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Fragment angular distributions in fission and fission-like reactions

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Abstract. Fragment angular distributions in fission is one of the oldest and well understood aspects of fission theory. However, recent heavy ion-induced fission and fission-like reactions have added a new dimension to this problem. We review here our present understanding of the fragment angular distribution theory in fission and fission-like reactions.

Keywords. Fission; angular distributions; double-humped fission barriers; heavy ion reactions; quasi fission; fast fission; pre-equilibrium fission; anisotropy versus asymmetry.

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1. Introduction

An important landmark in our theoretical understanding of the fission process has been the Bohr hypothesis (Bohr 1955) which postulates that the fissioning nucleus while passing over the saddle point exhibits a spectrum of quasi-stationary states similar to the quantum states observed for deformed nuclei near their ground states. With the reasonable assumption that the symmetry axis of the saddle point nucleus whose orientation is governed by symmetric top wavefunctions with appropriate quantum numbers (the total angular momentum I, its projection M on the beam axis and projection K on the symmetry axis) can also be identified as the fission axis, and that the orientation, once determined at the saddle point, remains unaltered up to the scission point, the Bohr hypothesis provided a natural explanation of the observed fragment angular distributions in photo and low energy neutron-induced fission of many nuclei. The theory was subsequently generalized by Halpern and Strutinsky (1958) to the region of medium and high excitation energies involving a statistical distribution of quantum states of the saddle point nucleus. The Halpern-Strutinsky theory not only was highly successful in explaining the angular anisotropy of the fragments observed in fission induced by nucleons and a variety of energetic-charged particles but also related the magnitude of the fragment anisotropy to the spin distribution of the fissioning compound nucleus and the variance of the K-distribution at the saddle point which in turn is related to the temperature and shape of the saddle point nucleus. The shape parameters of saddle point nuclei extracted from the analysis of the fragment angular distributions in a number of nucleon and light-ion-induced fission reactions were indeed found to be in good agreement with those calculated on the basis of liquid drop model (LDM) and its refined versions (Reising *et al* 1966). This can be considered to be a big triumph both for the fission fragment angular distribution theory and for the liquid drop model calculations of the static fission barrier shapes.

The realization in the late sixties (Strutinsky 1967) that the fission barriers of actinide nuclei were double-humped due to nuclear shell effects added a new dimension to the problem of fission fragment angular distributions. The question arose as to which of the two barriers determine the K-distribution. The near-threshold fission fragment angular distribution data clearly pointed to the second barrier being the shape where K distribution is determined (Strutinsky and Pauli 1969). This also appeared justified since the K distribution determined on the top of the first barrier can be expected to be significantly altered during the passage of the nucleus through the second well. However, the picture of the second barrier determining the fragment angular distributions did not fit the transition state shapes deduced from the fragment angular distribution data at medium excitation energies for these have been shown earlier to be in agreement with the saddle point shapes calculated by the liquid drop model (Reising *et al* 1966). This anomaly was soon resolved on the basis of a washing out of shell effects with the excitation energy. At a given excitation energy of the fissioning nucleus, one has only to identify the point of minimum entropy along the fission path as the fission transition state shape which describes both the fission probability and the fragment angular distributions. This results in the emergence of the LDM saddle point as the fission transition state at high excitation energies.

In recent years, with the availability of energetic heavy ion beams, it has become possible to produce fissioning nuclei with high fissility and/or spin and to study their fission properties including the fragment angular distributions with respect to the beam direction (Vaz and Alexander 1983). In an early study of this kind (Glassel *et al* 1979), fissioning nuclei with near-zero barriers were populated in deep inelastic collisions and the measurements showed that the fragment anisotropy was much larger than expected on the basis of Halpern-Strutinsky theory with equilibrium saddle shapes. Subsequently, a number of studies involving fusion-fission reactions with vanishingly small fission barriers of the intermediate systems have been carried out which again showed that the observed fragment angular distributions were much more anisotropic than those predicted by the Halpern-Strutinsky theory using equilibrium saddle shapes. While some speculate this to be an evidence for the breakdown of the standard fission transition state theory of fragment angular distribution for fissioning nuclei with large fissilities and spins, we have shown recently (Ramamurthy and Kapoor 1985) that these distributions can be explained by simply recognizing that in heavy ion-induced fission studies, the observed fission events contain an admixture of fission events following compound nucleus formation and fission-like events which have not achieved full K-equilibration and therefore exhibit a memory of the entrance channel reaction plane and an unusually large fragment anisotropy. For events of the latter type, the Halpern-Strutinsky transition state theory is clearly not applicable.

