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Heavy-ion induced fission reactions at near-barrier energies – what have we learnt ?

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Abstract. Systematic studies of heavy-ion induced fission reactions at near-barrier energies carried out in the last decade have brought out many interesting aspects of fission process in general. The recent experimental findings which show dependence of fission fragment angular distributions on entrance channel, shape, size and spin of the interacting nuclei and shell closure of the intermediate compound nucleus are summarised in the present paper.

Keywords. Heavy-ion fission reactions; near-barrier energies; fission fragment anisotropies; Th, U, Np, Pt, Pb, W, Bi targets; B, C, O projectiles.

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1. Introduction

Heavy-ion induced fission reactions at near Coulomb barrier energies performed during the last decade have provided many new interesting features of fission phenomena [1]. These studies suggest [1–5] dependence of fission fragment anisotropy (A) on the entrance channel of the colliding nuclei, size, spin and shape of the target/projectile, bombarding energy with respect to the fusion barrier and compound nucleus shell closure. In this review some of the recent results, their implications and the new puzzles in this area are summarized.

2. Saddle-point statistical model (SPSM)

In the present work, the saddle-point statistical model (SPSM) [6] has been taken as the reference model whose predictions are compared with the experimental data of fission anisotropies. If the fission data for a target plus projectile system are in agreement with the SPSM calculations, then the system is considered to exhibit 'normal' values of anisotropies. However, the system whose anisotropy values are significantly larger than the SPSM predictions, is considered to show 'anomalous' values of anisotropies. According to SPSM, the fission anisotropy is written as $A = 1 + \langle l^2 \rangle / 4K_0^2$ where $\langle l^2 \rangle$ is the second moment of the compound nucleus spin distribution and K_0^2 is the variance of the K distribution at the saddle-point where the orientation of the fission axis with respect to the angular momentum vector is determined. The quantity K_0^2 is defined as $K_0^2 = I_{\text{eff}}T$, with I_{eff} as the effective moment of inertia of the configuration of the fissioning nucleus and T as the effective temperature, both evaluated at the saddle-point. The value of T is calculated from the expression $T = \sqrt{E_x/a}$, where E_x is the excitation energy and 'a' is the level density parameter. The excitation energy E_x at the saddle is computed using the following expression $E_x = E_{c.m} + Q - B_f - E_R - E_n$ where B_f and E_R are the ℓ dependent fission barrier and rotational energy respectively. E_n is defined as the energy removed by the pre-scission (pre-saddle) neutrons. The ℓ distribution of the fissioning compound system is obtained by fitting the fission excitation function (or fusion excitation function) and the $B_f,\ I_{\text{eff}}$ and E_R values have been taken from the Sierk prescription [7].

3. Fission data at near-barrier energies

3.1 Fission data for $E/V_B > 1$

In the last few years systematic measurements of fission angular distribution data have been carried out by different groups to bring out interesting features of fission dynamics [1,8–16]. The fission data for both deformed actinide targets having small B_f/T values and spherical targets like Pb, Bi having large B_f/T values have been measured for a range of projectiles (Li, Be, B, C, O and F). It has been observed that the anisotropies for actinide targets are well accounted for by SPSM for the lighter projectiles such as Li, Be, B and C but are larger than expected for the heavier projectiles such as O and F [1,8,9]. These observations have been interpreted as an entrance channel effect arising from contributions of fission like events from preequilibrium fission [17] expected only in the case of heavier projectiles such as ^{16}O and ^{19}F, on the basis of the variation of the liquid drop model driving force at the saddle in the mass asymmetry degree of freedom. The mass asymmetry value where the driving force changes direction is called the Businaro-Gallone critical asymmetry(α_{BG}). For values of entrance channel mass asymmetry (α) greater than α_{BG}, the driving force favours amalgamation of the nascent partners, whereas for smaller values the smaller partner gains in mass at the expense of the heavier, and the dinuclear system may re-separate as a fissionlike event without K equilibration and formation of a compound nucleus. In the latter case the fission events will consist of both K equilibrated and non-equilibrated (pre-equilibrium) components and hence systems with entrance channel mass asymmetry values less than the BG critical value will exhibit anomalous anisotropies. The above study, however, involved formation of different compound nuclei. Thus, a definitive test of entrance channel mechanism requires making the same compound nucleus at the same excitation energies and if possible, even with similar angular momenta. With this motivation, fission data have been measured [3] for three entrance channels that lead to the same compound nucleus (^{248}Cf). Two of these entrance channels ^{11}B + ^{237}Np ($\alpha = 0.911$) and ^{12}C + ^{236}U ($\alpha = 0.903$) have alpha greater than $\alpha_{\text{BG}} = 0.9$ and the third, ^{16}O + ^{232}Th (α = 0.871), has alpha smaller than the critical asymmetry. The fission anisotropy data are plotted in figure 1 as a function of E/V_B. In figure 1 the data of Liu *et al* [18], Back *et al* [19], Ramamurthy *et al* [8] and Vandenbosch *et al* [20] are also shown along with the data from ref. [3].

