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Saddle-point shapes and fission barriers of rotating nuclei

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Abstract. This article reviews the work relating to the development of a rotating liquid drop model together with a chronology of its confrontation with the experimental interpretation of data. It is brought out that the zero temperature rotating finite range model is quite successful in the interpretation of data obtained from heavy ion-induced reactions.

Keywords. Saddle point shapes; fission barrier; rotating liquid drop model; rotating finite-range model.

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1. Introduction

This review article on the fission of rotating nuclei was solicited for inclusion in a special issue of *Pramāṇa–J. Phys.* dedicated to the 50th anniversary of the discovery of fission. From my days as a graduate student at the Lawrence Berkeley Laboratory until recently, I have worked actively in the field of heavy-ion-induced fission. Having gained some understanding of the stability limits of rotating nuclei and of their fission properties, I have moved to a different field of research, and I take pleasure in this opportunity to review and summarize this important area of nuclear physics. I hope that my somewhat personal approach here is understandable, under the circumstances.

The infancy of the field of heavy-ion-induced fission goes back to the Lawrence Berkeley Laboratory (LBL) in the early 1960s. The heavy-ion linear accelerator (HILAC) had, at that time, come into routine operation, and several excellent nuclear physics programmes centered around it. Heavy-ion-induced fission was one of these programmes. This pioneering work was directed by T Sikkeland, who together with his coworkers, laid the experimental foundations of the field by investigating such varied aspects as fission excitation functions (Viola and Sikkeland 1962; Sikkeland 1964; Sikkeland *et al* 1971), fission fragment kinetic energies (Viola *et al* 1963; Sikkeland 1970), angular correlations (Sikkeland *et al* 1962; Sikkeland 1968), and angular distributions (Gordon *et al* 1960). Activity in theoretical aspects of fission was equally intense at LBL at that time. W J Swiatecki and S Cohen had just completed their classic work on the liquid drop model (Cohen and Swiatecki 1962, 1963), and Swiatecki suggested that I help them extend it to the case of rotating

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drops, building on earlier studies of the effects of angular momentum on fission barriers (Pik-Pichak 1958, 1962; Beringer and Knox 1961; Hiskes 1960).

2. The rotating liquid drop model

The first results from our studies of the rotating liquid drop model (RLDM) were presented in the early sixties (Cohen *et al* 1963), but it was not until ten years later that all of the results were published (Cohen *et al* 1974). During that decade, heavy-ion research had grown from a highly specialized branch to a major field having broad appeal to a large segment of the nuclear physics community. The most dramatic and, at the same time, intuitively obvious (see below) conclusion from our studies was that, given a sufficient amount of angular momentum, all nuclei reach a point at which their fission barrier vanishes. Thus, instability towards fission imposes an absolute limit on the amount of rotational energy that a nucleus can carry. This conclusion has, of course, far-reaching implications for the whole field of heavy-ion-induced reactions. For an intuitive understanding of the existence of such a limit, it is sufficient to remember that the rotational force is a disruptive force that acts in concert with the disruptive Coulomb force and that both are counterbalanced by the cohesive nuclear force. Since the rotational energy, E_R, is given by

$$E_R = L^2/2\mathscr{I},$$

where L is the angular momentum and $\mathscr{I}$ the moment of inertia of the configuration in question, it follows that the rotational energy increases with the square of the angular momentum and inversely with the moment of inertia. In the liquid drop model, for non-rotating nuclei, ground states are spherical while the saddle-point shapes are elongated (Cohen and Swiatecki 1962, 1963). Thus, with increasing angular momentum, provided that the shapes do not change, the rotational (and hence the total) energy of the spherical ground state increases more rapidly than the rotational energy of the elongated saddle-point shape until, at some value of the angular momentum, the two curves cross. In this crude shape-constrained picture, this is the point at which the fission barrier (difference in energy between the two configurations) vanishes, and the limit of stability is reached.

Of course, rotating liquid drops (and presumably nuclei) do change their shape with increasing angular momentum. In fact, these shape changes and the associated energy changes form the whole basis of the RLDM (Cohen *et al* 1974). Calculations are carried out as a function of two dimensionless parameters, x (the fissility parameter) and y, which denote the degree of the disruptive Coulomb and rotational energies, respectively. They are given by

$$x = E_c^0/2E_s^0 = [50{\cdot}883(1 - 1{\cdot}7823 I^2)]^{-1} Z^2/A,$$

and

$$y = E_R^0/E_s^0 = \frac{1{\cdot}9249 L^2}{(1 - 1{\cdot}7826 I^2) A^{1/3}},$$

where E_c^0, E_s^0, and E_R^0 are the Coulomb, surface, and rotational energies of a sphere. In these expressions the right-hand side is used to relate the idealized liquid drops to nuclei. Here $I = (N - Z)/A$, and Z, and N are the mass number, atomic number, and neutron number of the nucleus in question. A rigid body moment of inertia is assumed, and the configurations are confined to gyrostatic equilibrium with all fluid elements in uniform rotation about a common axis. Configurations of equilibrium are obtained by differentiation of the effective potential energy, which consists of a linear combination of the surface, Coulomb, and rotational energies. The top of the fission barrier is an unstable equilibrium point on the potential energy surface, while the rotating ground state is a stable equilibrium point.

