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Angular-momentum-dependent fission barriers in the rare-earth region

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Fission and evaporation residue excitation functions of ^{153}Tb and ^{181}Re compound systems are investigated in the context of angular-momentum-dependent fission barrier calculations in which effects of the finite range of the nuclear force and of the diffuseness of the nuclear surface are included. Carbon- and neon-induced reactions are studied in both the ^{153}Tb and ^{181}Re cases. Reasonable agreement is found between experimental and calculated excitation functions without adjustments of the theoretical fission barriers.

The study of heavy-ion-induced fission and of angular-momentum-dependent fission barriers has been an active field of investigation in recent years.[1–18] In most of these studies, fission excitation functions have been measured and analyzed within the framework of the statistical model by means of two-parameter fits. Typically, one of these parameters is related to the fission barrier B_f, and the other is the ratio of the Fermi-gas level density parameter for fission to that for particle emission a_f/a_ν. The values of the parameters are determined by the slopes and the magnitudes of the excitation functions and are valid in the region of angular momentum where the fission barrier is in the same energy range as the binding energies of the evaporated particles.[10,12] Due to this constraint, it is not possible to extract the angular momentum dependence of the fission barriers over a large range, in a model independent manner, and reference must be made to theoretical calculations.

Until recently the only calculated angular-momentum-dependent fission barriers available were those obtained from the rotating-liquid-drop model (RLDM).[19] These liquid-drop fission barriers, $B_f^{\rm LD}(J)$, were used in statistical model calculations and were adjusted with angular-momentum-independent parameters k_f or Δ_f, defined by $B_f(J)=k_fB_f^{\rm LD}(J)$ and by $B_f(J)=B_f^{\rm LD}(J)+\Delta_f$, respectively. For an adequate description of the measured excitation functions, $B_f(J)$ values smaller than $B_f^{\rm LD}(J)$ have been found in almost all cases. Thus, for example, k_f was found to vary from about 0.55 to 0.85.[4,6,8,9,12,14,15,17] This basic conclusion was not entirely surprising[4–6] since more realistic calculations, which take into account the finite range of the nuclear force and the diffuseness of the nuclear surface,[20,21] result in lower calculated fission barriers. The finite-range model of Refs. 20 and 21, however, applies only to nonrotating nuclei, and although Blann and Komoto[13] have applied it successfully to rotating fissioning systems by an *ad hoc* angular momentum scaling procedure, direct comparison of theory with experiment requires the development of a rotating finite-range model (RFRM). Recently, such calculations of fission barriers as a function of angular momentum have been performed.[22,23] In this work we reexamine our earlier results for the ^{153}Tb system[6] in the context of these new calculations,[23] and we also consider new results for the ^{181}Re system. We find that, when the fission barriers of Ref. 23 are inserted into the statistical model caclualtions, the measured excitation functions are adequately described without any adjustment of $B_f(J)$, thus reducing the fitting procedure to one that involves a single adjustable parameter a_f/a_ν. In the cases considered here, calculations performed with the barriers of Mustafa, Baisden, and Chandra[22] were also found to describe the measured excitation functions adequately.

It has been pointed out[4,6] that, in order to apply a statistical model treatment to heavy-ion-induced fission excitation functions, it is necessary to measure not only fission cross sections, but also those for evaporation residues. Furthermore, in order to understand angular momentum effects, at least two different reactions leading to the same compound nucleus should be investigated. Finally, the systems studied must be chosen so that the observed fission yield results from the fission of equilibrated compound nuclei.[24] All of these conditions have been met in this study of the fission of ^{153}Tb and ^{181}Re compound nuclei. The ^{153}Tb system was produced in the reactions ^{12}C + ^{141}Pr and ^{20}Ne + ^{133}Cs, while ^{181}Re was produced in ^{12}C + ^{169}Tm and ^{22}Ne + ^{159}Tb reactions.