In what follows, we first discuss the fission transition state theory for the fragment angular distributions in the fission of fully equilibrated compound nuclei. This is followed by a discussion of the apparent anomalies of large fragment anisotropies seen in heavy-ion induced fission reactions. We show that these deviations do not necessarily point to a breakdown of the standard transition state theory but result due to the presence of non-equilibrium fission-like events. Finally, we present a discussion of what we can learn from the investigations of fragment angular distributions for specified fragment mass ratios.

2. Transition state theory of fission fragment angular distributions

It has been established for a long time that in fission induced by any energetic projectile, the fragments exhibit an anisotropy with respect to the beam direction. Bohr (1955) applying the concepts of the unified model of the nucleus to the highly deformed transition state nucleus as it passes over the saddle point on its way to fission postulated that the fissioning nucleus spends a sufficiently long time near the fission transition state shape to be able to define a spectrum of quasi-stationary states at the saddle point. The transition state nuclei are assumed to be axially symmetric and are described by symmetric top wavefunctions $d^I_{MK}(\theta)$ where the quantum numbers I, M and K are the total angular momentum of the fissioning nucleus, its projection on the space-fixed beam axis, and on the nuclear symmetry axis of the fissioning nucleus at the transition state (figure 1). The angular distribution of the symmetry axis for a given state is given by

$$P^I_{MK}(\theta) = \tfrac{1}{2}(2I+1)|d^I_{MK}(\theta)|^2, \tag{1}$$

where θ is the angle with respect to the space-fixed axis. One then makes the further assumption that the fission fragments are emitted along the direction of the nuclear symmetry axis at the fission saddle point implying that the K-quantum number is conserved during the saddle-to-scission dynamics. This model was found to be very successful in explaining the fragment angular distributions in a number of photon and neutron-induced fission near the fission threshold on the basis of available quantum states at the saddle point.

Halpern and Strutinsky (1958) extended this model to the high excitation energy region with a statistical distribution of quantum states for the transition state nucleus with spectacular success. In the Halpern-Strutinsky model, for fusion-fission reactions one sums up the functions $P^I_{MK}(\theta)$ over the allowed values of I, M and K to obtain the final angular distribution of the fragments. Neglecting the intrinsic spins of the target and the projectile, one obtains

$$W(\theta) = \sum_I \sigma(I) \sum_{K=-I}^{+I} \rho_t(I,K) P^I_{0K}(\theta), \tag{2}$$

where $\rho_t(I,K)$ is the level density of intrinsic states at the saddle point. The

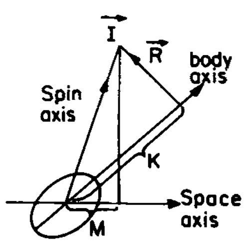

Figure 1. Saddle point quantum numbers determining the fragment angular distributions in fission of a fully equilibrated compound nucleus.

spin-dependent cross-section $\sigma(I)$ is given by:

$$\sigma(I) = (\pi/k^2)(2I + 1)T(I).$$

The entrance channel wave vector k is given by

$$k^2 = 2\mu E_{cm}/\hbar^2, \tag{4}$$

where E_{cm} is the centre-of-mass bombarding energy and μ is the reduced mass. The transmission coefficients $T(I)$ are obtained from a reaction model that reproduces the measured compound nucleus fission cross-section. This equation is applicable when spin fractionation through competing decay modes is negligible, as in the case of fissioning nuclei with high fissilities and spins. Otherwise, one has to allow for multichance fission events.

Two separate approaches can be considered for calculating the spin distribution of the compound nuclei. In the often used one-dimensional barrier penetration model approach, the passage over the barrier is taken as the necessary and sufficient condition for fusion to take place and the height and the width of the barrier are so chosen as to reproduce the measured fusion cross-sections. For near sub-barrier energies, a coupled channel formalism which includes the effects of static deformations of the colliding nuclei and the known nuclear vibrational and rotational degrees of freedom provides a more fundamental basis for calculating the fusion cross-sections for different partial waves.

The distribution of K at the transition state is determined from the K-dependence of the density of intrinsic states at the fission transition state. In the absence of nuclear shell effects, the fission transition state is the same as the liquid drop saddle point. Using the constant temperature expression for the transition state level densities,

$$\rho_t(I, K) \approx \exp[(E - E_{def} - E_{rot})/T]. \tag{5}$$

On the assumption that the saddle point shape is not dependent on the K value, ρ_t can be written as

$$\rho_t(I, K) \approx \exp[-K^2/2K_0^2],$$

where

$$K_0^2 = \frac{J_{eff}T}{\hbar^2} = (J_0/J_{eff})^{-1}\frac{J_0 T}{\hbar^2}. \tag{6}$$

and

$$J_{eff} = J_{\parallel}J_{\perp}/(J_{\perp} - J_{\parallel}). \tag{7}$$

Here $J_{\parallel}$ and $J_{\perp}$ are the moments of inertia parallel and perpendicular to the nuclear symmetry axis of the fissioning nucleus at the fission transition state and J_0 is the moment of inertia for the spherical shape. Hence, it is possible to deduce the values of J_0/J_{eff}, which depend only on the shape of the fissioning nucleus while passing over the fission transition state, from an analysis of the fragment angular distributions in the fission process induced by energetic projectiles.