The qualitative features of the RLDM as a function of x and y exhibit a surprising degree of complexity. For example, depending on the value of x, as y increases, the rotating ground state may remain oblate (Hiskes shapes) (Hiskes 1960) until the fission barrier vanishes, or it may turn triaxial (Beringer-Knox shapes) (Beringer and Knox 1961) at high values of angular momentum. Examples of ground-state and saddle-point shapes of equilibrium are shown in figure 1 for $x = 0{\cdot}6$. This value of fissility parameter corresponds to nuclei in the region of ytterbium. In the top part of

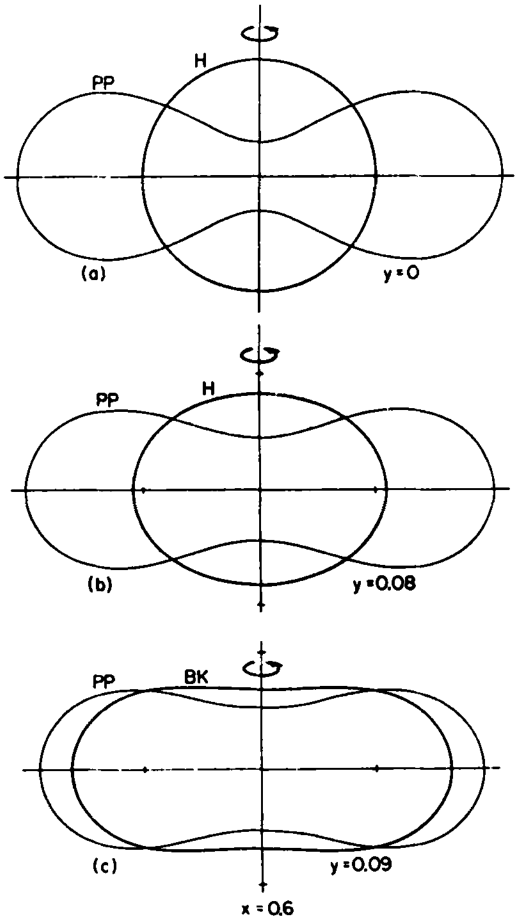

Figure 1. Ground state (heavier lines labeled H or BK) and saddle shapes (lighter lines labeled PP) for $x = 0{\cdot}6$ and various values of y. The shapes labeled H have axial symmetry about the vertical axis. The shapes labeled PP and BK have approximate symmetry about the horizontal axis. This figure is taken from Cohen *et al* (1974).

the figure the stable spherical nucleus and the non-rotating elongated saddle-point nucleus are shown for zero angular momentum ($y=0$). As the rotational energy increases, the ground-state nucleus flattens and maintains axial symmetry about the axis of rotation, while the saddle-point nucleus contracts slowly and its neck thickens. This situation is shown in the central portion of the figure for $y=0{\cdot}08$. If rotation is increased still further, the ground-state Hiskes shape loses stability and undergoes a conversion to the triaxial Beringer-Knox shape, which resembles a flattened cylinder with rounded edges. Such a shape is shown in the lowest section of figure 1 for $y=0{\cdot}09$. As the angular momentum continues to increase, a point is reached at which the stable and unstable families of equilibrium shapes merge, and the fission barrier vanishes. This behaviour is typical provided that $x \lesssim 0{\cdot}8$.

In figure 2 the energies of the saddle-point and of the ground-state nuclei are shown for the specific case of the ^{149}Tb nucleus. It can be seen that as the angular momentum is increased, both the ground-state energy, E_R^{min}, and the saddle-point energy, E_R^{saddle}, increase but that the rate of increase is smaller in the E_R^{saddle} case than in the E_R^{min} case. The difference between the two curves, the fission barrier B_f, is also shown. The figure also illustrates the point made earlier about the intuitive nature of the vanishing fission barriers. Thus, if the nuclei are assumed to be constrained to their non-rotating shape, i.e., the nuclei are not allowed to deform with increasing angular momentum,

