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Abstract

The conditional saddle point heights (conditional barriers) that preside over the emission of complex fragments (Z = 2-11) from compound nuclei have been obtained from the excitation functions of individual fragments in the reaction ^{3}He + ^{nat}Ag. The magnitudes of the barriers and their dependence on mass asymmetry may be used to verify important features of the potential energy surface including shell effects at the conditional saddle and to verify the validity of the liquid drop model and recent refinements such as finite range effects and surface diffuseness.

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Experimentally determined saddle point masses (fission barriers) have played an essential role in establishing key features of nuclear models. For instance, the ambiguity between the surface and Coulomb energy in the liquid drop model has been resolved by fitting simultaneously both the ground state and saddle point masses in heavy nuclei.[1] Furthermore, shell effects for both the ground state and saddle point configurations have been verified by measuring the fission barriers of nuclei in the vicinity of closed shells and in the actinide region, respectively.[2]

Apparent deviations from the rotating liquid drop model predictions[3] for a range of compound nuclei[4] has led to the introduction of a more realistic liquid drop model, which includes the effects of the finite range of the nuclear force and surface diffuseness.[5,6] The magnitude of these corrections can be seen in Fig. 1 where the predicted barriers for $J = 0$ as a function of Z^2/A of the compound nucleus are shown. The upper curve is calculated with the standard liquid drop model and the lower curve includes the effects of finite range and diffuseness. The barriers and the finite range corrections are very large in the vicinity of $A \sim 80 - 100$ and decrease as the mass or the angular momentum of the compound nucleus increases. To date adequate experimental information on fission barriers[4,7] is available mainly for compound nuclei with mass numbers substantially greater than 100.

The information obtained from fission barriers can be greatly expanded if other important topological points in the nuclear potential energy surface become experimentally accessible. It has been shown[8] that the compound nucleus emission of intermediate size particles is controlled by a barrier associated with a "conditional" saddle point constrained to have the required mass asymmetry. The measurement of the conditional barrier for individual mass asymmetries is of great importance for testing the liquid drop model and its finite range and surface diffuseness refinements. By measuring barriers for the entire or even a limited range of mass asymmetries, one can obtain more detailed information on the saddle-point shapes adopted by the decaying compound nucleus. We have obtained for the first time such barriers from excitation functions for the emission of complex fragments.

In the present experiment, excitation functions have been measured for the fragments of $2 \leq Z \leq 11$ emitted from Indium compound nuclei formed by bombarding ^{nat}Ag with ^{3}He beams of 45-130 MeV from the 88-Inch Cyclotron at the Lawrence Berkeley Laboratory. The compound nucleus origin of these heavy fragments was demonstrated in a previous paper.[9] The Z-values measured in this experiment cover the range of asymmetries $Z/Z_{CN} = 0.05 - 0.23$, where 0.5 corresponds to symmetric splitting. The complete range of decay products was not measured because of the low cross sections (less than 50 nb) and difficulties in identifying the Z of the low energy heavy fragments.

The excitation functions obtained from the $^{3}He + ^{nat}Ag$ measurements are shown in Fig. 2 for a series of decay products. The measurements were restricted to the backward angles (120 - 160°) in order to insure measurement of only the equilibrium component. The total cross sections were obtained by integrating over angle using the angular distribution formula of Moretto.[8] The total cross sections so obtained differ by less than 10% from the values obtained assuming $d\sigma/d\Omega$ to be constant over angle.

With increasing bombarding energy, the cross sections (see Fig. 2) rise rapidly and then more slowly at higher energies. This is a characteristic signature of compound nucleus emission, and reinforces the assignment of compound nucleus decay that was made previously on the basis of data obtained at 90 MeV.[9] The cross section for $Z = 3$ is a factor of 500 lower than that for $Z = 2$, and for the heavier fragments the cross sections are even lower. In spite of these low cross sections, excitation functions were measured over 2-3 orders of magnitude up to $Z = 11$, with a detection limit of about 50 nb.

