Fission Barrier of ^{153}Tb

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The fission barrier of ^{153}Tb was found to be 28.5 ± 1.7 MeV, which is about 83% of the predicted liquid-drop value. This result is consistent with calculations of nuclear masses and with barriers obtained from ^{4}He-induced fission. Barrier estimates of (51–65)% of liquid-drop values deduced for nonrotating nuclei from results of others appear to be in error.

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The increased fissility of systems having high angular momenta[1,2] makes it possible to obtain fission barriers, B_f, of relatively light nuclei from heavy-ion–induced fission measurements. These B_f values, deduced for nonrotating nuclei, are important because they reflect macroscopic nuclear properties and because they provide a valuable input for (or a test of) calculations of nuclear masses.[3,4] Furthermore, the fission excitation functions needed to obtain the barriers also allow us to test theories describing nuclear deformations at high angular momenta, such as the rotating–liquid-drop (RLD) model.[1] The RLD model is used extensively in the interpretation of data from many different types of experiments, such as studies of heavy-ion fusion reactions and of γ multiplicities. Doubts about its general validity could thus have an important effect on conclusions drawn from a large segment of heavy-ion–induced reaction studies.

Recently, Beckerman and Blann[5] have analyzed heavy-ion–induced fission excitation functions for systems ranging from ^{62}Ni + ^{35}Cl to ^{141}Pr + ^{35}Cl and have reported fission barriers that range from 51% to 65% of the calculated liquid-drop[1,3] values. It was pointed out in Ref. 5 that these barriers are statistical-model parameters determined in a rather narrow range of high partial waves. It is reasonable, however, to deduce from these results fission barriers of the nonrotating systems, B_f, on the assumption that the angular momentum dependence of the barriers is given by the RLD model. For example, for ^{141}Pr + ^{35}Cl (^{176}Os compound nucleus) we may deduce from Ref. 5 that $B_f = 11.5$ MeV (65% of the liquid-drop value). In contrast, measured B_f values obtained from ^{4}He-induced fission of compound nuclei in the same mass region range from 23.4 MeV for ^{186}Os to 17.0 MeV for ^{213}At.[6] The 11.5-MeV B_f value deduced from Ref. 5 for the nonrotating ^{176}Os nucleus is in the region usually associated with heavy nuclei such as radium.

In this work we present results for the fission of the compound nucleus ^{153}Tb which was produced in the reactions ^{12}C + ^{141}Pr and ^{20}Ne + ^{133}Cs. As was pointed out earlier,[2,5] in order to extract reliable fission barriers from heavy-ion–induced fission data by means of statistical-model calculations, it is necessary to measure excitation functions for both fission and the production of evaporation residues (ER). This condition has been met in this work, and our systems constitute the only case in which both fission and ER cross sections, σ_f and σ_{ER}, have been measured for two different reactions that produce the same compound nucleus.

Beams of ^{12}C ions of energy ranging from 90 to 138 MeV and of ^{20}Ne ions from 103 to 166 MeV were obtained from the Oak Ridge Isochronous Cyclotron. In the case of σ_f measurements, several primary beam energies were used, and intermediate values were obtained by means of aluminum degrader foils. The targets consisted of CsF, CsO, and PrO_2 deposits on 20-μg/cm^2 carbon foils. Their thicknesses were less than 400 μg/cm^2. Fission cross sections were obtained from measurements of coincident fission fragments, and σ_{ER} values were obtained from separate measurements in which ER were identified by means of their energy and time of flight (T.O.F.).