For fissioning nuclei with large values of spin, one often modifies the Halpern-Strutinsky theory to include an I-dependent fission barrier height and shape as given by the rotating liquid drop model (Cohen *et al* 1974). It has recently been shown by Prakash *et al* (1984) that for fissioning nuclei with large spins, it is not reasonable to assume that the saddle point shapes are independent of the value of K for a given I. The flexible rotor model involves a calculation of the deformation potential energy and location of the saddle point for each value of K for a given I.

3. Fragment angular distributions in the fission of nuclei with double-humped fission barriers

For nuclei in the actinide region where the shell effects result in a pronounced double-humped fission barrier, the question arises as to which nuclear shape does the effective moment of inertia derived from the angular distribution data correspond. In the near-threshold fission, the anisotropy data seem to suggest that the angular distributions are characteristic of the second barrier shape (Strutinsky and Pauli 1969). However, at medium excitation energies, the data seem to be in agreement with the liquid drop model saddle point shapes (Reising *et al* 1966). This apparent anomaly was resolved by Ramamurthy *et al* (1970) who showed that there is a rapid washing out of shell effects on the thermodynamic properties of nuclei with excitation energy and at excitation energies where shell effects have completely disappeared, the nucleus should thermodynamically behave as a liquid drop model nucleus with the liquid drop model saddle point emerging as the fission transition state. Consequently, one would expect a gradual shift of the transition state shape from the second barrier shape at low excitation energies to the liquid drop model shapes at high excitation energies. This would imply that the moment of inertia parameters become excitation energy-dependent not only because of the shell and pairing effects on them for a given shape but also because of the shape changes with excitation energy. Figure 2 shows the dependence of fragment anisotropy on neutron energy in neutron-induced fission of several heavy nuclei (Strutinsky and Pauli 1969). It can be seen that while for lighter nuclei there are fluctuations in the anisotropy versus the neutron energy near

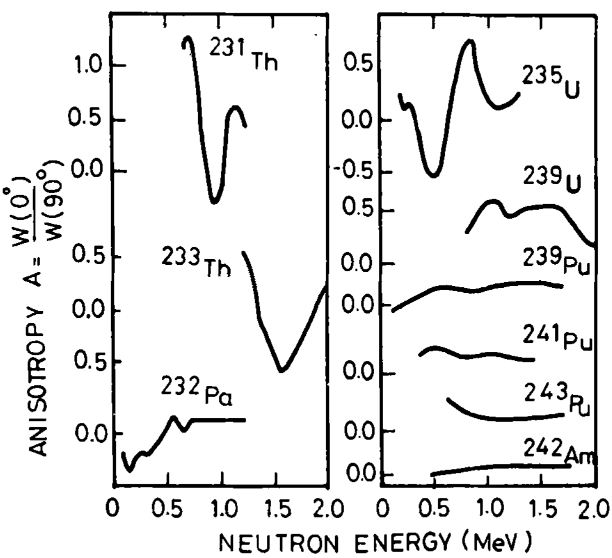

Figure 2. Fission fragment anisotropies versus neutron energy in neutron-induced fission of several heavy nuclei (figure reproduced from Strutinsky and Pauli 1969).

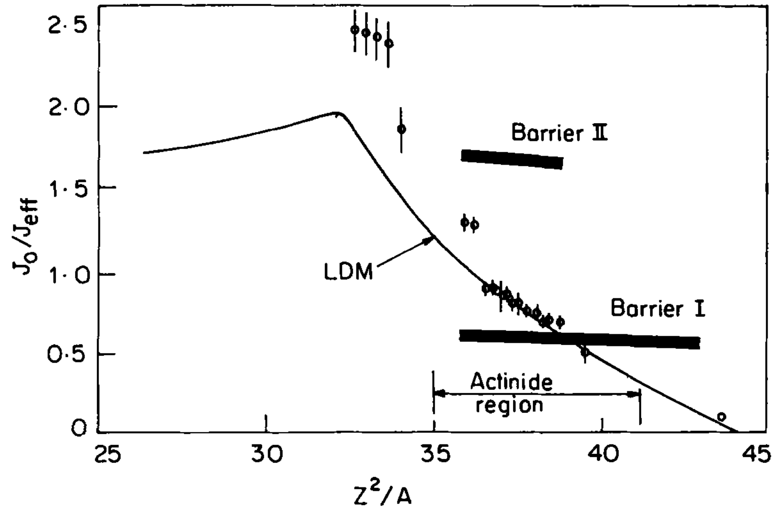

Figure 3. "Experimental" values of J_0/J_{eff} versus Z^2/A deduced from fragment anisotropies measured in alpha induced fission of heavy nuclei. The liquid drop model predictions as well as the calculated values for barriers I and II of the double humped barriers are also shown in the figure (figure reproduced from Ramamurthy *et al* 1970).