The experimental excitation function data have been fitted using a transition state formalism, analogous to that used to fit fission excitation functions.[10] As shown in Ref. 10, the decay width for first-chance emission of a fragment of charge Z can be written as

$$\Gamma_Z = \frac{1}{2\pi\rho(E)} \int_0^{E-B_Z} \rho_Z^*(E - B_Z - \varepsilon)d\varepsilon \tag{1}$$

where $\rho(E)$ is the compound nucleus level density, B_Z is the conditional barrier height, and $\rho_Z^*(E - B_Z - \varepsilon)$ is the level density at the conditional saddle with a kinetic energy ε in the decay mode. The neutron width Γ_n can be written[10] as

$$\Gamma_n = \frac{2mR^2g}{2\pi\rho(E)} \int_0^{E-B_n} \varepsilon\rho(E - B_n - \varepsilon)d\varepsilon \quad . \tag{2}$$

We make the assumption that the ratio of the decay widths, Γ_Z/Γ_n, is proportional to the ratio of the cross section for complex fragment emission, σ_Z, to that for complete fusion, σ_f, i.e.,

$$\Gamma_Z/\Gamma_n \simeq \frac{\Gamma_Z}{\Gamma_t} \simeq \frac{\sigma_Z}{\sigma_f} \quad . \tag{3}$$

This is reasonable in this mass region because $\Gamma_n > \sum_{Z\geq 1}^{\infty} \Gamma_Z$. One can then calculate $\Gamma_Z/\Gamma_n(E)$ using an appropriate choice for the level density expressions. A Fermi gas level density was used because it gives an analytical expression for Γ_Z/Γ_n. A simple angular momentum dependence has been included by adding to the barriers the rotational energies appropriate to the ground and saddle point deformations.

Using the above expressions for Γ_Z/Γ_n, the barriers (B_Z), and the ratio of the level density parameters (a_Z/a_n) were extracted from fits to σ_Z/σ_f, where $\sigma_f(\ell)$ was determined from the sharp cutoff model with $\ell_{crit} = 16\hbar$, as given by the Bass Model.[11] These fits are shown by the solid lines in Fig. 2. The agreement between the data and the fits is remarkably good for all Z-values and again confirms that these products originate from compound nuclear decay.

The extracted barriers and level density parameters are subject to several uncertainties due to the assumptions made in this simple analysis. The effects of preequilibrium emission on the initial excitation energy were estimated using the geometry dependent hybrid model from the statistical code ALICE.[12] Preequilibrium emission is negligible at the lowest bombarding energies, but significantly reduces the average excitation energy of the compound nucleus at bombarding energies of 90 and 130 MeV. However, when at each bombarding energy, the calculated excitation energy distribution after precompound emission was used to fit the data, the values of the barriers are lowered only slightly, less than 1 MeV, and the values of a_Z/a_n are raised by ~7%. This is understandable since the barriers are most sensitive to the steep part of the excitation function at lower energies and a_Z/a_n is sensitive to the curvature at higher energies.

First chance emission is expected to dominate for $Z > 2$, but this is not the case for $Z = 2$. Thus in the following discussion, the fitted parameters for $Z = 2$ are ignored. Otherwise first-chance emission from a fully equilibrated system was assumed. The uncertainty due to the choice of $\sigma_f(\ell)$ is negligible in this case because the barriers are constant with ℓ for this range of angular momenta. The sensitivity of the fit to the various other input parameters has been examined. A variation of each of these parameters within reasonable limits introduces an uncertainty in the extracted barriers and values of a_z/a_n of at most 7% for all values of Z. In addition, the formalism was tested for "fission" by fitting ordinary fission excitation functions. The values of the fission barriers and a_f/a_n extracted with our fitting procedure agree quite well with values quoted in the literature.[2] This agreement indicates that our simple formalism gives a reasonable approximation to more sophisticated codes.

The barriers and values of a_z/a_n extracted from the fits are shown by the circles in Fig. 3 as a function of Z/Z_{CN}. The extracted barriers increase dramatically as the exit channel becomes more symmetric. Some evidence of shell effects in the exit channel is visible, for instance, in the barrier for carbon emission, $Z = 6$, which is lower than those of the neighboring elements. The values of a_z/a_n extracted from the fits tend to oscillate in the range of 0.98-1.02 and are 7% larger if precompound emission is included. The values of a_f/a_n obtained in fitting fission excitation functions have been shown to reflect shell effects in the saddle point configuration.[2] One can confidently hope that in the future it will be possible to relate the variation of a_z/a_n with exit channel charge and mass to saddle point shell effects.

