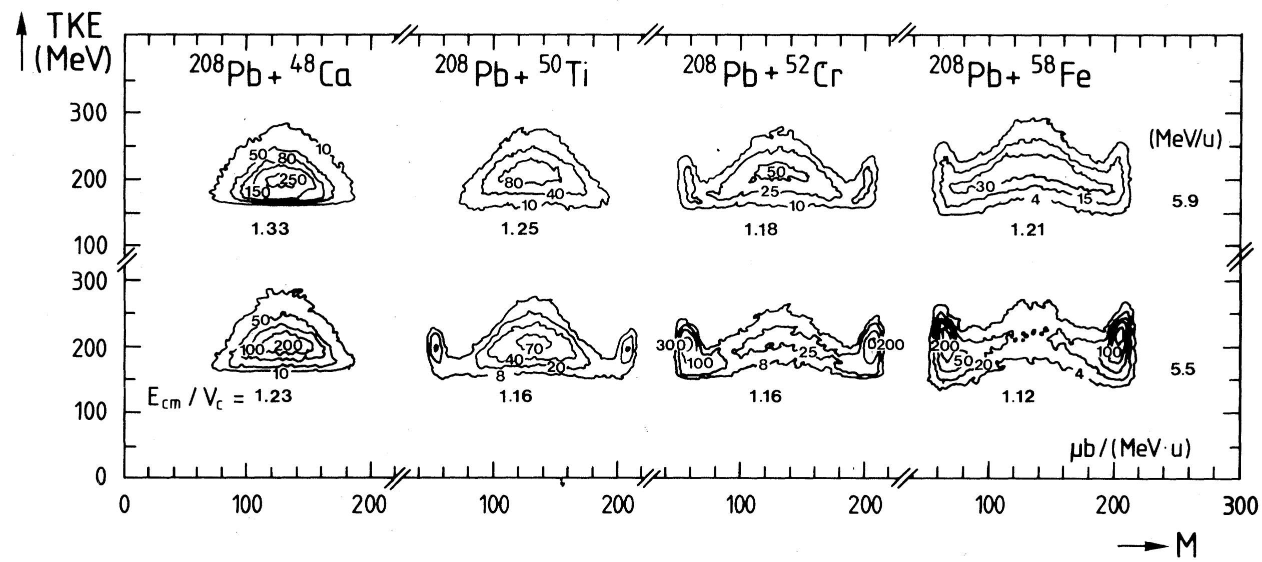

FIG. 1. Double-differential cross sections, $d^2\sigma/dE\,dM$ as a function of fragment mass and total kinetic energy assuming a $1/\sin\theta$ angular distribution for all values of mass and energy, cf. text. The figure illustrates the separation between scattering and inelastic reaction products centered at the target and projectile masses, and capture with the yield broadly distributed around the symmetric mass. Notice that, e.g., for $^{208}Pb + ^{58}Fe$, at an incident energy 1.12 times the Coulomb barrier, the symmetric fragmentation cross section is very small.

varies with bombarding energy and is a function of mass asymmetry, center-of-mass angle, and reaction Q value. For the fully relaxed events in the symmetric mass range $(90 > A > 160)$,[2,3] the detection efficiency of coincident fragments with a $1/\sin\theta$ distribution is about 75%. It has therefore been possible to measure the total cross section for the capture reaction by determining the yield around the symmetric mass, mostly but not always completely separated from the partially measured scattering products. The detection losses at center-of-mass angles near 0° and 180° are corrected by an extrapolation with a $1/\sin\theta$ function. Figure 1 shows results for selected targets and bombarding energies.

The measured capture cross sections are plotted in Fig. 2 together with the predictions of a simplified version of the capture model.[1] In this model capture is assumed to take place for all l values for which the barrier of the effective interaction in the entrance channel is smaller than the available c.m. energy and for which a pocket exists. Under the assumption that the capture configuration is described by rolling, this model reproduces the capture cross section obtained with the more elaborate version[1] of the proximity model[4,5] within better than 10%.