The ^{153}Tb data have been taken from Ref. 6. The evaporation residue cross sections, $\sigma_{\rm ER}$, for the ^{181}Re system are measured by a method similar to that described in Ref. 6. The ^{12}C and ^{22}Ne beams are obtained from the Oak Ridge Isochronous Cyclotron. The targets consist of Tm_2O_3 ($\sim$98 μg cm^{-2}) and Tb_2O_3 ($\sim$275 μg cm^{-2}) deposits on 25-μg cm^{-2} carbon foils. The flight distance over which time-of-flight measurements are made is 9 cm. The $\sigma_{\rm ER}$ results are given in Table I. These results are consistent with fusion cross section values calculated with the 1977 version of the Bass model.[25] The ^{12}C + ^{169}Tm and ^{22}Ne

TABLE I. Measured cross sections for production of evaporation residues from the deexcitation of ^{181}Re compound nuclei.

Reaction	E_{lab} (MeV)	σ_{ER} (mb)
$^{12}C+^{169}Tm$	78.2	962 ±70
	100.8	1386 ±75
	122.6	1741 ±80
$^{22}Ne+^{159}Tb$	113.0	765 ±45
	130.0	933 ±50
	161.5	929 ±100

$+^{159}$Tb fission cross sections were taken from Sikkeland.[1] We have checked the results of Ref. 1 for the $^{12}C+^{169}Tm$ reaction at the energies given in Table I and have found the agreement to be good. Excellent agreement between Sikkeland's results and those obtained by more modern techniques (multiwire counters) was also found in Ref. 18 for the $^{16}O+^{170}Er$ and $^{12}C+^{174}Yb$ systems. We were not able to check the $^{22}Ne+^{159}Tb$ fission cross sections due to a 5–14% tungsten contaminant in our Tb target. This contaminant had a negligible effect on our σ_{ER} measurement.

Statistical model fits to the data are performed as described earlier[6,18] by means of PACE,[26] which is a modified version of the computer code JULIAN.[27] As was stated above, the single adjustable parameter is the ratio of the level density parameters a_f/a_ν. The value of this parameter is, of course, constrained to a single value for the two reactions leading to the same compound nucleus. The angular-momentum-dependent fission barriers $B_f(J)$, calculated with the RFRM,[23] were incorporated into PACE.

The fission barrier calculations used here include, in addition to corrections to the surface energy discussed above, corrections to the rotational energy due to the diffuseness of the matter distribution,[28] as well as corrections to the Coulomb energy due to the diffuseness of the charge distribution.[28] The highly deformed nuclear shapes are parametrized in terms of Legendre polynomials,[29] and the shapes are not constrained to axial symmetry as was the case in most previous calculations, including those of the RLDM.[19] (The calculations of Ref. 22 also include axial asymmetry.) The calculated $B_f(J)$ values are shown as a function of angular momentum for ^{153}Tb in Fig. 1. The RLDM values[19] are also shown in Fig. 1, and as expected, the RFRM values lie significantly below the RLDM values. The relative positions of the two curves for ^{181}Re are similar to those for ^{153}Tb, and, in fact, this trend is a general one.[18,22,23]

The fission excitation functions, together with the statistical model fits, are shown for ^{153}Tb and ^{181}Re in Figs. 2 and 3, respectively. The values of a_f/a_ν were found to be 1.08 for ^{153}Tb and 1.02 for ^{181}Re. In the steep portions of the excitation functions, which are most sensitive to variations in the fission barrier,[6] the calculated curves represent the measurements very well. This indicates that the calculated barriers of the RFRM agree with experiments in the mass