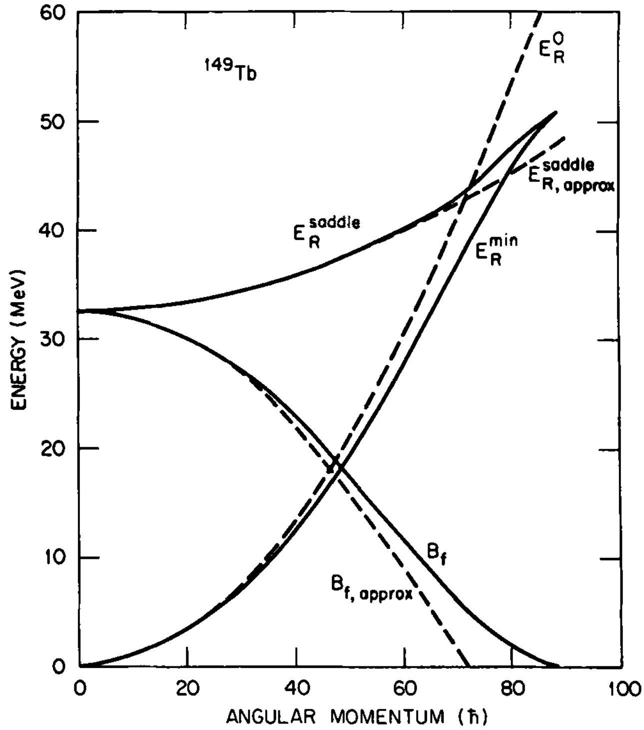

Figure 2. Liquid drop energies (Cohen *et al* 1974) of the rotating ground-state (E_R^{min}) and of the rotating saddle-point shape (E_R^{saddle}) as functions of angular momentum for the nucleus ^{149}Tb. The difference between E_R^{saddle} and E_R^{min} is the fission barrier B_f and is also shown. See the text for an explanation of the dashed curves which refer to shapes that are not allowed to deform with increasing angular momentum. This figure is taken from Plasil (1974).

their rotational energies are as shown by the dashed lines labeled E_R^0 (rotational energy of a sphere) and $E_{R,\text{approx}}^{\text{saddle}}$. The approximate dependence of the fission barrier on angular momentum is given by the difference between these two curves and is indicated by $B_{f,\text{approx}}$. It is seen that the qualitative behaviour with changing angular momentum of $B_{f,\text{approx}}$ and of the RLDM B_f are similar, both resulting in $B_f = 0$ at high angular momentum.

3. The RLDM and limits of stability

The main conclusion of the RLDM, that the fission barrier of every nucleus is reduced to zero at a sufficiently high value of angular momentum, is illustrated in figure 3, taken from Plasil (1974). Here, the $B_f = 0$ limit is given as a function of angular momentum and of the mass number of nuclei in the valley of β stability. It can be seen that no nucleus can support an angular momentum greater than about $100\hbar$. For purposes of estimating competition between fission and particle emission, it is sufficient that the fission barrier be small compared to the binding energy of individual nucleons in order for fission to dominate. The shaded region divides the diagram

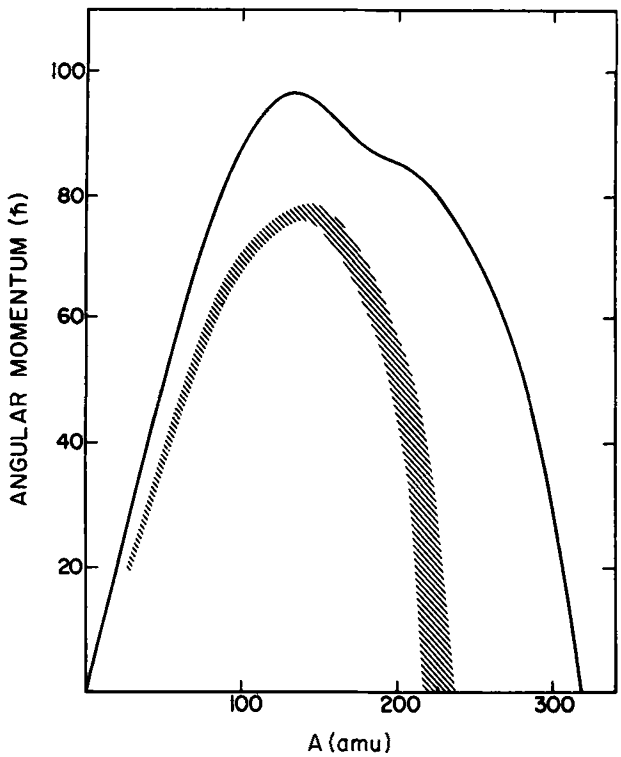

Figure 3. Limits of stability determined by the RLDM (Cohen *et al* 1974). The solid line gives the value of angular momentum at which the fission barrier of beta-stabel nuclei of mass number A is predicted to vanish. The hatched area indicates the region of competition between fission and particle emission (see text). This figure is taken from Plasil (1974).

roughly into two parts: above the shaded line compound nuclei are expected to de-excite primarily by fission, and below it, primarily by particle emission.