The lower part of the ^{26}Mg and ^{27}Al cross sections are in good agreement with the prediction of the standard model. But with the heavier systems deviations of increasing magnitude set in. These cannot be understood in terms of an l cutoff, nor by invoking an effective capture radius[6] of the order $(1.0 \pm 0.05)A^{1/3}$ fm. The data rather seem to indicate that an extra amount of energy is required to produce a given capture cross section. The necessary extra push appears to increase when a certain threshold is exceeded.

The concept of an extra push is introduced in a recent dynamical description of nuclear coalescence and reseparation by Swiatecki.[7] This model departs from the one-dimensional description of capture and fusion processes and introduces to the radial separation coordinate a neck degree of freedom and a mass asymmetry coordinate. Neck formation expresses nuclear deformability through one variable. It is a fast process compared to changes in mass asymmetry. Capture takes place when the colliding system is caught behind a potential barrier in the two-dimensional space of radial and neck coordinates. This potential barrier is called the conditional saddle (the condition being frozen mass asymmetry). Qualitatively one finds[7] that when the shape of the conditional saddle is more elongated than two spheres in contact, capture takes place in accordance with the standard one-dimensional mode.[1] But when the conditional saddle becomes more compact than two spheres in contact, an extra push is required to bring the system behind the conditional

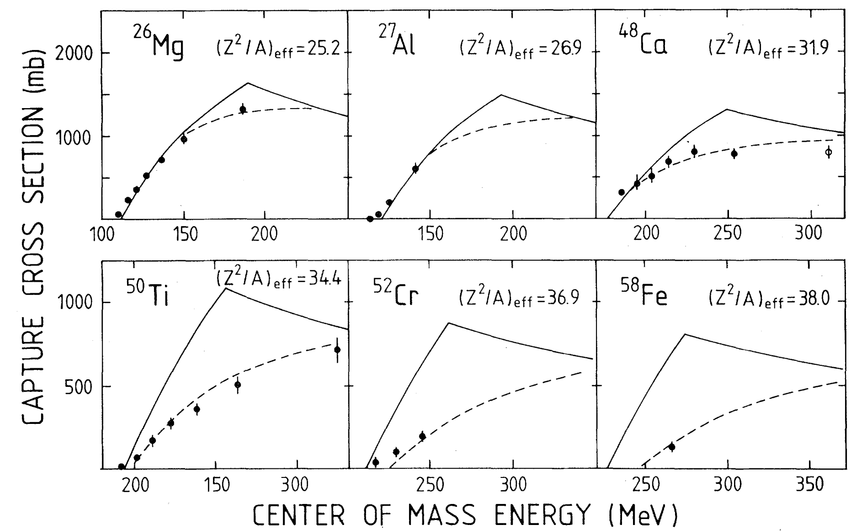

FIG. 2. Excitation functions for capture reactions. The full line is the prediction based on the one-dimensional proximity model of capturing spheres, Refs. 1, 4, and 5. As suggested by the analysis in Ref. 1 the sum of the two nuclear radii has been increased by 0.23 fm to obtain normalization with the Pb + Mg and Pb + Al data. Dashed lines are predictions of Swiatecki's two-dimensional, extra-push model (Ref. 7) with the fitted values of $a = 10$ and $(Z^2/A)_{\rm eff}{}^{\rm thr} = 32.5$.

saddle. Systems with equal values of the parameter

$$(Z^2/A)_{\rm eff}(l=0) = 4Z_1Z_2[A_1^{1/3}A_2^{1/3}(A_1^{1/3}+A_2^{1/3})]^{-1} \tag{1}$$

have similar saddle shapes, and the extra push ΔE required for central collisions is

$$\Delta E = a^2\eta_0[(Z^2/A)_{\rm eff} - (Z^2/A)_{\rm eff}{}^{\rm thr}]^2, \tag{2}$$

where $\eta_0 = C(A_1^{1/3}A_2^{1/3})(A_1^{1/3}+A_2^{1/3})^2/(A_1+A_2)$ and the constant $C = (32/45^2)(3/\pi)^{2/3}(e^2/\hbar c)^2 m_0 c^2 = 7.60\times 10^{-4}$ MeV (see Ref. 7). The quantities a and $(Z^2/A)_{\rm eff}{}^{\rm thr}$ are universal parameters to be determined from the experiment.