The small uncertainties of the extracted conditional barrier (~2 MeV) make these overall results ideal for testing the possible finite-range correction to the liquid drop model. This is especially true in the mass region covered by this experiment since both the barriers and the corresponding finite-range corrections are quite large. Furthermore, the predicted barriers are constant with angular momentum over the range of angular momenta contributing to compound nucleus formation in this reaction.[6]

At present adequate theoretical predictions of saddle point masses from the liquid drop model are available only for the case of symmetric splitting. The size of the expected corrections to the liquid drop model due to surface diffuseness and finite range effects for the mass asymmetric case can be inferred from the calculations at symmetry shown in Fig. 1 and from the symmetric saddle point masses shown in Fig. 3 for the compound nucleus decay considered in this experiment. Qualitatively, the corrections to the liquid drop model due to finite range and diffuseness effects are expected to decrease slowly with increasing mass asymmetry as the saddle point shapes become more extended. An attempt to extend the theoretical calculations to the whole mass asymmetry range is currently in progress.

In conclusion, we have shown that excitation functions for complex fragment emission from compound nuclei can be used to extract the conditional (mass asymmetric) emission barriers. The experimental barriers should permit a determination of the role of diffuseness and finite range corrections in describing the barriers for complex fragment emission. The measurement of mass asymmetric barriers opens up a sensitive new coordinate for which liquid drop models can be tested and refined. Furthermore, future measurements of both the Z and A of the complex fragment should allow a detailed examination of shell effects at the conditional saddle point.

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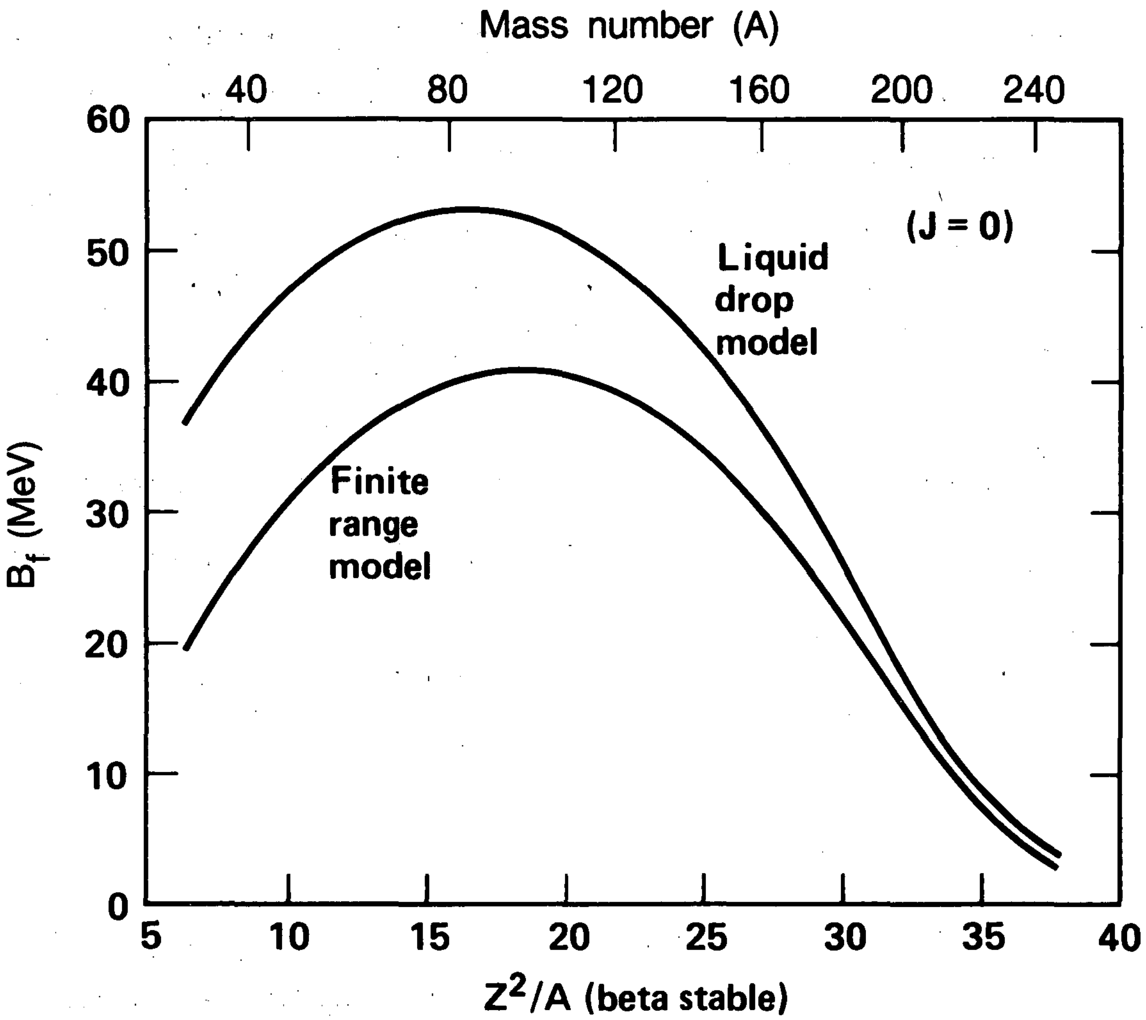
Figure Captions