It is found that although the anisotropies differ at lower excitation energies (E_x = 45–60 MeV and energies upto 20% above the fusion barrier) for the three systems, this

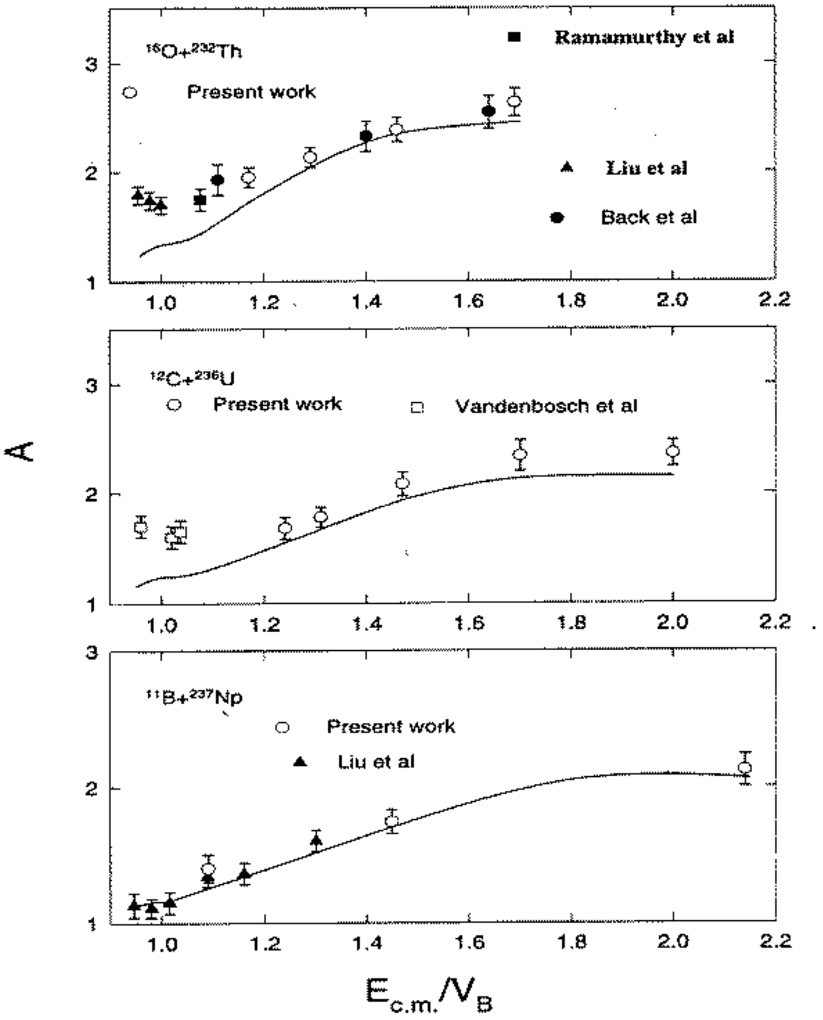

Figure 1. Fission anisotropies measured for ^{11}B + ^{237}Np, ^{12}C + ^{236}U and ^{16}O + ^{232}Th systems plotted as a function of E/V_B. The continuous lines are the SPSM calculations.