the fission threshold, for heavier nuclei the anisotropy is found to vary rather smoothly. This feature can be understood on the basis that the height of barrier II decreases as the nuclei become heavier and that the K-quantum number is not conserved in going over the well from the first barrier to the second barrier. Thus, the results of the figure imply that near threshold, fragment angular distributions are determined by a small number of open channels on the top of barrier II. However, in the case of heavy nuclei, where the height of barrier II is smaller than that of barrier I, the number of open channels on barrier II is sufficiently large to apply the statistical theory and the anisotropies are smooth functions of the neutron energy. The transition state shapes deduced from analysis of the fragment angular distributions of various fissioning nuclei at medium excitation energies are shown in figure 3 in terms of a plot of J_0/J_{eff} versus Z^2/A along with the results of calculations for a liquid drop barrier as well as for the barriers I and II of the double-humped barrier. This figure clearly shows that the transition state shapes of a heavy nucleus like uranium, excited to about 20–30 MeV correspond to the liquid drop model saddle shapes rather than that corresponding to the second barrier of the double-humped fission barrier. This is also substantiated by the observed dependence of K_0^2, on excitation energy as shown in figure 4. It shows that the transition state changes smoothly from barrier II shape to LDM barrier shape with increase in excitation energy.

4. Fragment angular distributions in heavy ion-induced fission reactions

In the fission of compound nuclei formed with low Z projectiles at medium energies, where many partial waves contribute to the fission channel, the magnitude of the anisotropy is basically determined by two parameters $\langle I^2 \rangle$ and K_0^2 where $\langle I^2 \rangle$

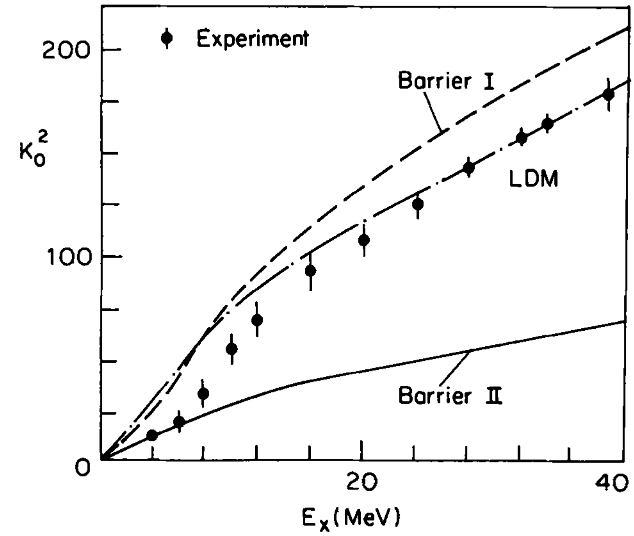

Figure 4. Measured variation of the parameter K with excitation energy for the fissioning nucleus ^{242}Pu. The calculated values corresponding to the shapes of the barriers I and II are also shown illustrating the change of transition state shape from barrier II to the LDM barrier in the excitation energy range 4–30 MeV (figure reproduced from Ramamurthy *et al* 1970).

corresponds to the mean square spin of the fissioning nucleus. If one is in the excitation energy regime such that shell and pairing effects are wiped out and the fission transition state corresponds to that given by LDM, one can easily calculate K_0^2 by making use of the calculated LDM universal curve of J_0/J_{eff} versus fissility parameter X, and a level density parameter to estimate T. In such cases, the fragment angular distributions can be analysed to deduce the values of $\langle I^2 \rangle$ (and hence the fusion cross-section σ_{fus} on the basis of the sharp cut-off approximation for the contributing partial waves). As an example, such a determination of σ_{fus} from the analysis of fragment angular distributions (Choudhury *et al* 1979) in the case of some light ion-induced reactions is shown in figure 5, along with the results of calculations of σ_{fus} from the heavy ion trajectory calculations using proximity potential with and without friction. It can be seen that the values of the fission cross-sections as deduced from the angular distribution data are in good agreement with the trajectory calculations. Thus fragment angular distributions can serve as an alternative way to deduce mean square spin values and fusion cross-sections in some cases, where direct measurements are difficult.

