Mass-Asymmetric Fission of Light Nuclei

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Barriers to the mass-asymmetric fission of ^{111}In are calculated in the liquid-drop and in the Yukawa-plus-exponential finite-range models. The calculated barrier heights are compared to those previously inferred from fission excitation functions for $3 \leq Z \leq 11$. The liquid-drop-model barriers are about 12 MeV too high, while the finite-range model gives barriers an average of 1.6 MeV too high. This type of experimental data should make possible a more precise determination of the surface-energy and surface-asymmetry coefficients in semiempirical nuclear mass formulas.

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Moretto[1] has emphasized the unity of particle-evaporation and fission decay modes of highly excited compound nuclei. The major factor determining the branching ratios of various particle decay modes is the barrier to binary fission into the appropriate fragment masses. This barrier is the energy (with respect to a sphere) of the saddle-point shape with constrained mass asymmetry or the conditional saddle point.[1,2] For nuclei with mass numbers greater than about 150, the barrier to symmetric fission is lower than the barrier to asymmetric fission. This barrier reaches a maximum at a relatively large asymmetry, and decreases in height for still greater asymmetries, which correspond to light-particle emission. When such nuclei are highly excited the dominant decay modes will be symmetric fission and light-particle emission. For lighter nuclei, the barrier to symmetric fission is a maximum, with a monotonic decrease in height as the fragment asymmetry is increased. Such light compound nuclei will therefore decay primarily by light-particle emission. In Fig. 1, reproduced from Ref. 2, I show the calculated energies of conditional saddle points as a function of mass asymmetry and parametrically as a function of fissility in the liquid-drop model.

In actuality, the statements of the preceding paragraph about the nature of the decay of highly excited compound nuclei are only qualitatively correct, since fission decays of any mass asymmetry are energetically allowed.[1] Recent experimental advances[3-5] have made possible the measurement of decay into fragments of charge number $Z=2$ to $Z_{\text{cn}}/2$, where Z_{cn} is the total charge of the compound nucleus. Measurements of angular distributions have established that asymmetric decay proceeds from equilibrated compound nuclei,[3] while measurements of fragment mass distributions[4] have shown directly the Businaro-Gallone[6,7] transition from a local maximum in the yield at symmetry to a minimum at symmetry as the nuclear mass is decreased (implied by Fig. 1). Most recently, measurements of excitation functions for light-to-heavy particle emission have allowed the inference of fission barrier heights as a function of mass asymmetry.[5]

In this paper I report on a comparison of calculated conditional barrier heights with those inferred from experimental excitation functions.[5] The method of calculation is explained in Ref. 2. The experiment reported in Ref. 5 utilized the reaction $^{3}\text{He} + {}^{\text{nat}}\text{Ag} \rightarrow {}^{110,112}\text{In}$ at various energies. The energies of the conditional saddle points relative to the spherical ground state are shown for ^{111}In in Fig. 2 (the differences due to addition or removal of one neutron are relatively insignificant). The barriers are calculated both for the liquid-drop model with constants determined by Myers and Swiatecki[8] and for the finite-range Yukawa-plus-exponential model[9] with constants previously adjusted to nuclear radii, scattering potentials, fission barriers, and nuclear mass.[9,10] The

