Quest for consistent modelling of statistical decay of the compound nucleus

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Abstract

A statistical model description of heavy ion induced fusion-fission reactions is presented where shell effects, collective enhancement of level density, tilting away effect of compound nuclear spin and dissipation are included. It is shown that the inclusion of all these effects provides a consistent picture of fission where fission hindrance is required to explain the experimental values of both pre-scission neutron multiplicities and evaporation residue cross-sections in contrast to some of the earlier works where a fission hindrance is required for pre-scission neutrons but a fission enhancement for evaporation residue cross-sections.

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I. INTRODUCTION

Heavy ions impinging upon a heavy nucleus at beam energies below and above the Coulomb barrier had led to a number of important discoveries, both in nuclear structure as well as in reactions. While disappearance of pairing correlation with increasing spin of a compound nucleus (CN) is observed in ‘backbending’ phenomenon in nuclear structure [1], a diffusion mechanism of momentum and mass between the projectile and target is found in the strongly damped collisions [2] and a fission hindrance in fusion-fission reactions [3, 4]. Fission hindrance manifests in observation of excess neutrons from the CN before fission with respect to the standard statistical model predictions, indicating a slowing down of fission process in comparison to the fission rate from the transition state theory as given by Bohr and Wheeler [5]. Fission hindrance is found to decrease with increase of mass and fissility of the CN formed in heavy ion induced fusion-fission reactions [6]. It was early recognized that a dissipative fission dynamics can account for the fission hindrance and the resulting delayed onset of fission [3].

Fission hindrance is expected to impact not only the multiplicity of pre-scission neutrons and other light evaporated particles or photons but also the fission and evaporation residue (ER) cross-sections of fusion-fission reactions. It is observed that at least two or more input parameters in statistical model (SM) calculations, namely those defining the fission barrier, the level density parameter, the fission delay time and the dissipation coefficient are required to be adjusted for simultaneous fitting of both the fission/ER and the pre-scission neutron multiplicity excitation functions [3, 4, 7–9]. Different values of parameter sets are found necessary for different systems. Further, an increase of fission probability is usually required by way of reducing the fission barrier while fitting fission/ER cross sections in standard statistical model calculations [10, 11] whereas a slowing down of fission is demanded to reproduce experimental pre-scission neutron multiplicities [3]. This apparent contradiction clearly points to an inadequate modelling of compound nucleus decay.

In the present work, we show that a consistent description of both the pre-scission neutron multiplicity and fission/ER cross sections can be obtained with only one adjustable parameter when all the other factors which influence the fission and various evaporation widths are taken into account. To this end, we consider the shell correction effects on both the nuclear level density and the fission barrier, the collective enhancement of level density
(CELD) and the effect of orientation ($K$ state) degree of freedom of CN spin on fission width. We also include the effect of nuclear dissipation on fission width. Different combinations of the above effects have been considered by many authors in the past for statistical model analysis of fusion-fission reactions [7, 12–14]. All the four effects have been included in the statistical model analysis of pre-scission and post-scission multiplicity by Yanez et al. [15]. Here we consider all the effects for statistical model analysis of both pre-scission neutron multiplicity and fission/ER cross sections.

II. DESCRIPTION OF MODEL AND RESULTS

The various input quantities for the statistical model calculation are chosen as follows. We argue that nuclear properties which are well defined and well understood from independent studies should be used without any further modification in the statistical model of compound nuclear decay. Accordingly, we first obtain the macroscopic part of the fission barrier from the finite-range liquid drop model (FRLDM) which fits the systematic behaviour of ground state masses and the fission barriers at low angular momentum $\ell$ for nuclei over a wide mass range [16]. The full fission barrier $B_f(\ell)$ of a nucleus carrying angular momentum $\ell$ for nuclei over a wide mass range is then obtained by incorporating shell correction to the FRLDM barrier [9]. The shell correction term $\delta$ is given as the difference between the experimental and the liquid-drop model (LDM) masses ($\delta = M_{exp} - M_{LDM}$). The fission barrier then is given as

$$B_f(\ell) = B_{fLDM}(\ell) - (\delta_g - \delta_s)$$

where, $B_{fLDM}(\ell)$ is the angular momentum dependent FRLDM fission barrier and $\delta_g$ and $\delta_s$ are the shell correction energies for ground-state and saddle configurations, respectively. The ground-state shell corrections are taken from Ref. [17]. For $\delta_g$ and $\delta_s$, the prescription given in Ref. [18] for deformation dependence of shell correction is used which yields a very small value of shell correction at large deformations and full shell correction at zero deformation.