entrance channel dependence is washed out at higher energies. In order to compare the measured data with the SPSM calculations, the fission events were arbitrarily divided [3] into two types: (1) $\ell < l_c$, for which $B_f > T$, (2) $\ell > l_c$ for which $B_f < T$, where l_c is the angular momentum for which $B_f = T$. The anisotropy $A_{\rm exp}$ is defined as $A_{\rm exp}$ = $(\sigma_1/\sigma_f)A_1 + (\sigma_2/\sigma_f)A_2$ where A_1 and A_2 are the anisotropy values for the two components respectively. The corresponding cross sections are σ_1, σ_2 and σ_f is the measured fission (fusion) cross section. For component (1), the anisotropy values have been calculated using the SPSM. The Sierk prescription has been used to obtain the ℓ-dependent B_f,

E_R and $I_{\rm eff}$ values. The pre-saddle neutron corrections have been applied starting from the systematics of Saxena *et al* [21]. From the above analysis, the A_2 values have been deduced. Knowing $\langle l^2 \rangle$ values from calculation, the corresponding K_0^2 values have been obtained starting from the expression for A_2. It was interesting to note that the $I_{\rm eff}$ values deduced from the corresponding K_0^2 values for the region $B_f < T$, are consistent with the ones expected from the SPSM, implying that the SPSM works even for cases where $B_f < T$. The reason for this surprising result is not very clear. One reason could be that the fission barriers are actually much larger than predicted by Sierk. A similar conclusion was recently reached [22] in another observation involving evaporation residues for ^{12}C + ^{236}U system. In view of the above findings, the SPSM calculations have been performed without any restriction on ℓ values for both the components mentioned above. In figure 1, the calculations are shown as continuous curves. For $E/V_B > 1$, they adequately represent the data except for ^{16}O + ^{232}Th at energies above but close to the barrier, implying entrance channel dependence at these energies. At higher energies, the SPSM calculations are in good accord with the data for all the three systems and no entrance channel dependence is indicated.

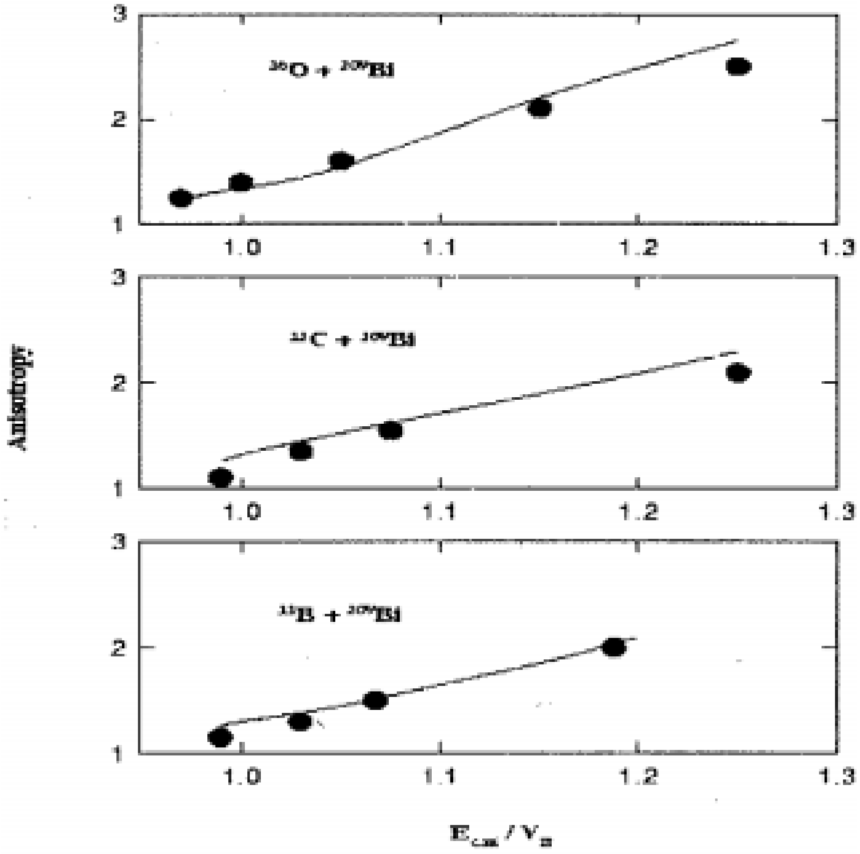

Figure 2. Fission anisotropies for ^{11}B, ^{12}C and ^{16}O + ^{209}Bi systems. The measured data are compared with the SPSM calculations.