While the potential of the RLDM for predicting certain aspects of heavy-ion-induced reactions was immediately apparent, its usefulness to make even semiquantitative estimates remained to be demonstrated. The first major test came at about the same time as the publication of RLDM. It was reported by Gauvin *et al* (1974) that evaporation residue cross-sections for $^{40}Ar + Sb$, i.e., cross-sections for the production of compound nuclei that de-excite primarily by the evaporation of protons and neutrons, increase from 600 mb at 200 MeV to about 1000 mb at 280 MeV. The observation of such a high cross-section was in clear contradiction to the prediction of the RLDM since it implied that nuclei with calculated fission barriers $B_f = 0$ survived de-excitation and did not undergo fission.

The results of Gauvin *et al* (1974) were obtained by the helium-jet technique, which was used to measure the α-radioactivity of residual nuclei, and were inconsistent with measurements of much lower cross-sections obtained by a direct counting technique by Gutbrod *et al* (1973) for the neighbouring system of $^{40}Ar + {}^{109}Ag$. To determine which experimental results are correct, I was fortunate to have had the opportunity to join forces with some of the authors (Gauvin *et al* 1974) and help them remeasure both the $^{40}Ar + Ag$ and $^{40}Ar + Sb$ evaporation residue cross-sections with a modified version of the technique described by Gutbrod. It was gratifying to find that the measured evaporation residue cross-section from $^{40}Ar + Sb$ at the highest energy (296 MeV) was only 520 mb (Gauvin *et al* 1975) well within RLDM expectations.

4. RLDM fission barriers and excitation functions

The most complete tests of the RLDM came in the form of the confrontation of theory with measured fission excitation functions in the context of the statistical model. The first step was the incorporation of the RLDM barriers into a deexcitation computer calculation, in which the full range of impact parameters involved in a given reaction was accounted for. This was done in collaboration with Blann (Blann and Plasil 1972; Plasil and Blann 1975) and resulted in the computer code ALICE (Blann and Plasil 1973), which was widely used during the seventies until its replacement by more sophisticated computer programs. Early theory-experiment comparisons centered on evaporation residue cross-sections and were semiquantitative. Beckerman and Blann were the first to perform systematic quantitative analyses of fission excitation functions for a large number of systems (Beckerman and Blann 1977, 1978; Beckerman 1978). Other studies, including our own, soon followed (Plasil *et al* 1980; Cabot *et al* 1980; Cabot 1982; Leigh *et al* 1982; Sikora *et al* 1982; Blann and Komoto 1982; Hinde *et al* 1982, 1983). The general conclusion from most of these studies was that for an adequate description of the measured excitation functions, fission barrier values smaller than those of the RLDM were needed.

In most of the early studies of angular-momentum-dependent fission barriers, fission excitation functions had been analysed within the framework of the statistical model by means of two-parameter fits. Typically, one of these parameters was related to the fission barrier, B_f, and the other was the ratio of the Fermi-gas level density parameter for fission to that for particle emission, a_f/a_v. The values of the parameters were 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. 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 such as the RLDM. The RLDM fission barriers, $B_f^{LD}(J)$, were used in statistical model calculations and were adjusted with angular-momentum-independent parameters k_f or Δ_f, defined by $B_f(J) = k_f B_f^{LD}(J)$ and by $B_f(J) = B_f^{LD}(J) + \Delta_f$, respectively. As was noted above, $B_f(J)$ values smaller than $B_f^{LD}(J)$ were needed to fit the data in almost all cases. Thus, for example, k_f was found to vary from about 0·55 to 0·85 (Beckerman and Blann 1977, 1978; Plasil *et al* 1980; Cabot *et al* 1980; Cabot 1982; Leigh *et al* 1982; Sikora *et al* 1982; Hinde *et al* 1982, 1983). This basic conclusion was not entirely surprising (Beckerman and Blann 1977, 1978; Beckerman 1978; Plasil *et al* 1980) since more realistic calculations, which take into account the finite range of the nuclear force and the diffuseness of the nuclear surface (Krappe and Nix 1973; Krappe *et al* 1979), result in lower calculated fission barriers; particularly in the case of the highly necked-in shapes associated with the saddle-point shapes of light nuclei. The finite-range model of Krappe *et al* (1973, 1979), however, applies only to non-rotating nuclei, and although Blann and Komoto (1982) applied it successfully to rotating fissioning systems by an ad-hoc angular momentum scaling procedure, direct comparison of theory with experiment required the development of a rotating finite-range model (RFRM).