We next consider the level density parameter ‘$a$’, which is taken from the work of Ignatyuk et al. [19], who proposed the following form which includes shell effects at low excitation energies and goes over to its asymptotic form at high excitation energies.
\[ a(E^*) = \tilde{a} \left[ 1 + \frac{g(E^*)}{E^*} \delta \right], \quad (2) \]

where, \( g(E^*) = 1 - \exp \left( -\frac{E^*}{E_D} \right) \), \( \tilde{a} \) is the asymptotic level density and \( E_D \) is a parameter which decides the rate at which the shell effects disappear with an increase in the intrinsic excitation energy \( (E^*) \). A value of 18.5 MeV is used for \( E_D \), which was obtained from an analysis of \( s \)-wave neutron resonances \([20]\). The shape-dependent asymptotic level density is also taken from Ref.\([20]\).

The effect of collective motion in nuclear Hamiltonian on nuclear level density was investigated earlier by Bjørnholm, Bohr and Mottelson \([21]\). They observed that the total level density \( \rho(E^*) \) can be obtained from the intrinsic level density \( \rho_{\text{intr}}(E^*) \) as

\[ \rho(E^*) = K_{\text{coll}}(E^*)\rho_{\text{intr}}(E^*) \quad (3) \]
where, $K_{\text{coll}}$ is the collective enhance factor. A significant role of collective enhancement of level density (CELD) in reproducing the mass distribution from fragmentation of heavy nuclei was observed by Junghans et al. [22]. CELD is also found to be important for calculating the survival probability of super-heavy nuclei [14, 15]. Evidence of CELD has also been found in the spectrum of evaporated neutrons from deformed compound nuclei [23].

The effect of CELD is incorporated in the present calculation following the work of Zagrebaev et al. [24] where a smooth transition from a vibrational enhancement $K_{\text{vib}}$ to a rotational enhancement $K_{\text{rot}}$ for a nucleus with quadrupole deformation $|\beta_2|$ was achieved through a function $\varphi(|\beta_2|)$ as follows

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

(4)

where,

$$\varphi(|\beta_2|) = \left[ 1 + \exp \left( \frac{\beta_0^2 - |\beta_2|}{\Delta \beta_2} \right) \right]^{-1}. $$

(5)

The values of $\beta_0^2 = 0.15$ and $\Delta \beta_2 = 0.04$ are taken from Ref. [25]. The Fermi function $f(E^*)$ accounts for the damping of collectivity with increasing excitation energy $E^*$ and is given as

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

(6)

with $E_{\text{cr}} = 40$ MeV and $\Delta E = 10$ MeV [22]. The rotational and vibrational enhancement factors are taken as $K_{\text{rot}} = \tau_{\perp}T\frac{\hbar}{2},$ and $K_{\text{vib}} = 0.055 \times A^{\frac{2}{3}} \times T^{\frac{4}{3}},$ where $A$ is the nuclear mass number, $T$ is the nuclear temperature and $\tau_{\perp}$ is the rigid body moment of inertia perpendicular to the symmetry axis [26].

We next include the effect of $K$-degree (angular momentum component of the CN along symmetry axis) of freedom in fission width. The angular momentum of a CN can change its orientation from its initial direction along the perpendicular to the symmetry axis ($K = 0$) to non-zero values of $K$ due to the coupling of the $K$-degree of freedom with intrinsic nuclear motion [7]. Assuming a fast equilibration of the $K$-degree of freedom, the fission width can be expressed as [27]

$$\Gamma_f(E^*, \ell) = \Gamma_f(E^*, \ell, K = 0) \frac{K_0 \sqrt{2\pi}}{2\ell + 1} \text{erf} \left( \frac{\ell + \frac{1}{2}}{K_0 \sqrt{2}} \right).$$

(7)
with \( K_0^2 = \frac{\tau_{\text{eff}}}{\hbar^2} T_{\text{sad}} \), where, \( \tau_{\text{eff}} \) is the effective moment of inertia \( \left( \frac{1}{\tau_{\text{eff}}} = \frac{1}{\tau_{\parallel}} - \frac{1}{\tau_{\perp}} \right) \), \( \tau_{\parallel} \) and \( \tau_{\perp} \) being the moments of inertia at saddle of the nucleus perpendicular to and about the nuclear symmetry axis and \( \text{erf}(x) \) is the error function.