The fission anisotropy data measured for the spherical systems at energies above the barrier are all consistent with the SPSM calculations which take into account corrections for pre-saddle neutron emission. No entrance channel dependence has been observed [1,11,23] in varying the projectile mass from ^{11}B to ^{19}F interacting with ^{209}Bi target. In figure 2 the anisotropy values measured for ^{11}B, ^{12}C and ^{16}O + ^{209}Bi systems are compared with the SPSM calculations.

It is seen from the figure that SPSM theory is consistent with the data over the entire energy range. As per the pre-equilibrium fission model [17], the contribution of K non-equilibrated fission events will be smaller for systems with larger B_f/T values. Hence the mechanism which leads to observation of 'anomalous' anisotropies (and entrance channel dependence of fission anisotropies) is not expected to play a significant role for systems having large B_f/T. Thus the observation of 'normal' anisotropies is consistent with the above expectation for the spherical systems which have relatively larger values of B_f/T compared to the ones of the deformed actinides.

3.2 Fission data for $E/V_B < 1$

The fission data for deformed actinide targets when extended to lower energies exhibit very interesting features quite unanticipated. It was observed that the fission anisotropies for essentially all target-projectile combinations involving an actinide target do not decrease when energy is lowered (up to 10% below barrier) in the sub-barrier region [18,24–26]. Several plausible explanations have been suggested to understand this feature [24]. However, the spherical targets do not exhibit this 'anomalous' feature. This clearly points to the fact that deformation (shape) of the target has a strong role to play in influencing this behaviour. Hinde *et al* [25] have proposed a 'quasi-fission' mechanism to explain this observation. According to this model, while collisions of the incoming projectile with the tips of the deformed target lead to quasi-fission, collisions with the sides lead to compound nucleus fission. Recently, Lestone *et al* [2] have reported anisotropy data for ^{12}C + ^{235,236,238}U systems. They found that while the even U targets exhibited 'anomalous' anisotropies,the odd U target (having spin 7/2) showed almost normal anisotropies at sub-barrier energies. This is taken as strong evidence for an influence of target spin on sub-barrier fission anisotropies. The same feature is observed in the case of data for B+Np, C+U and O+Th systems (figure 1) for $E/V_B < 1$. While the zero spin O + Th and C + U systems show anomalous values of anisotropies at energies below the barrier, the B+Np system involving large spin values for both projectile and target shows near normal anisotropies, confirming the influence of (projectile/target) spin on the measured anisotropies. However, the anisotropy data measured for the spherical systems, ^{16}O,^{19}F + ^{208}Pb (spin = 0) or ^{209}Bi (spin = 9/2) do not show noticeable effect due to target spin [23] and both are in agreement with the SPSM calculations. Hence it can be concluded that both shape and spin together are important factors in influencing the fission data at sub-barrier energies.

In figure 3 the deviation of measured anisotropies from the SPSM calculations at near-barrier energies, $(A_{\rm exp} - 1)/(A_{\rm cal} - 1)$, are plotted for O + Th (deformed) and O + Pb (spherical) systems to bring out the features discussed above. While the deformed system exhibits anomalous values of A, the spherical system shows normal values. In addition Lestone *et al* [2] have also shown that observed anomaly for even mass number actinide