5. The rotating finite-range model

The rotating finite-range model was introduced by Mustafa *et al* (1982) and was considerably improved by means of better shape parametrizations and computing techniques by Sierk (1986). In both cases the theoretical work was probably motivated in part by the ready access to experimental results. Both Mustafa and Blann are located at the Lawrence Livermore National Laboratory, while Sierk performed most of his calculations at Oak Ridge while on leave from the Los Alamos National Laboratory. A comparison of the RLDM and RFRM fission barriers is shown in figure 4 for ^{153}Tb. As expected, the RFRM barrier falls below the RLDM barrier over the entire angular momentum range. It is also apparent that neither of the two ad-hoc procedures that had been used to reduce RLDM barriers [$B_f(J) = k_f B_f^{LD}(J)$ and $B_f(J) = B_f^{LD}(J) + \Delta_f$] is correct.

A complete systematic fission excitation function analysis using the RFRM was first carried out for the compound nuclei of ^{153}Tb and ^{181}Re (Plasil *et al* 1984). In this work, three conditions deemed to be of crucial importance in applying the statistical model treatment to heavy-ion-induced fission excitation functions (Plasil 1980) were satisfied. These conditions are: (i) measured fission cross-sections and measured evaporation residue cross-sections must be accounted for simultaneously; (ii) at least two different reactions leading to the same compound nucleus must be investigated simultaneously; and (iii) systems studied must be chosen such that all observed fission yield originates from the decay of equilibrated compound nuclei. The ^{153}Tb data are shown in figure 5 together with statistical model calculations from Sierk's RFRM (Sierk 1986) incorporated in the computer code PACE (Gavron 1980). It should be noted that only one parameter (a_f/a_v) was adjusted to obtain the simultaneous fit to

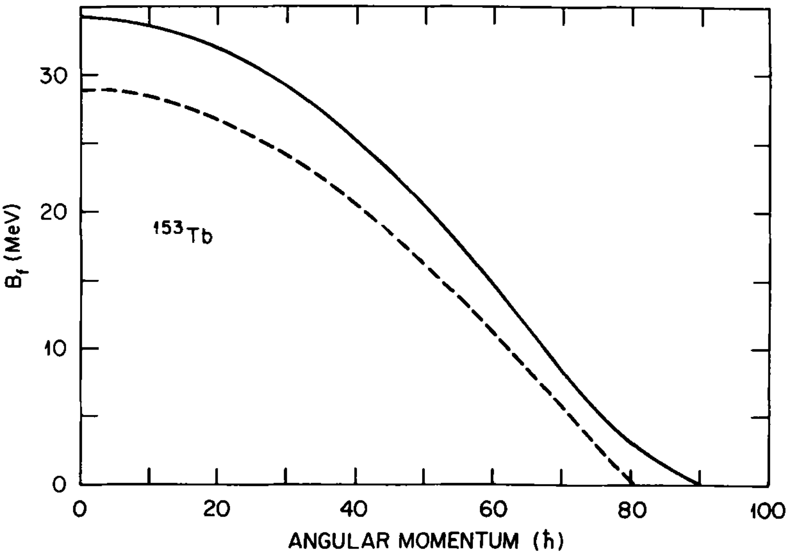

Figure 4. Calculated fission barriers, B_f, for ^{153}Tb as a function of angular momentum. The solid curve represents values from the rotating-liquid-drop model (Cohen *et al* 1974). The dashed curve represents values calculated in the rotating-finite-range model (Sierk 1986). This figure is taken from Plasil *et al* (1984).

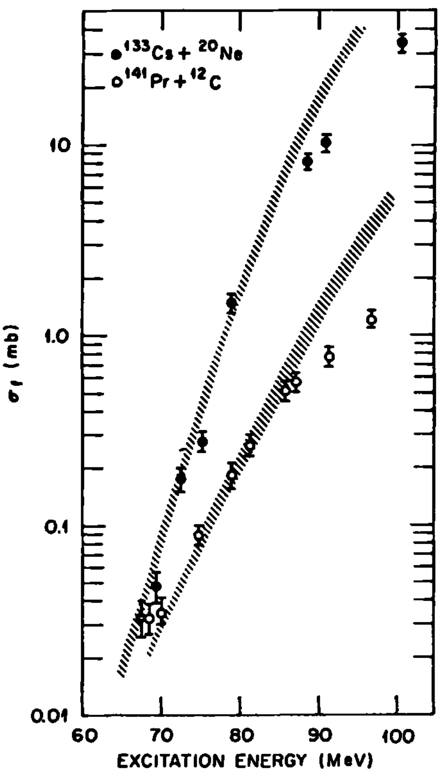

Figure 5. Measured (circles) and calculated (cross-hatched bands) fission excitation functions for two reactions leading to the ^{153}Tb compound nucleus. The calculations are performed in the framework of the statistical model with the rotating-finite-range model fission barrier values (Sierk 1986) shown in figure 4. The widths of the bands indicate computational uncertainties. This figure was taken from Plasil *et al* (1984).