In the fission experiment two silicon surface-barrier detectors, each collimated to an active area of 250 mm^2, were operated in coincidence with each other. One detector was located 33 mm from the target at an angle of 90° with respect to the beam, while the other detector was placed 75 mm from the target and at 180° in the c.m. system from the first detector. Care was taken to ensure that the partners of all fragments observed in the far detector were registered by the near detector. Fragment masses were deduced from the measured energies. In both the ^{12}C and the ^{20}Ne reactions, fission fragments were found to be well separated in terms of their mass distribution from any other reaction products (including deeply inelastic products), and all measured coincident events were thus unambiguously associated with fission. Absolute σ_f values were deduced from measurements of Rutherford scattering in a pair of monitor detectors located at ~ 18° relative to the beam. It was assumed that the angular distribution of fission fragments follows a $1/\sin\theta$ function. The measured fission excitation functions are given in Fig. 1.

Values of σ_{ER} were obtained from T.O.F. measurements after it became apparent that, because of the low kinetic energies of the ER in our case, it is not possible, with the usual ΔE-E technique, to separate ER from slit-scattered events. Timing signals were produced by a carbon-foil channel-plate assembly at the beginning of the flight path and by a silicon surface-barrier detector at the end of the path. The silicon detector had an active area of 900 mm^2 and was located 64 cm from the target. Multiple scattering in the carbon foil of the timing detector could be neglected, because the flight distance was only 25 cm. ER events were clearly separated from all other products in T.O.F. versus kinetic energy arrays. σ_{ER} values were obtained, relative to Rutherford scattering, by integrating measured angular distributions of ER. The results are given in Table I.

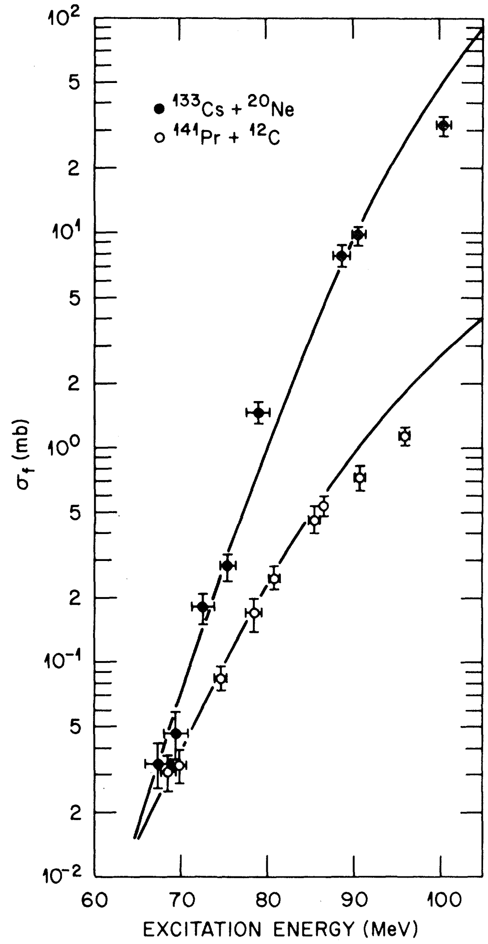

FIG. 1. Excitation functions for the fission of the ^{153}Tb compound nucleus produced in reactions of ^{12}C with ^{141}Pr and ^{20}Ne with ^{133}Cs. The circles indicate experimental results. The curves are statistical-model fits to both sets of data with $a_f/a_v = 1.08$ and $B_f = 28.5$ MeV (see text).

The statistical-model analysis of the σ_f and σ_{ER} excitation functions was performed by means of the computer program ORNL ALICE,[7,8] which is a modified version of a program described earlier.[9] The program includes spin-dependent level densities, multiple particle emission in competition with fission, and angular-momentum-dependent fission barriers. It does not include couplings to individual final states, and the variation of angular momentum during deexcitation is treated only in terms of limiting approximations. It was shown,[5] however, that if the angular-momentum-removal option is selected in the ALICE calculations the fission barriers obtained are essentially the same as those obtained with the more rigorous computer program MB-II.[10] We have used the approximation in which each evaporated proton and neutron changed the angular momentum of the residual nucleus by $1\hbar$ and each alpha particle by $4\hbar$.[7,8]

In our calculations, we considered only those partial waves that contribute to the sum of σ_f and σ_{ER}, i.e., to the measured compound-nucleus cross section. For this purpose the sharp-cutoff approximation was used after it was determined that it did not have a significant effect on the re-

TABLE I. Measured cross sections for production of evaporation residues.