Fig 1. Fission barriers of nonrotating nuclei with Z^2/A along the line of beta stability. The upper line, identified by LDM, represents the results of the calculations with liquid drop model parameters.[3] The lower line represents the results of a liquid drop model which includes the finite range of the nuclear force and surface diffuseness.[13]

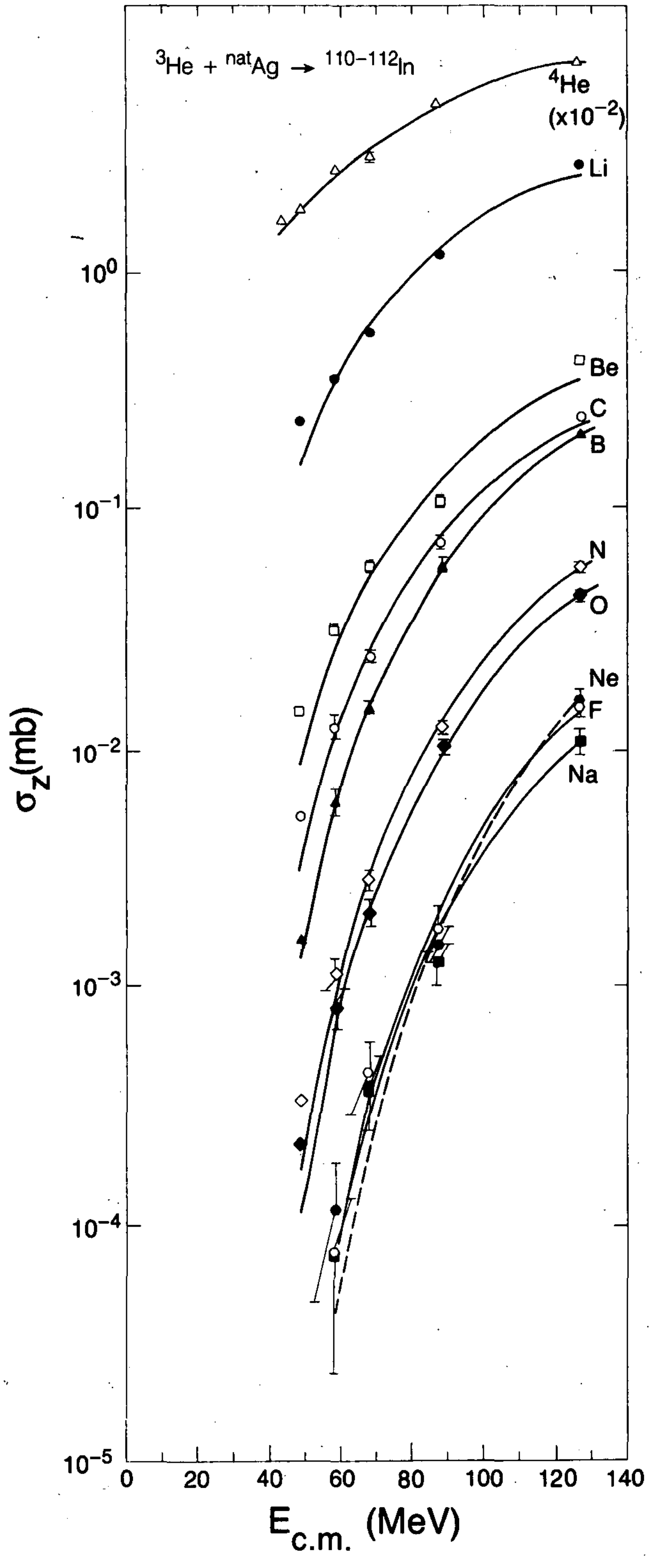
Fig 2. Dependence of the total integrated cross sections for emission of complex fragments on the center-of-mass energy, $E_{c.m.}$ in the reaction ^{3}He + ^{nat}Ag. The points and error bars correspond to the experimental cross sections with statistical errors. The absolute errors may be as large as 20%. The curves are fits with the parameters of Fig. 3.