Using the various quantities as given in the above, statistical model calculations are performed for pre-scission neutron multiplicity, fission and ER cross sections for a number of systems. The fission width \( \Gamma_f(E^*, \ell, K = 0) \) in Eq. \( 7 \) is obtained from the transition state theory due to Bohr and Wheeler \([5]\) where shell-corrected fission barrier (Eq. \( 1 \)) and level density parameter (Eq. \( 2 \)) are used. CELD (Eq. \( 4 \)) is also included in the level densities at both the ground state and at the saddle in fission width calculation. CELD at ground state is calculated using experimental values of \( |\beta_2| \) for deformed nuclei. The particle and \( \gamma \) emission widths are obtained from the Weisskopf formula as given in Ref. \([28]\). Shell correction and CELD are applied to the level densities of both the parent and the daughter nuclei.

In the present SM calculation, a CN is followed in time over small time steps and at each time step the fate of the compound nucleus is decided by a Monte Carlo sampling using the particle, \( \gamma \) and fission widths \([29]\). The process continues till fission occurs or an ER is formed. Fission in SM corresponds to crossing of the saddle point deformation by the CN. During transition from the saddle to the scission, the CN can emit further neutrons which would contribute to the pre-scission multiplicity. The saddle-to-scission time interval \( \tau_{ss} \) is taken from Ref. \([30]\) and the number of neutrons emitted during this period is calculated using the neutron decay width.

The systems chosen for the present study are (a) \( ^{16}\text{O} + ^{154}\text{Sm} \) \([31–33]\), (b) \( ^{19}\text{F} + ^{169}\text{Tm} \) \([4,34]\), (c) \( ^{16}\text{O} + ^{184}\text{W} \) \([35–39]\), (d) \( ^{19}\text{F} + ^{181}\text{Ta} \) \([3,4,34]\), (e) \( ^{18}\text{O} + ^{192}\text{Os} \) \([3,4,34]\), (f) \( ^{16}\text{O} + ^{197}\text{Au} \) \([4,40,41]\) and (g) \( ^{16}\text{O} + ^{208}\text{Pb} \) \([40,42–44]\). They cover a broad range of fissility (0.6 to 0.763) of the compound nuclei. Further, non-compound nuclear fission processes are expected to be small for the above highly asymmetric systems \([45]\). It may therefore be assumed that the entire incident flux leads to CN formation and consequently the SM becomes applicable to calculate various observables in the above reactions.

In order to illustrate the effects of shell, CELD and the \( K \)-degree of freedom, results for one reaction, namely \( ^{19}\text{F} + ^{181}\text{Ta} \) forming the CN \( ^{200}\text{Pb} \), are presented in Fig. \( 11 \). We first calculate pre-scission neutron multiplicity, fission and ER excitation functions without considering any shell correction, CELD or \( K \)-degree of freedom. Shell correction to fission
barrier (Eq. 1) only is added in the next calculation. Both the results are given in Fig. 1 (a) along with the experimental data. The observation that addition of shell correction to fission barrier increases $\nu_{\text{pre}}$ and decreases $\sigma_{\text{fiss}}$ (and correspondingly increases $\sigma_{\text{ER}}$) for the present system can be easily understood from the following relation

\[
\frac{\Gamma_f}{\Gamma_n} \approx \frac{e^{2\sqrt{a_s(E^*-B_f)}}}{e^{2\sqrt{a_g(E^*-B_n)}}}
\]

where, $\Gamma_n$ and $B_n$ denote the neutron width and binding energy, respectively. $a_s$ and $a_g$ represent the level density parameters at the saddle and the ground state configurations, respectively. Shell corrections for the CN $^{200}\text{Pb}$ and other nuclei populated by light particle evaporation are negative quantities and hence cause increase in the respective fission barriers (Eq. 1) resulting in decrease of the fission widths and consequently reduction in the fission cross-sections.

Shell correction is next added to the level density parameter and Fig. 1 (b) shows the results. Shell correction essentially affects the level density at the ground state and on account of it being a negative quantity reduces $a_g$ (Eq. 2) and thereby increases the fission probability and hence the fission cross-sections. Consequently, $\sigma_{\text{ER}}$ and $\nu_{\text{pre}}$ decreases as we see in Fig. 1 (b).

