Study of fission fragment angular anisotropy in pre-actinides

Tathagata Banerjee[1],* S. Nath[1], A. Jhingan[1], Gurpreet Kaur[2], R. Dubey[1], A. Yadav[1], P. V. Laveen[3], A. Shamlath[3], M. Shareef[3], J. Gehlot[1], N. Saneesh[1], E. Prasad[3], and P. Sugathan[1]
[1] *Inter University Accelerator Centre, Aruna Asaf Ali Marg, New Delhi 110067, India*
[2] *Department of Physics, Panjab University, Chandigarh 160014, India and*
[3] *Department of Physics, Central University of Kerala, Kasaragod 671314, India*

Complete fusion between two heavy nuclei is hindered by non-compound nuclear fission (NCNF) processes *viz.* quasi-fission, fast fission and pre-equilibrium fission. Presence of NCNF in a system makes *fusion probability* ($P_{\rm CN}$) to deviate from unity. In a recent systematic study, Banerjee et al. [1] examined evaporation residue (ER) excitation functions for 52 reactions with $A_{\rm CN}$=170–220. Comparison of measured cross sections ($\sigma_{\rm ER}$) with the predictions of statistical model (SM) VECSTAT [2] revealed approximate boundaries for the onset of NCNF. The transition from $P_{\rm CN} = 1$ to $P_{\rm CN} < 1$ occured in pre-actinide mass region. In this contribution, we report our investigation looking for signatures of NCNF in the pre-actinides from fission fragment (FF) angular distributions.

An experiment was carried out to measure FF angular distributions in six ^{28}Si-induced reactions involving ^{169}Tm, ^{176}Yb, ^{175}Lu, ^{180}Hf, ^{181}Ta and ^{182}W targets. The reactions led to probable formaton of compound nuclei (CN) in the pre-actinide mass region, *viz.* ^{197}Bi, ^{204}Po, ^{203}At, ^{208}Rn, ^{209}Fr and ^{210}Ra. Details of the experimental arrangement can be found elsewhere [3]. The experimental anisotropies ($A_{\rm exp}$) were obtained from the ratio $\frac{W(180^\circ)}{W(90^\circ)}$, in which $W(\theta_{\rm c.m.})$ were fitted with the standard theoretical expression for the angular distribution function.

In the transition state model of fission, angular anisotropy is given by the approximate expression $A_{\rm cal} \approx 1 + \frac{\langle J^2\rangle}{4K_0^2}$. Here, $K_0^2 = \frac{\mathcal{I}_{\rm eff}}{\hbar^2}T_{\rm sad}$ is the variance of the Gaussian K-distribution, $I_{\rm eff}$ is the effective moment of inertia and $T_{\rm sad}$ is the saddle point temperature of the CN. Mean of the square of total angular momentum, $\langle J^2\rangle$, of the fissioning nucleus was calculated using the statistical model code PACE3 [4] in trace back mode. The partial capture cross sections (σ_ℓ), used as the input of PACE3, were obtained from the coupled-channels code CCFULL [5]. The level density parameter (a), ratio of a at the saddle point to that in the ground state $\left(\frac{a_{\rm f}}{a_{\rm n}}\right)$ and the scaling factor for the RFRM [6] fission barrier ($k_{\rm f}$) were taken as $\frac{A}{10}$, 1.00 and 1.00, respectively, in PACE3 calculation.

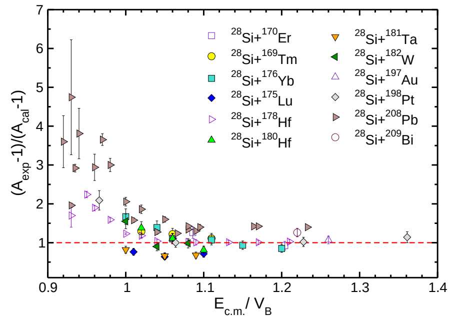

FIG. 1: $\frac{A_{\rm exp}-1}{A_{\rm cal}-1}$ as a function of $\frac{E_{\rm c.m.}}{V_{\rm B}}$ for reactions involving ^{28}Si projectiles on various targets. Data for systems other than the present ones were obtained from literature [7–14].

We have plotted $\frac{A_{\rm exp}-1}{A_{\rm cal}-1}$ for the current systems as well as six more ^{28}Si-induced reactions in Fig. 1. One may observe two general trends –(a) the ratio exceeds unity as $E_{\rm c.m.}$ approaches $V_{\rm B}$ ($E_{\rm c.m.}$ and $V_{\rm B}$ are energy of the projectile in the centre of mass frame of reference and the Coulomb barrier, respectively) and (b) deviation of the ratio