In a number of recent measurements of the fragment angular distributions in heavy-ion-induced fission reactions, the data are not consistent with the predictions of the transition state model of the fragment angular distributions in fission following compound-nucleus formation (Vaz and Alexander 1983). The discrepancy has been ascribed to a possible breakdown of the Halpern–Strutinsky theory for compound nuclei with high fissilities or spins or to the emergence of new reaction channels such as quasi- and fast fission which do not follow compound nucleus formation but result in fission-like fragments. Recently we have developed (Ramamurthy and Kapoor 1985a, b; Ramamurthy 1985) a model for the fragment angular distributions in heavy

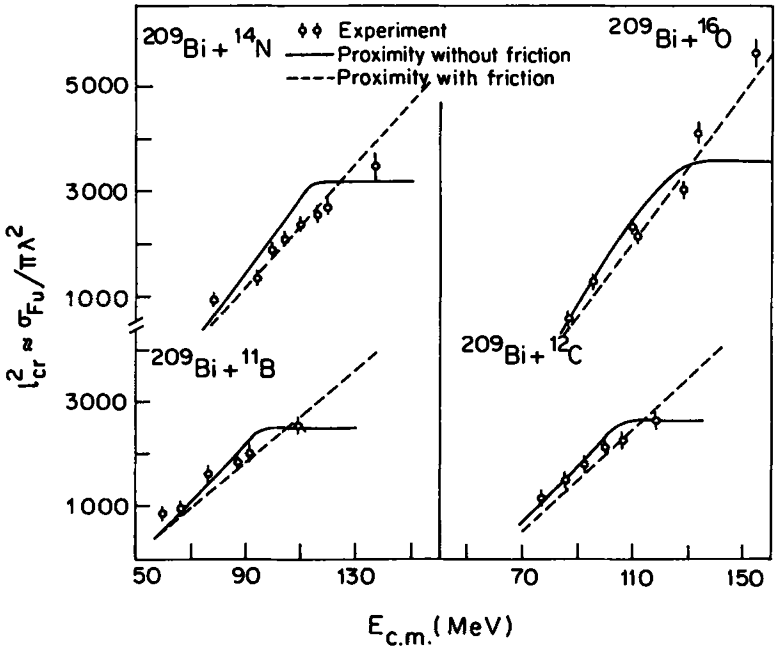

Figure 5. Calculated fusion cross-sections versus centre of mass bombarding energy using fission fragment angular distribution data. The corresponding values predicted by trajectory calculations are also shown in the figure (figure reproduced from Choudhury *et al* 1978).

ion-induced fission based on the suggestion that in heavy ion-induced fission reactions, the observed fission events consist of an admixture of events of two basically different types. These are (i) compound-nucleus fission (CNF), and (ii) fission-like decay of a composite system which has equilibrated in all degrees of freedom except the K degree of freedom (non-compound nucleus fission NCNF). Reaction mechanisms such as fast fission taking place for the case of composite systems with zero-fission barriers and quasi-fission taking place for composite systems with fission-barrier shapes more compact than the entrance-channel contact configuration, belong to fission-like events of type (ii). Another class of NCNF events proposed in our work is the "pre-equilibrium fission" events occurring in a time scale comparable to the characteristic relaxation time in the K-degree of freedom when the fission-barrier heights become comparable to the temperature of the composite system.

We use the transition state model of the fragment angular distributions in fission following compound nucleus formation with the rotating liquid drop model extension to high spins for the events of type (i). We also included the modifications proposed to take into account the dependence of the transition state energy and shape on both the magnitude of the spin I and its projection K on the symmetry axis. We also made the reasonable assumption for heavy composite systems that all compound nucleus fission events correspond to first chance fission.

There exists at present no theoretical formulation for calculating the fragment angular distributions for the type (ii) events. However, in some recent experiments (Lesko *et al* 1983) involving very high spins and large values of Z^2/A of the composite system where the compound nucleus formation probability is very small, highly anisotropic angular distributions have been measured. Based on this, we have proposed that the effective K distribution for all non-compound nucleus forming fission events can be represented by a narrow Gaussian with a variance given by

$$\sigma_K^2 = I^2\sigma_\theta^2,$$

where σ_θ is the angular variance representing the misalignment of the symmetry axis of the fused composite system with respect to the $K = 0$ plane. It was further assumed that σ_0 is nearly constant for all systems and bombarding energies considered in the analysis.

