The effect of CELD in the fission of ^{28}Si induced reactions

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The outcome of a heavy ion-induced fusion reaction is usually compared with predictions of a statistical model (SM). Any mismatch between the measured and the calculated quantities *e.g.* evaporation residue (ER) cross section ($\sigma_{\rm ER}$), fission cross section ($\sigma_{\rm fiss}$), pre-scission neutron multiplicity ($\nu_{\rm pre}$), fission fragment (FF) angular anisotropy ($\mathcal{A}$) etc. is interpreted as signatures of phenomena not described by the statistical models of compound nucleus (CN) decay. Presence of non-CN fission (NCNF) in a reaction causes the *fusion probability* ($P_{\rm CN}$) to deviate from unity, resulting in discrepancies between experimental observations and model predictions.

Since formation of ER is the clearest signature of fusion between two heavy nuclei, an attempt was made to quantify $P_{\rm CN}$ by comparing measured and calculated ER excitation functions for many reactions [1]. Banerjee *et al.* reported measuremnt of fission excitation functions and FF angular anisotropies [2] for a number of ^{28}Si-induced reactions. Based on comparison of data with predictions of the SM, onset of NCNF was confirmed in pre-actinide nuclei. Shell effects, both in the level density and in the fission barrier were included in the SM.

One must note here that some ambiguities still remain about the choice of the input parameters of the SM. These can be constrained significantly by trying to reproduce data from a large number of reactions, as was reported in Refs. [1, 2]. However, some physical effects *e.g.* orientation of K (projection of CN angular momentum on the nuclear symmetry axis), and collective enhancement in level density (CELD) were not taken into account.

Fission excitation function and FF angular anisotropy of a number of ^{19}F-induced reactions, in which presence of NCNF is expected to be insignificant, has recently been interpreted by Banerjee *et al.* [3] using an improved version of the SM code VECSTAT [4]. In addition to the shell effects in both the level density and the fission barrier, K-orientation ($K_{\rm or}$), CELD and dissipation (β) in fission dynamics have also been incorporated in the SM. A non-zero value of the dissipation parameter ($\beta = 2\times10^{21}$ s^{-1}) was found to reproduce the data of all the reactions. This report concerns itself with the interpretation of data from the ^{28}Si-induced reactions, reported in Ref. [2], in light of the improved SM predictions.

Inclusion of shell correction in the liquid-drop nuclear mass [5, 6] provides the fission barrier $B_{\rm f}$. The effects of K-orientation [8] on the Bohr-Wheeler fission width [7] ($\Gamma_{\rm BW}$) is included in the calculation as:

$$\Gamma_{\rm f}(E^*, J) = \Gamma_{\rm BW}(E^*, J, K=0)\frac{(K_0\sqrt{2\pi})}{2J+1}\ \mathrm{erf}\left(\frac{J+1/2}{K_0\sqrt{2}}\right) \quad (1)$$

with $K_0^2 = \frac{\tau_{\rm eff}}{\hbar^2}T_{\rm sad}$, where $\tau_{\rm eff}$ is the effective moment of inertia. erf(x) is the error function.

A collective enhancement ($K_{\rm coll}$) in the intrinsic level density ($\rho_{\rm intr}(E^*)$) [9, 10] would result in the total level density of the form $\rho(E^*) = K_{\rm coll}(E^*)\rho_{\rm intr}(E^*)$. The transition from vibrational ($K_{\rm vib}$) to rotational ($K_{\rm rot}$) type of collective enhancement with increasing quadrupole deformation $|\beta_2|$ of a nucleus, is implemented through a function $\varphi(|\beta_2|)$ as follows [11]:

$$K_{\rm coll}(|\beta_2|) = [K_{\rm rot}\varphi(|\beta_2|) + K_{\rm vib}(1-\varphi(|\beta_2|))]\ f(E^*) \quad (2)$$

where,

$$\varphi(|\beta_2|) = \left[1+\exp\left(\frac{\beta_2^0 - |\beta_2|}{\Delta\beta_2}\right)\right]^{-1} \quad (3)$$

with $\beta_2^0 = 0.15$ and $\Delta\beta_2 = 0.04$ [12]. The Fermi function $f(E^*)$ takes care of the damp-