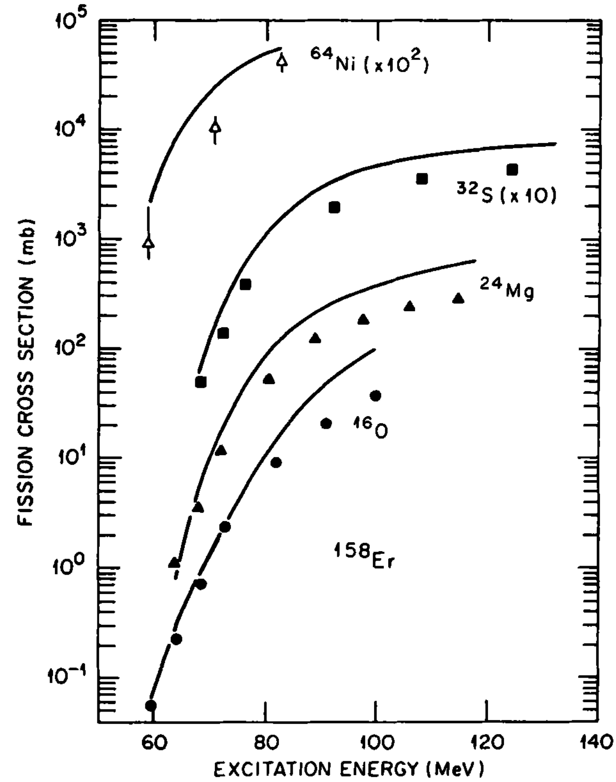

Figure 6. Comparison of measured (various symbols) and calculated (solid lines) fission excitation functions from a number of different reactions leading to the compound nucleus ^{158}Er. The projectiles involved are indicated. This is a modified version of a figure of van der Plicht *et al* (1983).

both excitation functions. A more extensive set of fission excitation functions was analysed with the RFRM by van der Plicht *et al* (1983). The range of compound nuclei investigated in this work extends from ^{158}Er to various isotopes of Po. Results from four reactions leading to ^{158}Er are shown in figure 6. The data are consistent with the RFRM without any adjustment of the fission barriers, although in this work the evaporation residue excitation functions were not measured but were estimated from the Bass model (Bass 1977). More recently, several other analyses of fission excitation functions using the RFRM (Lesko *et al* 1985, 1986; Charity *et al* 1986) have been performed. Generally, good fits to the fission excitation functions have again been obtained without any fission barrier adjustment.

My personal conclusion is that the above results constitute evidence that the RFRM describes fairly accurately the fission barriers of rotating nuclei. It should be noted, however, that this view is not universally accepted for a variety of reasons. For example, in some analyses (van der Plicht *et al* 1983; Lesko *et al* 1985, 1986; Charity *et al* 1986) a parameter δL has been introduced to account for a diffuse angular momentum distribution for fusion, and variation of this parameter tends to have the same effect as the scaling of the barrier height. Refinements in level densities have also been made (Vigdor and Karcwowski 1982). Furthermore, recent results of neutron and prefission particle emission studies indicate that dynamical effects are important and should be considered (Gavron *et al* 1981, 1982, 1986, 1987; Holub *et al* 1983; Zank *et al* 1986; Hinde *et al* 1986, 1988; Newton *et al* 1988). It is, of course, difficult to draw any firm conclusions about the fission barriers in the presence of a proliferating number of degrees of freedom or when the fundamental validity of the statistical model is questioned.

6. Recent experimental results

In recent years the Australian National University in Canberra has emerged as the prime centre for studies of heavy-ion-induced fission. In a beautiful series of experiments, (Leigh *et al* 1982, 1985; Hinde *et al* 1982, 1983, 1984; Charity *et al* 1986; Newton *et al* 1988; Ward *et al* 1983) extensive measurements were made of fission, evaporation residue, and prefission neutron-emission excitation functions. Data analyses were carried out using the computer codes of Blann and coworkers, MBII (Beckerman and Blann 1977) and ALERT1 (Blann and Komoto 1982) in which either