For a calculation of the relative probabilities of fission following compound nucleus formation and non-compound nucleus forming fission events, one first considers a fused composite system with an angular momentum I and temperature T. If I is larger than the rotational liquid drop model limit I_F^{RLDM} for vanishing fission barriers, no compound nucleus will be formed and the fused composite system will undergo fast fission with unit probability. If, however, I is less than I_F^{RLDM}, one has to consider the dynamics between the fission saddle point and the compound nucleus. Let us assume that the system has been brought to a configuration more compact than the unconditional fission saddle point. This system is also initially formed predominantly in a $K = 0$ configuration with a small width in the K distribution. Let $B_F(I \cdot K = 0)$ be the height of the barrier preventing this system from a fast binary split (fast fission). Left to itself, the system will then relax in the shape and orientation degrees of freedom to form a fully equilibrated compound nucleus. However, if the fission time is comparable to the characteristic time for K relaxation, the composite system has a finite probability of undergoing fission in a time shorter than the K equilibration time and fragment angular distribution of such events will carry the memory of the entrance channel K distribution. For a given $B_F(I, K)$, one can calculate the fission probability per unit time making use of the Bohr-Wheeler transition state theory. In principle, the evolution of the K distribution is continuous and the effective K distribution for fission events taking place at different times is different. However, for the sake of simplicity we assume that only those composite systems that survive fission for a time longer than τ will result in the formation of a fully equilibrated compound nucleus which subsequently undergoes fission while all fission events taking place in a time less than τ carry a memory of the entrance channel K distribution and have angular distributions similar to those of the fast fission events. In analogy with the emission of fast nucleons in nuclear reactions in time scales much shorter than the compound nuclear lifetimes, we call these fission events competing with compound nucleus formation as pre-equilibrium fission events. The experimental data on the fragment angular distributions were fitted in terms of the model described above for a number of systems. Figure 6 shows a comparison of the calculated fragment angular distributions and the experimental data for a few typical systems involving different projectiles on the same target and same projectile on different targets. It was found that all the data shown in the figure can be fitted with a single set of the parameters corresponding to $\tau = 8 \times 10^{-21}$ seconds and $\sigma_\theta^2 = 0{\cdot}06$. Figure 7 shows the differential cross-sections for fission following compound nucleus formation, pre-equilibrium fission and fast fission versus the entrance channel angular momentum l for the two typical cases of $^{19}F + {}^{208}Pb$ and $^{32}S + {}^{208}Pb$ as deduced from the above analysis. It can be seen that true compound nucleus formation is considerably reduced over a significant range of l values even below I_F^{RLDM}.