We now include CELD in the level densities for both the initial and final states in calculation of particle and $\gamma$ decay widths. CELD is also included in the level densities at the ground state and the saddle configuration to obtain the fission widths. The saddle shape being highly deformed, CELD at saddle is of rotational type while it is of vibrational nature for spherical nuclei at ground state. The typical value of $K_{\text{vib}}$ is $\sim 1$ –10. $K_{\text{rot}}$ takes the value $\sim 100$ –150. By definition of CELD, the lower limit of $K_{\text{coll}}$ is set as unity. Since, the transition-state fission width is determined by the ratio of the number of levels available at the saddle to those at the ground state, CELD can substantially increase the fission width for spherical nuclei. This is reflected in SM results given in Fig. 1 (c) for the present system for which the compound nuclei formed at various stages of evaporation are spherical at the ground state and thus an enhancement of fission cross-section is observed. It may however be remarked that for nuclei with strong ground state deformation, the enhancement factors at both the saddle and the ground state are of rotational type with similar magnitudes and this would result in a marginal effect on the fission width.
The $K$-degree of freedom is next included in the SM calculation through its effect on the fission width (Eq. 7). The tilting of the angular momentum vector away from the normal direction to the symmetry axis increases the angular momentum dependent fission barrier and reduces the fission width [27]. This results in a decrease in $\sigma_{\text{fiss}}$ and increase of $\sigma_{\text{ER}}$ and $\nu_{\text{pre}}$ as shown in Fig. II (d).

![Diagram](image.png)

FIG. 2: Measured and calculated $\sigma_{\text{ER}}$, $\sigma_{\text{fiss}}$ and $\nu_{\text{pre}}$ for (a) $^{16}\text{O}+^{154}\text{Sm}$ [31, 33], (b) $^{19}\text{F}+^{169}\text{Tm}$ [4, 34], (c) $^{16}\text{O}+^{184}\text{W}$ [35, 36, 38, 39], (d) $^{18}\text{O}+^{192}\text{Os}$ [3, 4, 34], (e) $^{16}\text{O}+^{197}\text{Au}$ [4, 40, 41] and (f) $^{16}\text{O}+^{208}\text{Pb}$ [40, 42–44]. Legends are same as in Fig. III (e). See text for details.

We thus find that both $\nu_{\text{pre}}$ and $\sigma_{\text{ER}}$ are underestimated and $\sigma_{\text{fiss}}$ is overestimated when all the factors which can influence the widths of various decay channels including fission are taken into account. This immediately suggests that fission hindrance is required to reproduce both $\sigma_{\text{ER}}$ and $\nu_{\text{pre}}$ (and also $\sigma_{\text{fiss}}$). In the framework of a dissipative dynamical model of fission, a reduction in fission width can be obtained from the Kramers-modified fission width given as [46]

$$
\Gamma_K = \Gamma_f \left\{ \sqrt{1 + \left( \frac{\beta}{2\omega_s} \right)^2} - \frac{\beta}{2\omega_s} \right\}
$$

where, $\Gamma_f$ is the Bohr-Wheeler fission width obtained with shell corrected level densities, CELD and K-orientation effect, $\beta$ is the reduced dissipation coefficient (ratio of dissipation coefficient to inertia) and $\omega_s$ is the local frequency of a harmonic oscillator potential which osculates the nuclear potential at the saddle configuration and depends on the spin of the CN [47].
The main mechanism of energy dissipation in bulk nuclear dynamics at low excitation energies \( (T \sim \text{a few MeV}) \) is expected to be of one-body type which arises due to collisions of the nucleons with the moving mean-field \([48, 49]\). The precise nature of nuclear one-body dissipation is yet to be established though a shape-dependence \([50]\) and temperature-dependence \([51]\) of one-body dissipation coefficient have been suggested on theoretical grounds. The values of \( \beta \) obtained from fitting experimental data vary in the range \( \sim (1 - 20) \times 10^{21} \text{s}^{-1} \) \([52-54]\). Thus \( \beta \) is the least precisely determined input parameter among all the others and hence is treated as the only adjustable parameter in the present SM calculation.

Apart from the fission width, the saddle-to-scission time interval also changes with inclusion of dissipation and is given as \([55]\)

\[
\tau_{ss} = \tau_{ss}^0 \left\{ \sqrt{1 + \left( \frac{\beta}{2\omega_s} \right)^2} + \frac{\beta}{2\omega_s} \right\}. \tag{10}
\]

Further, the fission width reaches its stationary value in a dissipative dynamics of fission after the elapse of a build up or transient time \( \tau_t \) and the dynamical fission width is given as \([56]\)

\[
\Gamma_f(t) = \Gamma_K \left\{ 1 - e^{-\frac{2\pi}{\tau_f}} \right\} \tag{11}
\]

which is used in the time evolution of the system in the present calculation. The neutron multiplicities and fission / ER cross-sections calculated with \( \beta = 1 \times 10^{21} \text{s}^{-1} \) are given in Fig. \( \text{Fig. 1 (e)} \) which fit the fission / ER excitation functions reasonably well and underestimate the neutron multiplicities to some extent.