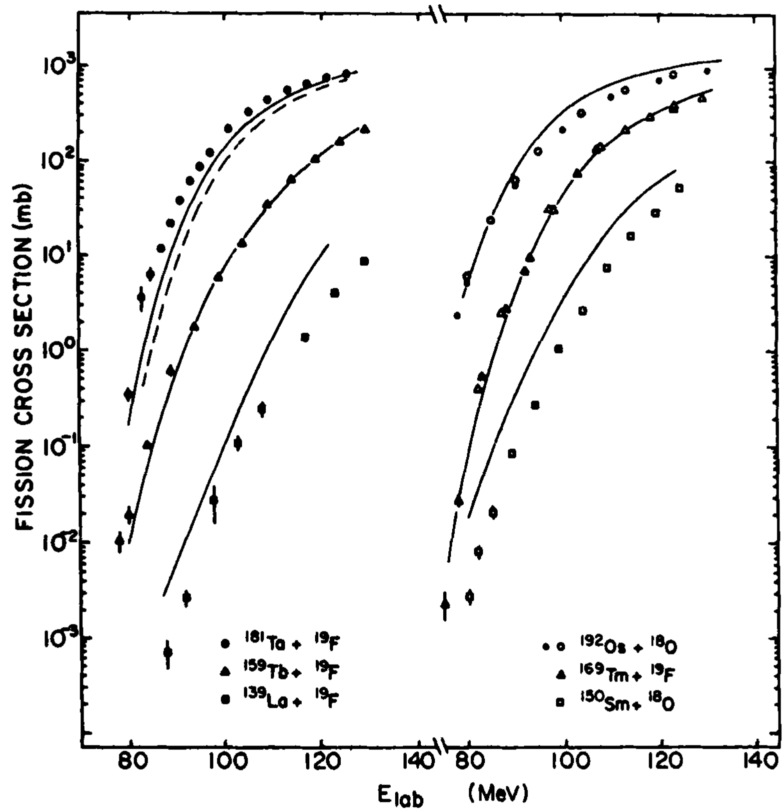

Figure 7. Fission excitation functions for the indicated systems. Data are denoted by a variety of symbols. The calculated cross-sections were obtained using the RFRM (Sierk 1986) (solid lines) and, in one case, the RLDM (Cohen *et al* 1974) (dashed line). The calculations did not involve any adjustable parameters. This figure is taken from Charity *et al* (1986).

RLDM or RFRM fission barriers were incorporated. Among the early results obtained by this group were the first measurement of the spin distribution associated with evaporation residues when limited by fission (Leigh *et al* 1982; Hinde *et al* 1982) and the prefission neutron-emission measurements for ^{200}Pb, which removed the ambiguity in the RLDM parameter k_f for this case (Ward *et al* 1983). More recently, Charity *et al* (1986) have reversed the trend in parameter proliferation by comparing their data for the systems ^{158}Dy, ^{168}Yb, ^{178}W, ^{188}Pt, ^{200}Pb, and ^{210}Po formed in reactions of ^{19}F and ^{18}O projectiles with various target nuclei to ALERT1 (Blann and Komoto 1982) calculations with no adjustable parameters. They used RFRM barriers, $a_f/a_v = 1{\cdot}0$, $a_v = A/10\,\mathrm{MeV}^{-1}$, and δL values calculated from the zero-point motion model of Esbenson (1981). The results are shown in figure 7 and indicate remarkable agreement between theory and experiment, except for the lightest systems.

Newton *et al* (1988) measured prefission neutron emission for a large number of the systems studied by the Canberra group and found that, in most cases, the results are consistent with the statistical model at low excitation energies but not at higher excitation energies, where prefission neutron emission is expected be decrease, but where, in fact, it is observed to continue to increase. The neutron, evaporation residue, and fission cross-section data were subjected to a comprehensive analysis with the ALERT1 computer code, and the RFRM barriers were allowed to vary via the multiplicative constant k_f defined earlier. The results are shown in figure 8. Of

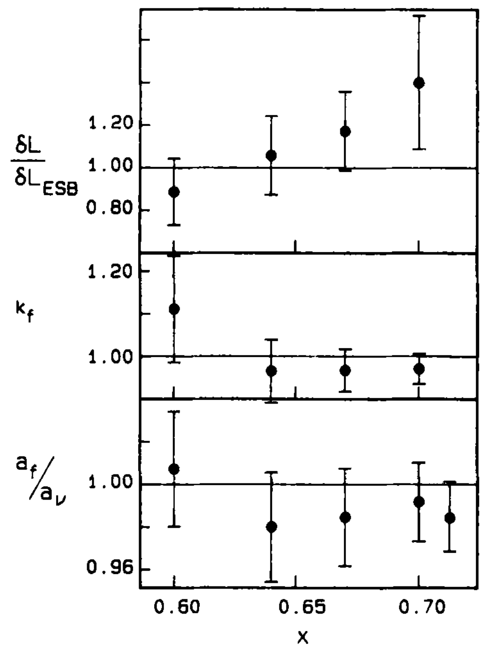

Figure 8. Ratio of level density parameters a_f/a_v, fission barrier scaling constant k_f, and ratio of the angular-momentum-diffuseness parameter δL to that predicted from the zero-point motion model (Esbenson 1981) as a function of the fissility parameter x. Values of these statistical model parameters were derived from fits to data (Newton *et al* 1988) (see text). With $k_f = 1{\cdot}00$, fission barriers used are those of the RFRM (Sierk 1986). This figure is taken from Newton *et al* (1988).

particular note is the fact that the data are consistent with $k_f = 1{\cdot}0$ (i.e., with RFRM values), albeit only within the rather large errors indicated.