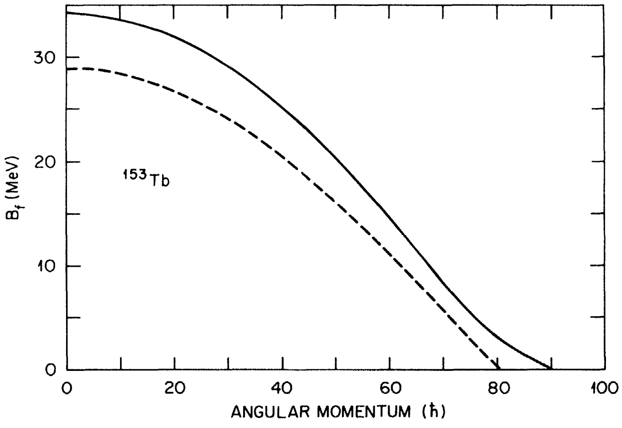

FIG. 1. Calculated fission barriers, B_f, for ^{153}Tb as a function of angular momentum. The solid curve represents values from the rotating-liquid-drop model (Ref. 19). The dashed curve represents values calculated in the rotating-finite-range model (Ref. 23).

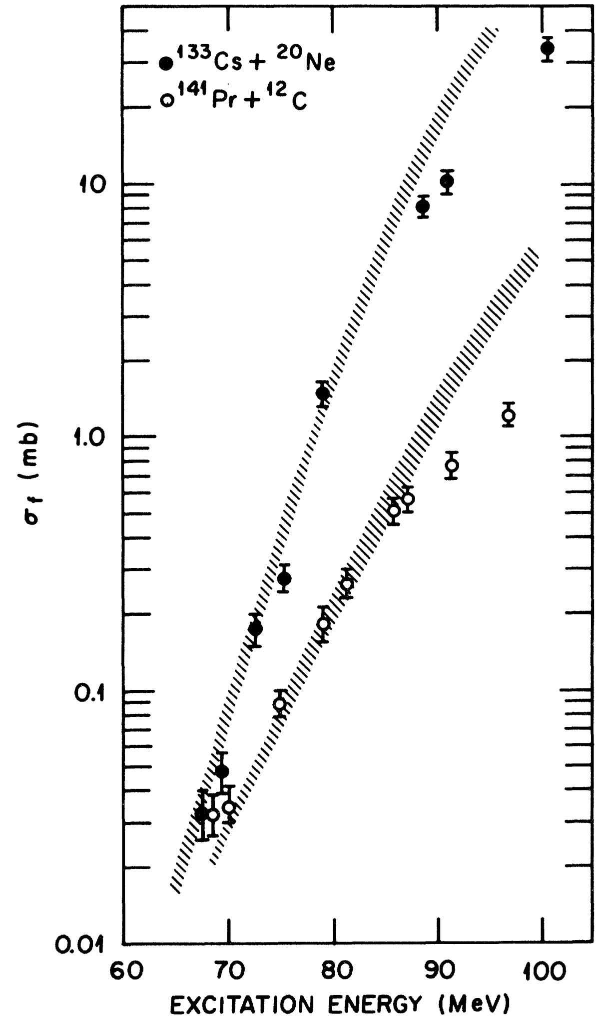

FIG. 2. Measured (circles) and calculated (cross-hatched bands) fission excitation functions for two reactions leading to the ^{153}Tb compound nucleus. The experimental values are taken from Ref. 6. The calculations are performed in the framework of the statistical model with the rotating-finite-range model B_f values (Ref. 23) shown in Fig. 1. The width of the bands indicates computational uncertainties.