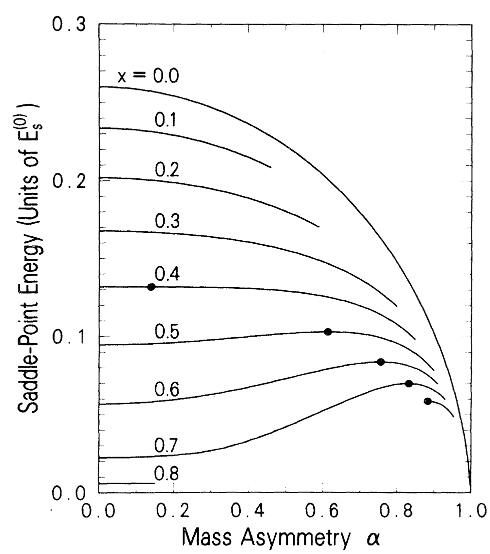

FIG. 1. Conditional-saddle-point energies (in units of the surface energy of a liquid-drop sphere) as a function of mass asymmetry α and fissility x. α is the difference of the masses of the two nascent fragments divided by the total mass. The fissility x is one-half the ratio of the Coulomb energy of a sphere of uniform charge density to its surface energy. The solid points correspond to the Businaro-Gallone family of unconstrained asymmetric saddle points with two unstable shape degrees of freedom.

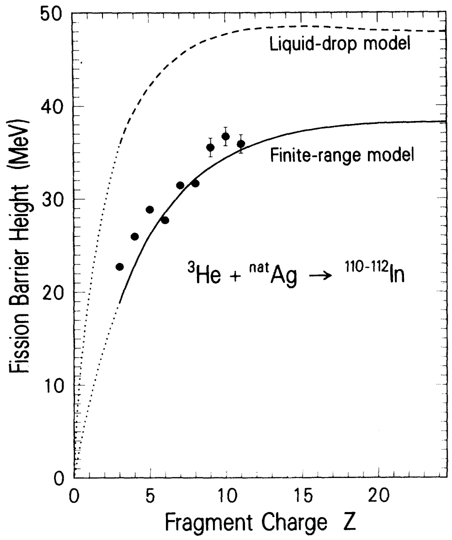

FIG. 2. Calculated and experimentally inferred (Ref. 5) fission barriers as a function of the lighter-fragment charge for the fission of ^{111}In. The calculated curves for the liquid-drop and Yukawa-plus-exponential models are shown dashed and solid, respectively. The dotted portions of the curves are interpolations.

liquid-drop model predicts, as studies of heavy-ion-induced fission have also shown,[11-15] barriers that are significantly higher than those measured (more than 10 MeV too high in this case). The finite-range model,[2,9] on the other hand, essentially reproduces the data, which are uncertain by about 2 MeV.[5]

In the nuclear mass formula of Ref. 10, the surface-energy constant a_s and the surface-asymmetry constant κ_s are determined from experimental fission barrier heights. However, all but two of the barrier heights used in determining the present set of constants were for nuclei with mass numbers greater than 185.[10] Use of this limited range of mass numbers and neutron-proton asymmetries precludes determination of a_s and κ_s with very great precision. More complete data on fission barriers of nuclei with mass numbers of 100 to 180 would allow a much better determination of these constants. The two previously used barrier heights for lighter nuclei were inferred from data by means of an evaporation model with many nuclides contributing to the fission decay, with consequently large uncertainties.[16] The data of Ref. 5, by contrast, provide more detailed and somewhat less model-dependent information about barrier heights. Data of this type, when coupled with improved consideration of angular momentum effects, preequilibrium emission of light particles, and fission following particle evaporation, should provide the desired information on fission barriers for lighter nuclei.

As a final remark, I would like to point out that a precise ($\Delta A \sim 10$) location of the Businaro-Gallone transition point by means of mass-distribution measurements, as proposed in Ref. 4, may not be possible because the barrier height is nearly constant with respect to mass asymmetric distortions in the neighborhood of the transition (see the curves labeled $x = 0.3$, 0.4, and 0.5 in Fig. 1). This comment should not detract in any way from the significance of the measurements already locating this transition between $A = 85$ and $A = 145$.[4]

To summarize, I have shown that experimentally measured barriers to asymmetric fission of ^{110,112}In are reproduced by calculations using the Yukawa-plus-exponential model with finite-surface-diffuseness effects, and with parameters previously fixed from other classes of data. Measurements of this type may in the future make possible a greatly improved determination of the surface-energy and surface-asymmetry constants in semiempirical nuclear mass formulas.

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