7. Recent theoretical studies – temperature-dependent barriers

On the theoretical front, recent developments have centered on the calculations of temperature-dependent fission barriers (Diebel *et al* 1981; Dalili *et al* 1985; Nemeth *et al* 1985; Mustafa 1988; Garcias *et al* 1988). The earliest investigation of temperature effects on fission barriers for rotating systems was made by Diebel *et al* (1981). It emphasized systems appropriate for the possible synthesis of superheavy elements. More recently, the combined effects of temperature and angular momentum were calculated by Dalili *et al* (1985). The calculations were performed for the ^{205}At nucleus in a self-consistent Thomas-Fermi approach. The fission barrier was found to decrease with increasing temperature (and also with increasing angular momentum). Not surprisingly, the angular momentum at which the fission barrier vanishes was found to decrease with increasing temperature. The same authors have also performed both Thomas-Fermi and Hartree-Fock calculations for the ^{144}Nd nucleus (Nemeth *et al* 1985). Similar conclusions were reached regarding the temperature dependence of the fission barrier, and it was also shown that the Thomas-Fermi method yields results (at a fraction of the computing cost) that are very similar to those of the Hartree-Fock method. In a recent paper by Garcias *et al* (1988) the Thomas-Fermi method, together with a more realistic nuclear force, was applied to several other nuclei in a systematic study of temperature effects. Unfortunately, confrontation between experiments and the above theoretical studies is lacking.

Mustafa (1988) has described temperature effects on fission barriers in the context of the RFRM. As in earlier stuides (Diebel *et al* 1981; Dalili *et al* 1985; Nemeth *et al* 1985) the fission barriers are found to decrease with increasing temperature. Results for the ^{178}W nucleus are shown in figure 9. An attempt was made to use the

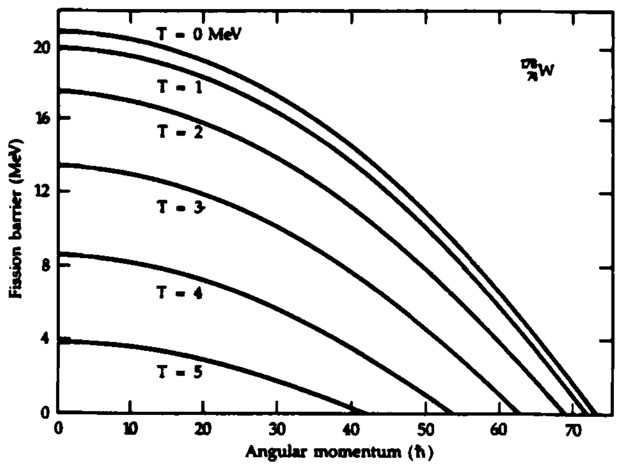

Figure 9. Calculated fission barriers of the nucleus ^{178}W as a function of angular momentum for selected values of nuclear temperature. The rotating-finite-range model (Mustafa *et al* 1982) extended to a finite temperature is used in the calculations (Mustafa 1988). This figure is taken from Mustafa 1988.

temperature-dependent barriers in a reanalysis of the $^{19}F + ^{159}Tb$ data of (Plasil *et al* 1984). These efforts, however, did not prove to be successful (Mustafa 1988). It was pointed out by Mustafa that a consistent description of the temperature dependence of the fission process may be obtained only if temperature effects on all parameters are considered simultaneously. Particularly important in this context may be the temperature dependence of the nuclear level density parameters.

8. Summary and conclusion

I have presented a brief history of the development of the rotating liquid drop model together with a chronology of its confrontation with experimental results. The studies described led to the introduction of the rotating finite-range model, which was shown to give an adequate quantitative (or semiquantitative, depending on the point of view) description of angular-momentum-dependent fission barriers. Recent experiments relating to these issues were discussed, and the emerging subject of the temperature dependence of fission barriers of rotating nuclei was introduced. It may be safely concluded that for the purposes of estimates of angular momentum effects and for use in interpretations of data obtained from heavy-ion-induced reactions, the zero-temperature RFRM is adequate and should replace the use of the RLDM.

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