Following Bass[8] and Swiatecki,[7] we introduce an equivalence between Coulomb and centrifugal forces at contact in terms of a generalized effective fissility:

$$(Z^2/A)_{\rm eff}(l) = (Z^2/A)_{\rm eff}(l=0) + g(fl)^2(A_1+A_2)A_1^{-4/3}A_2^{-4/3}(A_1^{1/3}+A_2^{1/3})^{-2}, \tag{3}$$

where $g = 4\hbar^2/m_0 r_0 e^2 = 95.19$, and f takes the values 1, $\frac{5}{7}$, or $J_{12}/(J_{12}+J_1+J_2)$, respectively, depending on the assumption of sliding, rolling, or sticking motion. Here J_{12} is the relative moment of inertia of two spheres in contact, whereas J_1 and J_2 are the intrinsic moments of inertia of the two spheres separately.

One can easily incorporate the effect of the extra push into the capture model mentioned above simply by increasing for each l value the height of the effective interaction barrier in the entrance channel by the amount given in Eq. (2) using the l-dependent $(Z^2/A)_{\rm eff}$ given in Eq. (3).

The trends in the measured capture cross sections (Fig. 2) are well described by this two-dimensional model, where $a = 10 \pm 1$, $(Z^2/A)_{\rm eff}{}^{\rm thr} = 32.5 \pm 1$, and $f = \frac{5}{7}$ (rolling); see Fig. 2.

It should be stressed that the model[7] and Eqs. (1)–(3) imply a scaling law, which reduces the three-dimensional space of target, projectile, and l value into one dimension, expressed through $(Z^2/A)_{\rm eff}(l)$, Eq. (3). We consider the model to be a major step forward in understanding how fusion reactions are initiated. The concept of an extra push has been discussed earlier in connection with fusion of symmetric systems by Nix and Sierk.[9]

The measurements described here are made with systems where the Coulomb force alone becomes comparable, though not quite equal, to the nuclear attractive force. The insights that they have opened into the dynamical processes that initiate fusion reactions are likely to be of importance also with lighter systems, where they may be helpful in understanding the observed saturation of fusion cross sections. It tends to occur when the centrifugal and Coulomb force together begin to become comparable to the nuclear attraction (as exhibited for example in the ^{26}Mg excitation function in Fig. 2). Improvement in our understanding of transfermium element synthesis through fusion is also expected.

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Systematics of the *K* X-Ray Multiplicity for Transitional Nuclei with $A \simeq 200$

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Measurements of the multiplicity of *K* x rays accompanying (Li,*xn*) reactions to residual nuclei with $Z \sim 80$ exhibit plateaus of high and constant multiplicity for neutron numbers between 110 and 120, with rapid falloff for both smaller and larger *N*. A proposed explanation for this systematic behavior assumes that strongly coupled, high-*K* rotational bands are a much more general feature of this transitional mass region than existing data indicate.

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We have previously reported[1] the first direct measurements of the multiplicity $\langle M_K \rangle$ of prompt *K* x rays emitted in (heavy ion, *xn*) reactions, and the application of such measurements to the determination of absolute evaporation-residue production cross sections. The x rays arise from internal conversion during the deexcitation cascades in the *xn* residual nuclides, and hence $\langle M_K \rangle$ is sensitive to both the multipolarities and the energies of the nuclear transitions through which the γ-decay proceeds. One might well expect local irregularities in nuclear level schemes to yield large fluctuations in $\langle M_K \rangle$ from one nuclide to another, as are apparent in recent measurements[2] of *K*-shell ionization yields accompanying nuclear reactions to Dy isotopes. In this Letter, we present data in marked contrast to this expectation: Experimental results for (Li, *xn*) reactions with a wider variety of target nuclei and bombarding energies than studied in Ref. 1 indicate an intriguing *systematic* behavior of $\langle M_K \rangle$, and hence of the nuclear structure, in the transitional mass region just below the $N = 126$ shell closure. These observations demonstrate that the measurement of x-ray multiplicities usefully complements more detailed γ-spectroscopy techniques in revealing certain persistent features of nuclear spectra.

The measurements were made at the Indiana University Cyclotron Facility with use of ^{6}Li^{+++}