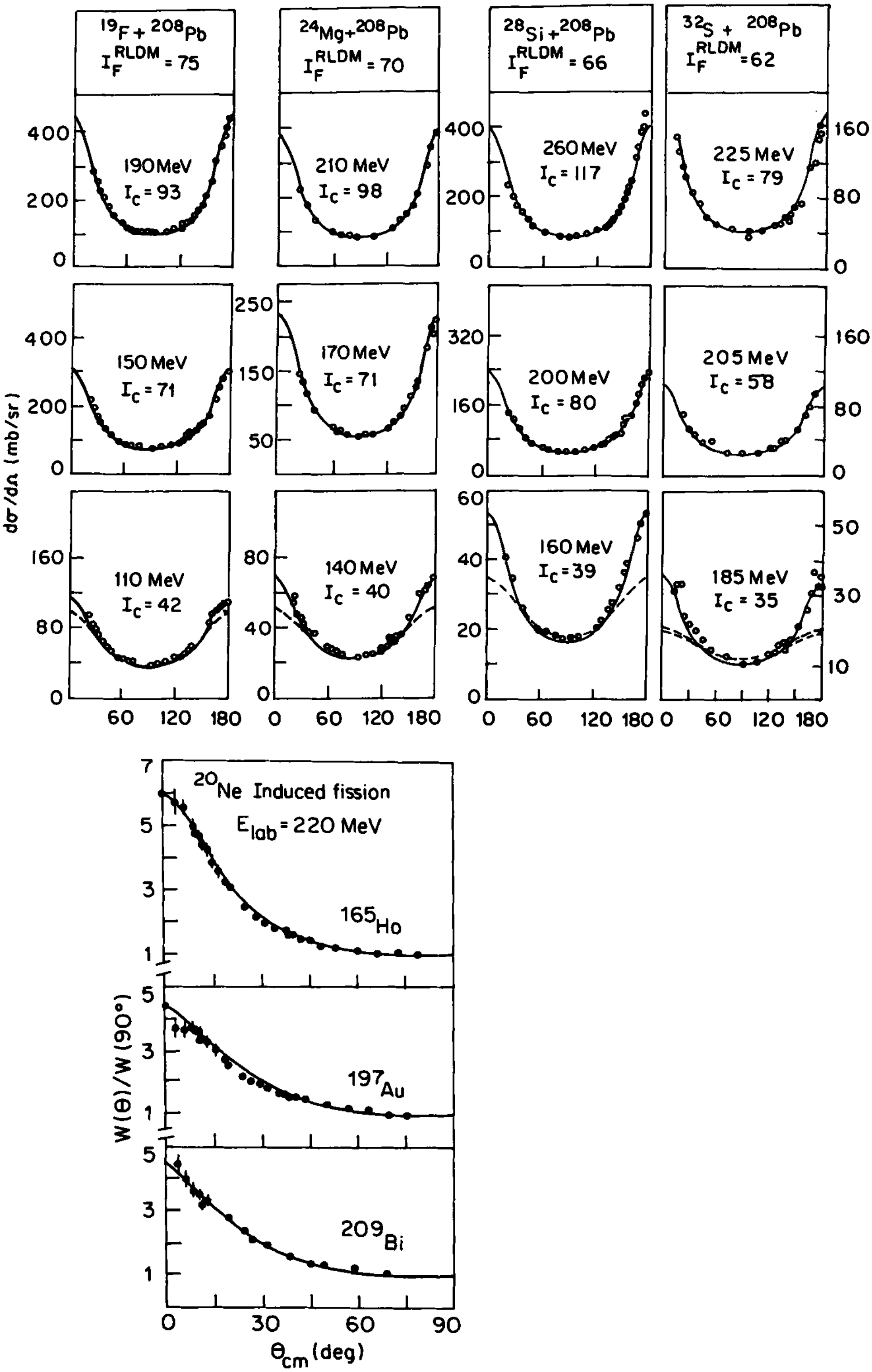

Figure 6. Experimental and calculated fragment angular distributions in a number of heavy ion-induced fission reactions (figures reproduced from Ramamurthy and Kapoor 1985 and Ramamurthy 1985)

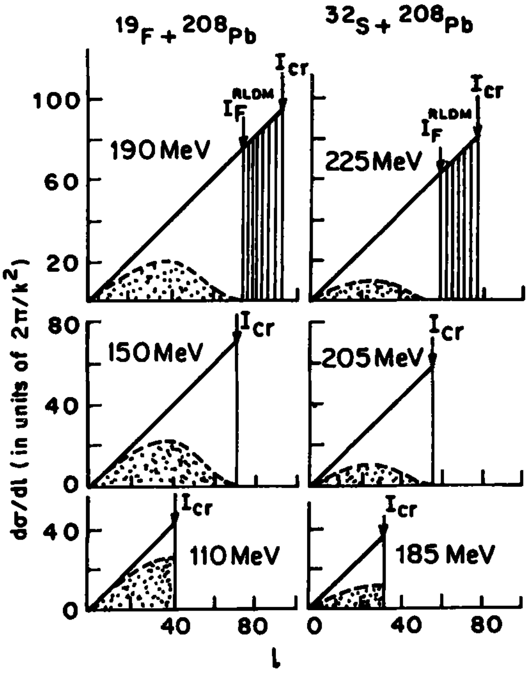

Figure 7. Differential fission cross-section versus angular momentum. The shaded area represents fission following compound nucleus formation after allowing for pre-equilibrium. The vertical lines define the angular momentum window for fast fission (figure reproduced from Ramamurthy and Kapoor 1985).

We have assumed in the above analysis that all non-compound nucleus forming fission events have similar angular anisotropies since they all take place in similar time scales although they have different physical origin. In the case of quasi-fission events, for example, the collision trajectory does not reach the unconditional saddle point whereas in the case of pre-equilibrium, the system passes over the unconditional fission saddle point but the barrier height is not adequate to contain the system long enough to equilibrate fully in all degrees of freedom before reseparation. Thus, pre-equilibrium fission is an additional limitation to compound nucleus formation over and above the dynamical limitations to reach the unconditional saddle point. Any attempt therefore to explain the unusually large anisotropies in heavy ion-induced fission reactions in terms of equilibrium fissions and quasi-fissions alone without taking into account pre-equilibrium fissions (Back *et al* 1983) is bound to lead to inconsistencies. Such an inconsistency has already been pointed out in literature (Keller *et al* 1987). In a number of heavy ion-induced reactions, the extra push energies deduced from fusion evaporation residue systematics and fission anisotropy measurements have been shown to follow different trends. For example, in the case of argon-induced reactions on lead isotopes, the measured cross-sections for fusion evaporation residues are consistent with unhindered fusion near the barrier. On the other hand, the measured angular distributions of charge separated fragments clearly demonstrate that the fission channel includes a substantial fraction of non-compound fission events and if these are identified as quasi-fission events, this will demand an extra push energy of about 4–9 MeV. We estimate that the fraction of pre-equilibrium fission events is about 76% in this case resulting in fragment anisotropies much larger than what is expected for the equilibrium fission events. At the same time, since pre-equilibrium fission takes place after the passage over the unconditional fission saddle point, a reduced equilibrium fission fraction does not signal a dynamical limitation to reach the saddle point. Thus, with the inclusion of pre-equilibrium fission, there is no inconsistency between the fusion evaporation residue data and the fission data in terms of the deduced extra-push energies.