Fig. \( \text{Fig. 2} \) shows the SM predictions for the other six systems where all the effects, namely shell, CELD and \( K \)-orientation are included (continuous black lines) along with the experimental data. Neutron multiplicity \( \nu_{\text{pre}} \) is found to be underestimated for all the systems. The \( \sigma_{\text{ER}} \) are also underestimated (consequently \( \sigma_{\text{fiss}} \) overestimated) for the systems with compound nuclear masses \( A_{\text{CN}} \geq 200 \) whereas for the two systems with \( A_{\text{CN}} < 200 \), the calculated ER and fission excitation functions are very close to the experimental data. SM results with fission hindrance are also given in Fig. \( \text{Fig. 2} \) (dashed magenta lines) where the value of \( \beta \) is adjusted to reproduce the experimental ER excitation functions for \( A_{\text{CN}} \geq 200 \) and \( \nu_{\text{pre}} \) for \( A_{\text{CN}} < 200 \).
III. DISCUSSIONS

We first note in Fig. 2 that $\nu_{\text{pre}}$ is underestimated for $\beta$ values which reproduce the ER (and fission) excitation functions for $A_{\text{CN}} \geq 200$ systems. Therefore, these values of $\beta$ though are adequate for pre-saddle fission dynamics are not large enough to cause sufficient delay for emitting large number of neutrons in the saddle-to-scission evolution of the CN. It has also been observed earlier that a shape-dependent $\beta$ with larger values in the post-saddle region is required in order to explain the experimental neutron multiplicities for heavy systems [54, 57]. It may be pointed out that though dissipative dynamical models such as the Langevin equation is better suited to describe fission dynamics with shape-dependent dissipation [58], the fission cross-sections are underestimated by the dynamical model possibly due to non-inclusion of CELD [29, 59]. It may however be noted that a hybrid approach, in which a statistical model with CELD provides the flux across the saddle point coupled with a Langevin dynamical calculation in the saddle-to-scission region, could provide a better description for heavy systems [60]. The present study indicates a pre-saddle dissipation strength of $\beta = (1 - 3) \times 10^{21}$ s$^{-1}$ over a broad range of excitation energies for $A_{\text{CN}} \geq 200$ nuclei.

For the lighter systems ($A_{\text{CN}} < 200$), it is observed that though experimental values of $\nu_{\text{pre}}$ can be reproduced with $\beta = 2 \times 10^{21}$ s$^{-1}$, the fission cross-sections are underestimated for the CN $^{188}$Pt. The former observation corresponds to the fact that the saddle configuration is more deformed for lighter nuclei than heavier ones and this makes the saddle-to-scission transition of shorter duration and consequently less number of saddle-to-scission neutrons for lighter compound nuclei. Thus, pre-saddle neutrons seem to account for the experimental numbers. The underestimation of $\sigma_{\text{fiss}}$ for $^{188}$Pt may possibly be traced to its ground state deformation ($\beta_2 = 0.18$). We have pointed out earlier that CELD effect on fission channel is weaker for CN with ground state deformation than spherical nuclei. We assume in the present work that ground state deformation persists at all excitations. However, it is possible that the nucleus tends to become spherical with increasing excitation energy [61]. The consequence of this aspect in SM calculation requires further investigations.

For systems with higher mass-symmetry, neutrons can also be emitted in the comparatively longer formation stage of the CN [62] and/or from the acceleration phase of fission fragments [63, 64] and/or during neck rupture [65, 66], which are not included in the present
work.

IV. CONCLUSIONS

A statistical model description of fission / ER cross-sections and pre-scission neutron multiplicity in heavy ion induced fusion-fission reactions is presented by including the shell effects, the collective enhancement of level density and the $K$-orientation effect with standard parameter values and by treating the dissipation strength as the only adjustable parameter. It is found that the inclusion of all the aforesaid effects eliminates the contradictory requirements of fission hindrance for pre-scission neutron multiplicities on one hand and fission enhancement for ER cross sections on the other. The present work thus provides a consistent picture of fusion-fission reactions where fission hindrance plays a role for both pre-scission emission of neutrons and formation of evaporation residues.

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