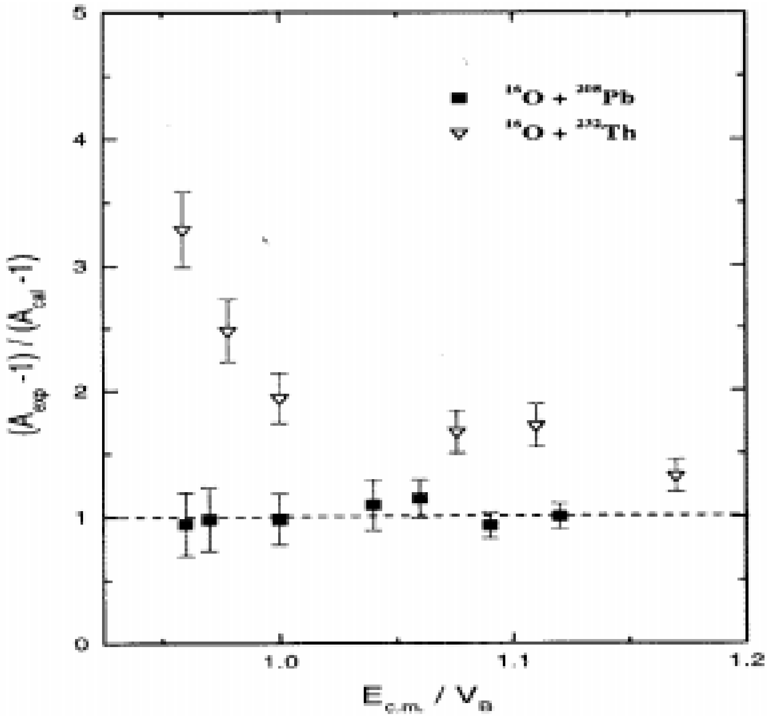

Figure 3. The $(A_{\rm exp} - 1)/(A_{\rm cal} - 1)$ values are plotted as a function of E/V_B for ^{16}O + ^{208}Pb and ^{232}Th systems.

targets, decreases with decrease of projectile mass number. This feature might imply some kind of entrance channel or fissility dependence of fission anisotropies.

3.3 Influence of shell closure on fission anisotropies

It is of interest to investigate the role of nuclear shell closure on fission anisotropies as shell effects are known to influence the potential energy surface in general. With this in view systematic measurements of fission fragment anisotropies and evaporation residue cross sections have been measured spanning a range of energies for two systems ^{12}C + ^{194,198}Pt [4].

It may be mentioned that the latter system forms a compound nucleus with $N = 126$. Detailed statistical model analysis of the fission and the evaporation residue cross section data yielded satisfactory fits to the data. The compound nucleus spin distribution and the l distribution related to fission decay have been determined from the above statistical model analysis. The Sierk parametrization has been used for the calculation of l-dependent $I_{\rm eff}, B_f$ and E_R values. The SPSM has been used to calculate the fission anisotorpies. While the anisotropy data for ^{12}C + ^{194}Pt system could be explained by the SPSM calculations, the ones for ^{12}C + ^{198}Pt are found to be significantly larger than the theoretical predictions.

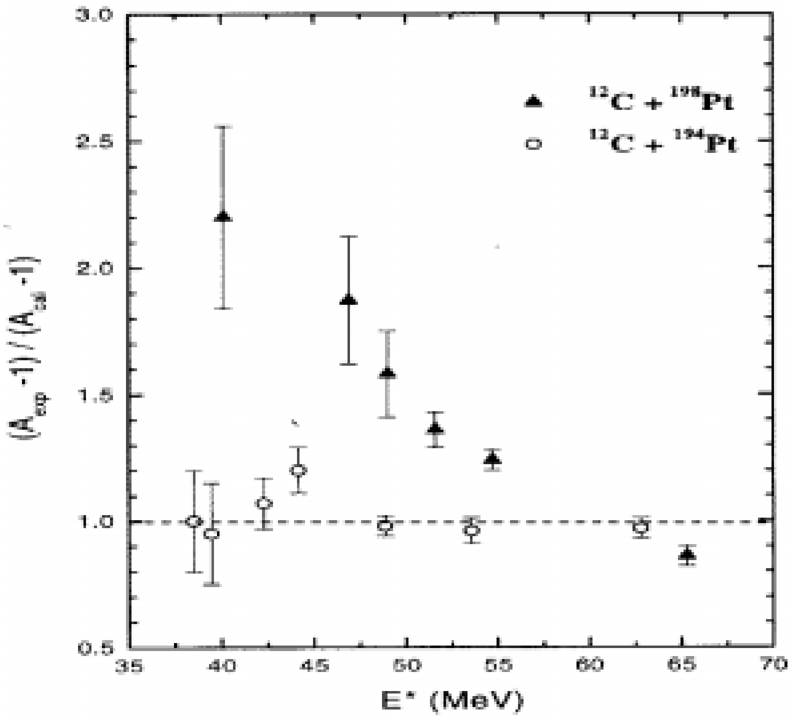

Figure 4. The $(A_{\rm exp} - 1)/(A_{\rm cal} - 1)$ values are plotted as a function of compound nucleus excitation energy, E^* for ^{12}C + ^{194,198}Pt.