While in the above analysis, the dependence of the ratio of pre-equilibrium fission to compound nucleus fission on the entrance channel mass-asymmetry is not included, some dependence of the above ratio on the mass asymmetry is to be expected (Ramamurthy and Kapoor 1986). Since the fragment angular distributions in the light ion-induced fission which have been explained on the transition state model, do not indicate presence of significant pre-equilibrium fission in those cases, it appears that the occurrence of pre-equilibrium fission becomes significant only for entrance channel mass asymmetries lower than some value. This question is related to the K-equilibration times in the fusion and compound nucleus formation dynamics as a function of entrance channel mass-asymmetries. It is known that in a heavy ion collision, if the entrance channel mass asymmetry is continuously varied, the nature of the collective dynamics leading to fusion exhibits an abrupt change across the Businaro-Gallone critical mass asymmetry. This should also reflect as an abrupt charge in the experimental anisotropy across the Businaro-Gallone asymmetry. This needs to be further investigated both theoretically and experimentally. Another question which arises and needs to be carefully looked into is whether the fission barrier heights derived from the measured fission excitation functions in heavy ion-induced fission can be in error if the measured fissions include some pre-equilibrium fissions from the fission decay of the intermediate system, which has not fully equilibrated in the K-degrees of freedom. These aspects are currently being examined in our further studies.

5. Correlation between mass-asymmetry and angular anisotropy

The fission fragment angular distribution theory as discussed above implies that the angle of emission of the fragments is uniquely determined as the fissioning nucleus passes the fission transition state. On the other hand it is known that the fragment mass and charge distributions are determined somewhere close to the scission point. It would therefore be interesting to study experimentally possible correlations between the mass asymmetry and the angular anisotropy which can lead to new information on the saddle-to-scission dynamics. A few experiments of this kind have been reported in literature. It should however be remembered that an apparent correlation between the asymmetry and the anisotropy can arise trivially from the presence of multiple chance fissions. This comes due to the fact that in an admixture of fissions taking place at different excitation energies in fissioning nuclei with $Z > 90$, fissions at lower excitation energies are expected to give a greater fragment anisotropy (due to lower value of T and hence K_0^2) as well as a larger mass-asymmetry or peak-to-valley ratio. Similarly, for fissioning nuclei with $Z < 90$, where the shape of the mass distributions is symmetric, both the width of the mass distribution as well as the fragment anisotropy are expected to be dependent on the temperature, and this can again result in an apparent dependence of the fragment anisotropy on the mass ratio if multiple chance fissions at different excitation energies are involved. Hence any attempt to detect the intrinsic dependence of anisotropy on mass ratio is best done if multiple chance fissions are not involved. This situation is however very difficult to realize in most cases. A unique experiment involving neutron-induced fission of ^{235}U has been reported by us (Kapoor *et al* 1965) which did not have multichance fissions contamination but indicated a clear dependence of the angular anisotropy with mass asymmetry. Similar results have also been obtained recently (Manohar *et al* 1988) on α-induced fission of ^{232}Th where they have measured the angular distributions for fragments of specific mass and charge. These results may imply that either the ultimate mass-division is predetermined to some extent at the fission barrier or the angle of emission changes somewhat during the saddle-to-scission dynamics and the scission configuration has an influence on it. As has been shown by Prakash *et al* (1984), the deformation potential energy landscape depends rather sensitively on the K quantum number. If the potential landscape at scission decides the fragment mass distributions, as is the case in most theories of fission fragment mass distributions, the K distribution of the fissioning nuclei will have an influence on the mass distributions. A correlation between mass asymmetry and angular anisotropy can therefore be expected in this case though they are decided at two different stages of the fission process. These are important questions from the point of view of investigating the mechanism of mass division in fission and the saddle-to-scission dynamics. Experimental work on these questions has been very limited and further investigations are clearly required.

In some recent studies of heavy ion-induced fissions another new feature has been reported (Ikezoe *et al* 1988). This is the observation of a small (of the order of few percent) forward-backward asymmetry in the angular distributions. As the statistical model implies that angular distribution for any mass ratio should be symmetric around 90°, it is of much interest to investigate the origin of this forward-backward asymmetry. We speculate that this forward-backward asymmetry is simply a reflection of the contamination of the true compound nucleus fission events with some fission events of the type (ii) discussed earlier which can result in fission-like decay of the composite system before one full rotation of the composite system. Further experimental studies are however needed in this direction to provide a definite and quantitative answer to the above questions and also to probe other aspects relating to correlation of mass-asymmetry with anisotropy.

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