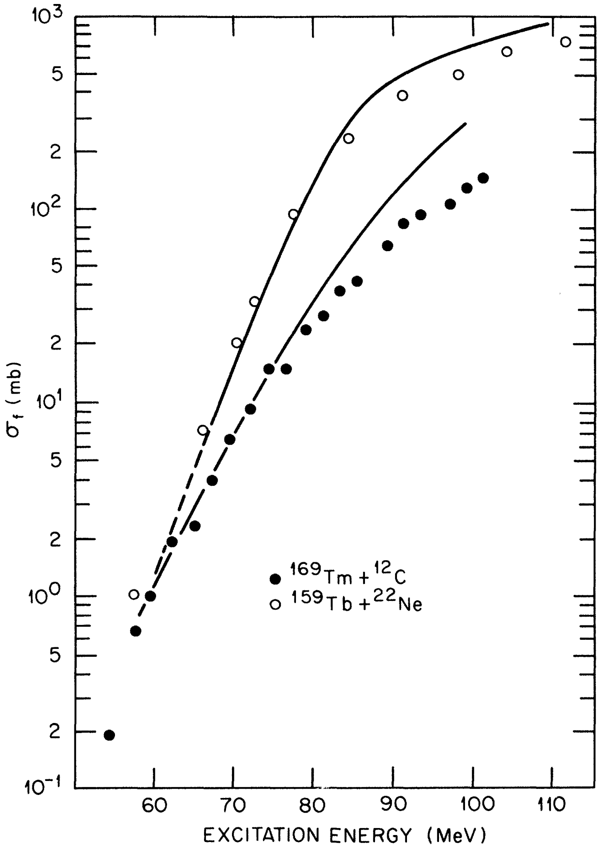

FIG. 3. Similar to Fig. 2, but for the ^{181}Re compound nucleus. The calculations are depicted by the solid and dashed curves. The fission data are from Ref. 1. The dashed portion of the ^{22}Ne + ^{159}Tb curve indicates the region where extrapolated values of evaporation residue cross sections had to be used in the calculations.

range from 150 to 180 and in a range of angular momenta from about 40 to 60 $\hbar$. A similar conclusion was reached in Ref. 18 for the compound nuclei ^{158}Er, ^{186}Os, and ^{210}Po formed in a large number of reactions with projectiles ranging from ^{9}Be to ^{64}Ni, thus covering even larger ranges of both mass and angular momentum. In Ref. 18, however, $\sigma_{\rm ER}$ measurements were not performed, and Bass model values[25] were used to obtain the total compound nucleus cross sections needed for the statistical model analysis.

At the highest exctiation energies shown in Figs. 2 and 3, significant deviations are seen between calculated and measured excitation functions. The agreement between experiment and theory can be improved in this region by the use of level densities other than the simple Fermi-gas level densities used in this work.[18,30] It is also possible that effects of incomplete fusion may contribute to the divergence of the theoretical and experimental excitation functions at the highest energies. The conclusions regarding the fission barriers are not modified either by changes in level densities or by the consideration of incomplete fusion. Different conclusions, however, would possibly have been arrived at had the steep portions of the fission excitation functions (below about 80 MeV in Figs. 2 and 3) not been measured, as was the case in some earlier studies.

Comparisons between experiment and theory were also made with the RFRM barriers of Mustafa, Baisden, and Chandra.[22,31] Agreement between experiment and their published ^{153}Tb barriers[22] was found to be acceptable, although not quite as good as that between experiment and the barriers of Ref. 23. Recently, however, Mustafa has added a sixth-order neck smoothing term to his calculations[31] and now obtains barriers that are very nearly the same as those of Ref. 23 (within 0.4 MeV at all values of angular momentum for ^{153}Tb and ^{181}Re).

On the basis of the results presented here and in Ref. 18, we conclude that the RFRM adequately represents the experimental fission cross sections without any renormalization and that the new calculated fission barriers are valid, at least in the mass region from 150 to 210. Thus the RFRM[22,23,31] should replace the widely used RLDM in interpretations of data obtained from heavy-ion reactions and in making predictions of various angular momentum effects. It was pointed out[4,10,13] that arbitrary extrapolation of empirical fission barriers to zero angular momentum is not a valid procedure in the absence of theoretical guidance. However, such extrapolation may be made here strictly in the framework of the RFRM. Thus we find that the data discussed in this work are consistent with RFRM B_f $(J=0)$ values of 28.9 MeV for ^{153}Tb and 19.0 MeV for ^{181}Re, neglecting any possible shell corrections.

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