The deviation from theory is represented as $(A_{\rm exp} - 1)/(A_{\rm cal} - 1)$ plotted as a function of the compound nucleus excitation energy (figure 4). It is found that the deviation from theory decreases as the excitation energy is increased. From the observation that the anomalous anisotropies are found only for ^{12}C + ^{198}Pt system (^{210}Po, $N = 126$) and that the discrepancy between measurement and calculations decreases at higher energies, it is conjectured that shell effect in the potential energy surface is responsible for this behaviour. The target isotope dependence as a plausible reason for this anomalous behaviour is ruled out as SPSM analysis of ^{12}C + ^{182,184,186}W fission anisotropy data [27] do not show any abnormal effect due to target isotope variation (figure 5).

Further, recently measurements have been extended to ^{19}F + ^{194,198}Pt systems. In this case the former system has $N = 126$ for the compound nucleus. If our earlier conjecture, that $N = 126$ is responsible for anomalous anisotropies is correct, then ^{19}F + ^{194}Pt should exhibit anomalous anisotropy and not ^{19}F + ^{198}Pt. Indeed the fission anisotropies measured for the above two systems are consistent with the above expectation [28]. Even though a complete description of this puzzle is not available at present, a definite correlation between the anomaly and the neutron shell closure $(N = 126)$ has been clearly demonstrated in these measurements.

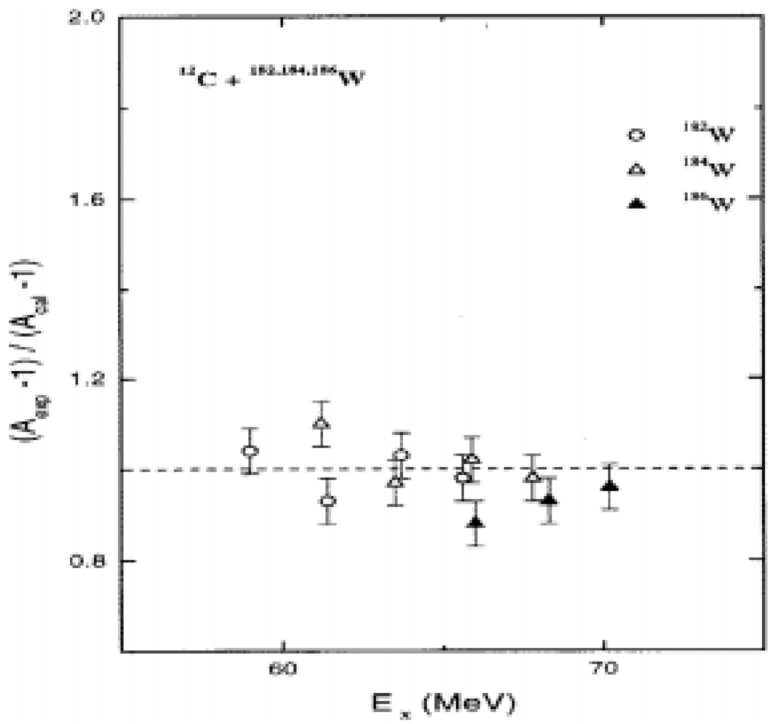

Figure 5. The deviations from SPSM calculations are plotted as a function E_x for ^{12}C + ^{182,184,186}W systems.

4. Conclusion

From a systematic study of heavy-ion induced fission reactions at near-barrier energies, the following conclusions can be drawn: For $E > V_B$, the fission fragment angular distributions measured for deformed actinides with low B_f/T values, are dependent on the entrance channel. However, the spherical target systems with large B_f/T values do not exhibit entrance channel dependence of fission anisotropies. Both these observations are consistent with the predictions of preequilibrium model. For well matched channels, having different entrance channels but leading to the same compound at similar excitation energies and angular momenta, entrance channel dependence of the measured anisotorpies is found only at lower E_x (up to 20% above the barrier) but not at energies well above the barrier. It is interesting that the fission anisotropy data for these systems could be described by SPSM calculations even in energy regions where $B_f < T$. For E/V_B <1, while the deformed actinide targets exhibit anomalous anisotropies, the spherical systems do not show this feature. Besides target shape, the role of target spin and size in influencing the fission anisotropy data has also been brought out. Lastly, interesting correlation has been observed between the anomalous anisotropy and the neutron shell closure, implying possible influence of shell effects on fission data.

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