Reaction	E_{lab} (MeV)	σ_{ER} (mb)
^{12}C + ^{141}Pr	92.6	1100 ± 50
	108.8	1290 ± 50
	137.7	1540 ± 50
^{20}Ne + ^{133}Cs	103.2	800 ± 75
	115.2	1200 ± 150
	128.9	1210 ± 50

sults. The yrast line and the angular momentum dependence of the fission barrier were given by the RLD model.[1] Fits were made with two variable parameters. The first, a_f/a_ν, is the ratio of the level density parameter for fission to that for particle emission. The second parameter, k, is a scaling factor defined by $B_f = kB_f^{\mathrm{LD}}(J=0)$ where $B_f^{\mathrm{LD}}(J=0)$ is the fission barrier from the RLD model at zero angular momentum. Effective J-dependent fission barriers used in the program are given by $B_f(J) = kB_f^{\mathrm{LD}}(J)$. It was found that in our cases the slopes of calculated excitation functions are sensitive primarily to changes in k and not very sensitive to changes in a_f/a_ν. The effect of varying k is shown in Fig. 2 for fits to the lowest σ_f point from the ^{12}C + ^{141}Pr reaction. It is clear that here the curve with $k = 0.8$ is the best fit to the measured excitation function, implying that B_f in this case is equal to 80% of liquid-drop value. A similar sensitivity of the calculated slope to B_f was found in the ^{20}Ne + ^{133}Cs case.

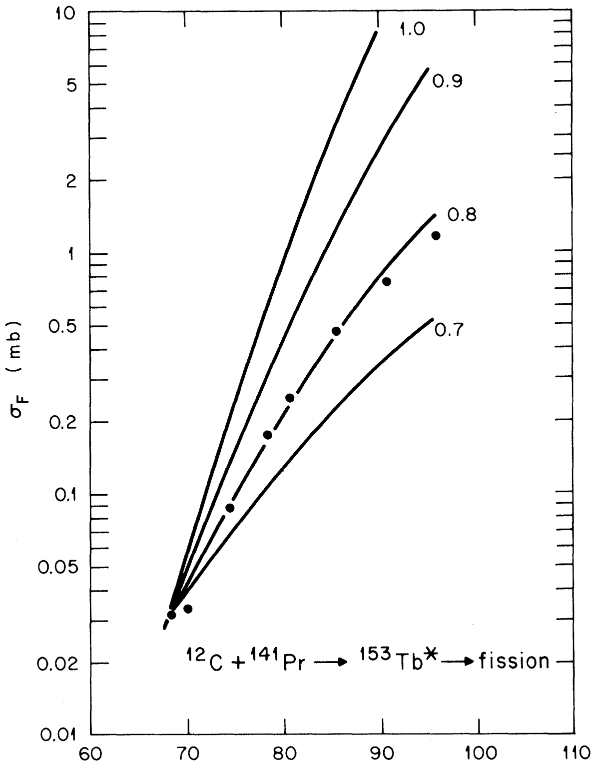

FIG. 2. Effect of fission barrier variation on statistical-model fits to the fission excitation function from the ^{12}C + ^{141}Pr reaction. The labels on the curves indiate values of k in the relationship $B_f = kB_f^{\mathrm{LD}}(J=0)$. The corresponding values of a_f/a_ν range from 0.985 for $k = 0.7$ to 1.245 for $k = 1.0$.