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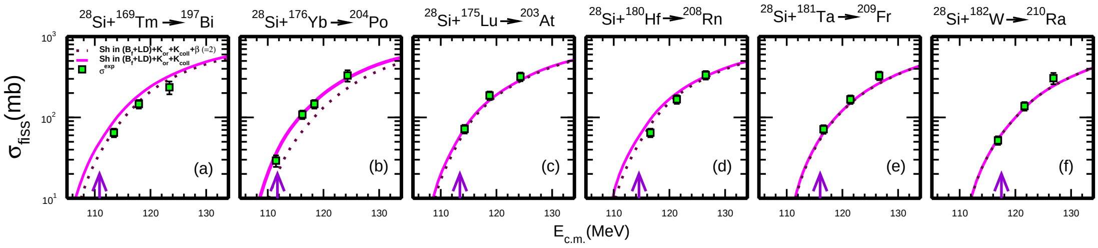

FIG. 1: Measured and calculated $\sigma_{\rm fiss}$ for (a) ^{28}Si+^{169}Tm, (b) ^{28}Si+^{176}Yb, (c) ^{28}Si+^{175}Lu, (d) ^{28}Si+^{180}Hf, (e) ^{28}Si+^{181}Ta and (f) ^{28}Si+^{182}W. The continuous lines indicate SM predictions without inclusion of dissipation. Dotted lines indicate results including the effects of dissipation.

ing of collectivity with increasing excitation enegy E^* and is given as

$$f(E^*) = \left[1 + \exp\left(\frac{E^* - E_{\rm cr}}{\Delta E}\right)\right]^{-1} \quad (4)$$

where $E_{\rm cr} = 40$ MeV and $\Delta E = 10$ MeV [13]. The vibrational and rotational enhancement factors are given as $K_{\rm vib} = e^{0.055\times A^{\frac{2}{3}}\times T^{\frac{4}{3}}}$ and $K_{\rm rot} = \frac{\tau_\perp T}{\hbar^2}$ where A, T and $\tau_\perp$ are the mass number of the nucleus, the nuclear temperature and the rigid body moment of inertia perpendicular to the symmetry axis [14], respectively.

Dissipation in the fission dynamics is introduced in the model using the Kramers-modified fission width [15].

$$\Gamma_{\rm K} = \Gamma_{\rm f}\left\{\sqrt{1+\left(\frac{\beta}{2\omega_s}\right)^2} - \frac{\beta}{2\omega_s}\right\} \quad (5)$$

where, $\omega_{\rm s}$ is the local frequency of a harmonic oscillator potential, β is the reduced dissipation coefficient. $\Gamma_{\rm f}$ is the Bohr-Wheeler fission width obtained with shell corrected level densities, CELD and K-orientation effect. It is clear from Fig. 1 that a non-zero value of the dissipation parameter ($\beta = 2 \times 10^{21}$ s^{-1}) is required in the calculation to reproduce measured $\sigma_{\rm fiss}$ for the reactions ^{28}Si+^{169}Tm and ^{28}Si+^{180}Hf. The results are insensitive to the variation of β for the reactions ^{28}Si+^{175}Lu, ^{28}Si+^{181}Ta and ^{28}Si+^{182}W. The underestimation of fission in ^{28}Si+^{176}Yb may then be attributed to the presence of NCNF. However, confirmation from other experimental probes and a dynamical description of the fission process are necessary.

One of the authors (T.B.) acknowledges IUAC, New Delhi, for financial support in the form of a fellowship (IUAC/FS-1027/5876).

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