Fig 3. The emission barriers, B_Z, and ratio of level density parameters, a_z/a_n, extracted in fitting the excitation functions as a function of asymmetry, Z/Z_{CN}. ($Z/Z_{CN} = 0.5$ corresponds to symmetric splitting.) The points are the extracted parameters, excluding pre-equilibrium emission. The error bars shown are those arising from the χ^2 of the fitting procedure. Where none are shown, the errors are smaller than the size of the points. The predicted values at symmetry are shown for the liquid drop (LD) and the liquid drop with finite range and surface diffuseness (LD + FR) models.



XBL 8411-9001

Fig. 1



XBL 848-8658

Fig. 2

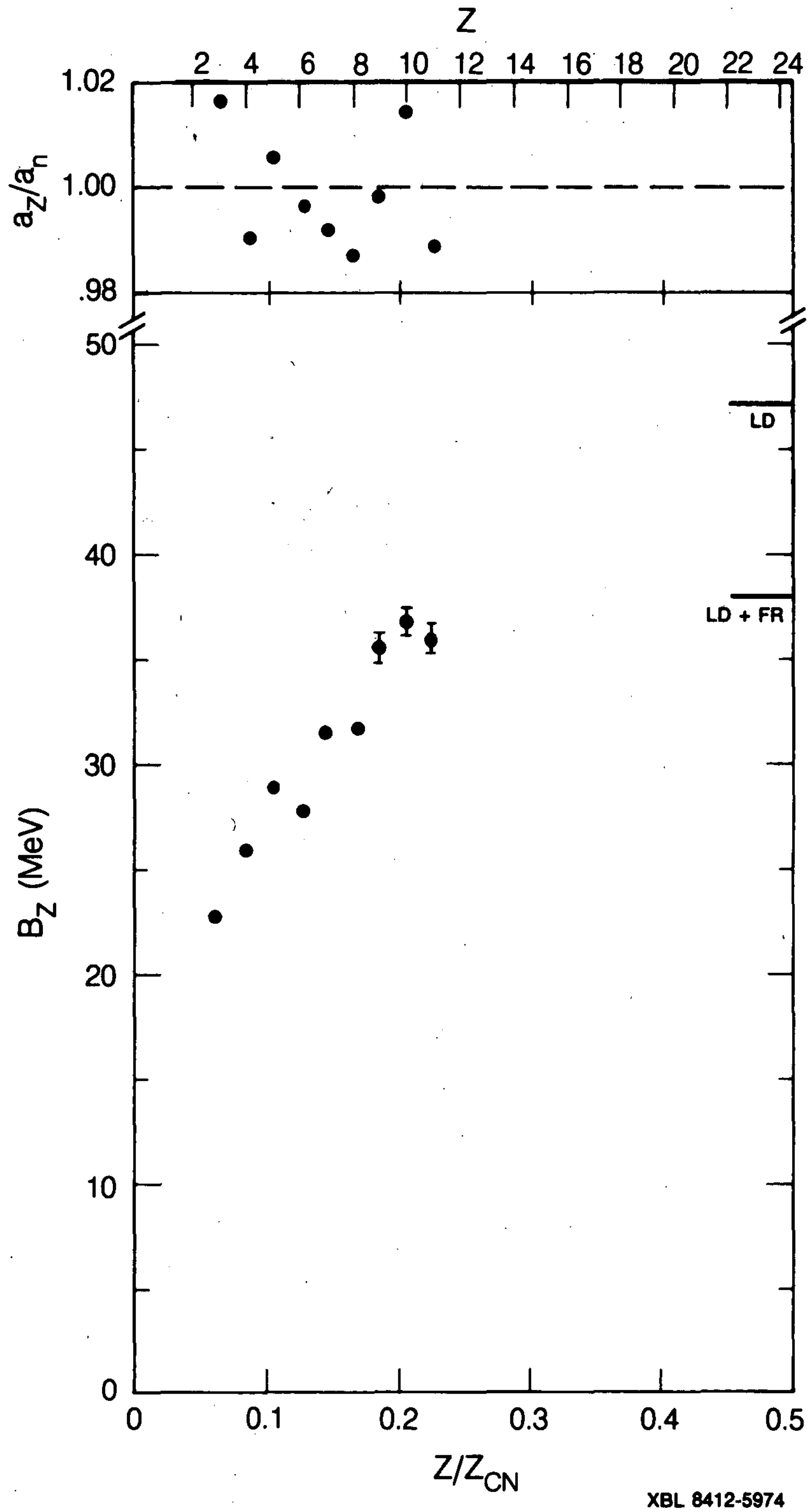


Fig. 3

XBL 8412-5974

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