Figure 1 shows the best fit to both sets of data, with $a_f/a_\nu = 1.08$ and $k = 0.83$. Since the value of $B_f^{\mathrm{LD}}(J=0)$ used in the calculation was 34.3 MeV, we conclude that the fission barrier of ^{153}Tb is 28.5 ± 1.7 MeV. This B_f value can be compared with the recent calculation of nuclear masses performed by Möller and Nix.[4] In this calculation a folded Yukawa single-particle potential has been used together with a Yukawa-plus-exponential macroscopic model. The calculated B_f value for ^{153}Tb of 26.0 MeV[4,11] is in reasonable agreement with our value of 28.5 MeV. Since Möller and Nix also underestimate somewhat the barriers of the lightest systems studied by Moretto *et al.*,[6] we conclude that our result is consistent with B_f values deduced from ^{4}He-induced fission.[6]

A very important aspect of our results is the fact that the measured fission excitation functions from the ^{12}C + ^{141}Pr and the ^{20}Ne + ^{133}Cs systems both lead to the same values of the parameters, a_f/a_ν and B_f. Since the difference in fissility between the two systems is due to the larger angular momenta involved in the Ne + Cs case, we conclude that the variation of B_f with angular momentum is adequately described by the RLD model. This supports the view that the RLD-model description of nuclear deformations as a function of angular momentum is also reasonable.

Our B_f value of 28.5 MeV for ^{153}Tb (83% of the liquid-drop value) is in marked contrast with $B_f = 16.4$ MeV (57% of the liquid-drop value) deduced for the neighboring nucleus ^{151}Ho from Ref. 5. The discrepancy between the two results cannot be attributed to the small differences in the methods of analysis since, by applying our method to the data used in Ref. 5, we obtained essentially the same B_f value as Beckerman and Blann did. Several other factors, however, contribute to the discrepancy. First, in at least three cases considered in Ref. 5 (^{35}Cl + ^{62}Ni, ^{20}Ne + ^{107}Ag, and ^{40}Ar + ^{109}Ag), there is no doubt that deeply inelastic events contribute to the apparent fission cross sections. For example, the ambiguous nature of the decomposition into fission and deeply inelastic yields was stressed in the paper giving the ^{40}Ar + ^{109}Ag results.[12] Our ^{20}Ne + ^{107}Ag[2] data quoted in Ref. 5 were difficult to decompose, as can be seen from the charge distributions obtained for this system by Babinet *et al.*[13] In contrast the Ne + Cs and C + Pr cases have fission distributions that are well separated from those of other reaction products, probably because these systems are heavier, and/or because they involve lighter projectiles. Second, the value of B_f extracted from the excitation functions depends primarily on the slope of these functions at the lowest energies. In this work the lowest σ_f values are in the region of 0.03 mb, while the lowest σ_f results for ^{35}Cl + ^{116}Sn and ^{35}Cl + ^{141}Pr are only about 20 mb.[5] In addition, we cover a range of 30 MeV in excitation energy in contrast to a range of only 15 MeV in the ^{35}Cl cases above.

In evaluating the error associated with our B_f result, we have considered (1) the effect of a large systematic uncertainty in the σ_{ER} determination, and (2) the possibility of incomplete fusion as discussed by Siwek-Wilczyńska *et al.*[14] In the Ne + Cs case, an assumed increase of 30% in σ_{ER} at all energies changed B_f only from 28.5 MeV to 27.5 MeV. Incomplete fusion is not expected at our lowest bombarding energies.[14] At the highest energies the deviation of the fits from the data seen in Fig. 1 could possibly be attributed to the onset of this effect.

By analyzing γ multiplicities and yields of specific ER, Gavron[15] has deduced that fission barriers appropriate to our mass region are approximately 80% of RLD-model values, thus corroborating our result. Our result is also in agreement with the conclusion of Videbaek *et al.*[16] who found fission excitation functions for ^{16}O + ^{181}Ta and ^{16}O + ^{208}Pb to be consistent with the RLD model.

We conclude that our value of 28.5 ± 1.7 MeV for the B_f of ^{153}Tb is consistent with mass calculations, with the RLD model, with B_f values obtained for heavier systems from ^{4}He- and ^{16}O-induced fission, and with statistical-model interpretations of γ-multiplicity and ER measurements.

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