*Electronic address: he.tatha@gmail.com

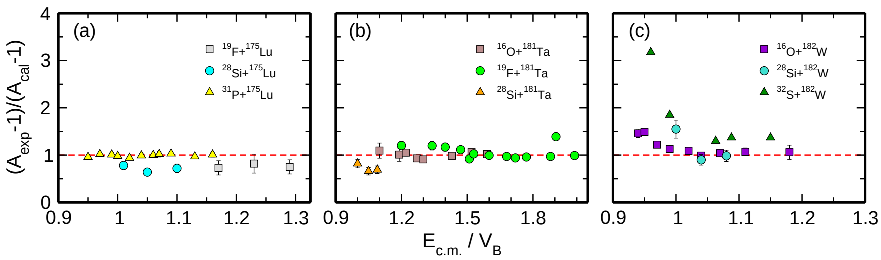

FIG. 2: Same as Fig. 1, but for different projectiles on (a) ^{175}Lu, (b) ^{181}Ta and (c) ^{182}W targets. Data for systems other than the current ones were obtained from literature [9, 17–25].

from unity increases as one moves towards the actinide mass region. The first observation can be explained by invoking the structural effects [15]. The probability of tip to tip collisions increases in such cases with decrease in projectile energy. Reasons for the second observation can be attributed to increasing fissility (and increasing entrance channel mass asymmetry), resulting in larger departure from model predictions.

However, exceptions to these general trends were observed upon closer scrutiny of Fig. 1. Departure of the ratio $\frac{A_{\rm exp}-1}{A_{\rm cal}-1}$ from unity is subdued for reactions involving targets with large non-zero ground state spin ($\mathcal{J}^\pi$) *viz.* ^{175}Lu and ^{181}Ta, both having $\mathcal{J}^\pi = \frac{7}{2}^+$. In such cases, the entrance channel K-distribution does not peak at $K^{'} = J\sin\omega$ (ω being the angle of orientation of the target nucleus with respect to the beam direction during capture), but at $K^{'} = J\sin\omega \pm I_0$ (I_0 is the ground state spin of the target), which results in lowering of the anisotropies [16]. This point is further highlighted in Fig. 2. One may note that the ratio does not exceed unity in case of reactions involving ^{175}Lu and ^{181}Ta targets (panel (a) and (b)) even when one moves from lighter to heavier projectiles. However, for reactions involving ^{182}W ($\mathcal{J}^\pi = 0^+$), $\frac{A_{\rm exp}-1}{A_{\rm cal}-1}$ exceeds unity as $E_{\rm c.m.}$ approaches $V_{\rm B}$. Also, departure of the ratio from unity increases with increasing mass of the projectile.

This systematic SM analysis of measured fission angular anisotropies and fission excitation functions [26], confirms the onset of NCNF in the pre-actinides.

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References

[1] Tathagata Banerjee, S. Nath, and Santanu Pal, Phys. Rev. C **91**, 034619 (2015).
[2] J. Sadhukhan and S. Pal, Phys. Rev. C **81**, 031602 (2010).
[3] Tathagata Banerjee *et al.*, Proc. DAE Symp. Nucl. Phys. **60**, 345 (2015).
[4] A. Gavron, Phys. Rev. C **21**, 230 (1980).
[5] K. Hagino *et al.*, Comput. Phys. Commun. **123**, 143 (1999).
[6] A. J. Sierk, Phys. Rev. C **33**, 2039 (1986).
[7] D. J. Hinde *et al.*, Nucl. Phys. **A398**, 308 (1983).
[8] R. Tripathi *et al.*, Phys. Rev. C **79**, 064607 (2009).
[9] R. D. Butt *et al.*, Phys. Rev. C **66**, 044601 (2002).
[10] D. C. Biswas *et al.*, Proc. DAE Symp. Nucl. Phys. **60**, 568 (2015).
[11] K. Nishio *et al.*, Phys. Rev. C **62**, 014602 (2000).
[12] B. B. Back *et al.*, Phys. Rev. C **32**, 195 (1985).
[13] D. J. Hinde *et al.*, Nucl. Phys. A **592**, 271 (1995).
[14] E. Williams *et al.*, Phys. Rev. C **88**, 034611 (2013).
[15] D.J. Hinde *et al.*, Phys. Rev. Lett. **74**, 1295 (1995).
[16] B. K. Nayak *et al.*, Phys. Rev. C **62**, 031601(R) (2000).
[17] A. Chatterjee *et al.*, Proc. DAE Symp. Nucl. Phys. **39B**, 170 (1996).
[18] B. R. Behera *et al.*, Phys. Rev. C **66**, 047602 (2002).
[19] F. Videbaek *et al.*, Phys. Rev. C **15**, 954 (1977).
[20] M. Ogihara *et al.*, Z. Phys. A **335**, 203 (1990).
[21] H. Ikezoe *et al.*, Phys. Rev. C **46**, 1922 (1992).
[22] B. Qi *et al.*, JAERI-M-91-188, November 1991.
[23] D. J. Hinde *et al.*, Phys. Rev. C **62**, 024615 (2000).
[24] B. B. Back *et al.*, Report no. CONF-860396-13, ANL 1986.
[25] H. Q. Zhang *et al.*, Phys. Rev. C **81**, 034611 (2010).
[26] Tathagata Banerjee *et al.*, submitted to Phys. Rev. C (2016).