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Statistical Model Analysis of Neutron Multiplicities from Fission of Compound Nuclei in ~ 200 and 250 Mass Region

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Statistical model analysis has been performed with and without the inclusion of shell correction in level density and the collective enhancement of level density (CELD) effect for two different mass regions of compound nuclei, *i.e.*, ~ 200 and 250 for the currently available data of neutron multiplicity (M_{pre}) in the literature in both mass regions. The chosen reactions have comparable excitation energy range. The measured neutron multiplicities are found to be increasing with the excitation energy of the compound nuclei for all the studied reactions except for $^{19}F + {}^{184}W$. The calculated values of pre-scission neutron multiplicities are found to be significantly underestimated when compared to the experimental values for overlapping excitation energy range for both mass regions and found to be further underestimated in the heavier mass region (A_{CN} ~ 250) as compared to the relatively lighter mass region (A_{CN} ~ 200). The dissipation strength required to reproduce experimental values is found to increase with an increase in excitation energy of the compound nucleus in both the mass regions. Dissipation strength was found to be higher when the effects of shell correction in level density and CELD were included as compared to the dissipation obtained without incorporating these effects.

Keywords: Heavy ion nuclear reactions; neutron multiplicity; excitation energy; nuclear dissipations.

1 Introduction

Since the past few decades, understanding the dynamics of heavy ion-induced fusion-fission reactions has been investigated in a large number of experimental and theoretical studies[1-10]. Prominent probes such as fission fragments mass distribution, angular distribution, evaporation residue cross-sections, and measurement of pre-scission neutron and light charged particle multiplicities are used to study the dynamics of heavy ion-induced fusion-fission reactions[7-16]. The pre-scission neutrons can be emitted at different stages of the reaction process, starting from the approaching stage of a projectile to the target till scission configuration[13-15]. The nuclear dissipation in such reactions alters the yield of light-charged particles as well as neutrons which when compared to model predictions, leads us to interpret the results in the context of the role of nuclear dissipation in fusion-fission reactions[13-19]. The experimental quantification of pre-scission neutron multiplicity and its comparison with model predictions is one of the most reliable probes to inquire about the time scale of the fission process as well as to study the role of nuclear dissipation involved in these reactions. Such measurements are also useful to distinguish between fusion-fission and quasi-fission processes[13-14]. Various studies have shown that the experimental neutron multiplicities are higher as compared to the statistical model calculations, and this excess of measured pre-scission neutron multiplicities over the model prediction is used to estimate the time scale of the fission process as well as to estimate the nuclear dissipation required to reproduce the experimental data. Statistical model calculations consider the fission rate given by Bohr and Wheeler, whereas the dissipative dynamical model given by Kramers is now considered to be necessary to elaborate the fission dynamics of heavy ion-induced reactions[13-16]. The role of the entrance channel on pre-scission neutron multiplicity has been studied by many groups, and it has been observed that different entrance channels forming the same compound nucleus at matching excitation energies result in different multiplicities. The pre-scission neutron multiplicity was found to be higher in the case of relatively symmetric reaction systems as compared to the asymmetric systems[13-14]. This observation can be interpreted in terms of the value of the entrance channel mass asymmetry (α) with respect to the Businaro-Gallone mass asymmetry (α_{BG}). An asymmetric entrance channel, with $\alpha > \alpha_{BG}$, leads to a lower yield of average pre-scission neutrons as compared to a symmetric

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entrance channel, with $\alpha < \alpha_{BG}$[14]. The N/Z dependence of neutron yield is another area explored in such studies. Such dependence was studied by Sandal *et al.*[16], by populating different isotopes of a given element and it was observed that pre-scission neutron multiplicity increases with an increase in N/Z ratio of the compound nucleus. Recently, the systematic study of pre-scission neutron multiplicity has been explored by Shareef *et al.*[17]. They calculated the fission delay in different reactions. They found that fission delay increases with an increase in the fissility (χ) of the compound nucleus. This finding suggests that dissipation also increases with an increase in fissility. In the present work, we have chosen two different mass regions of CNs, *i.e.*, ~ 200 and 250, in order to explore the nature of dissipation and its dependence on entrance channel mass asymmetry and excitation energy of the compound nucleus. The reason behind choosing different mass regions is to have different fissility, *i.e.*, CNs in the 250 mass region are more fissile as compared to those in the 200 mass region. It is also pertinent to mention here that the excitation energy range chosen for comparison in this study is from ~ 57 – 88 MeV for ~ 200 mass region, whereas, it is 47 - 65 MeV for 250 mass region. In order to have a reasonable comparison among the chosen reactions, data is considered only for the reactions with comparable excitation energy range within their respective mass regions. The pre-scission neutron multiplicity for the chosen reactions $^{28}Si+^{170}Er \rightarrow ^{198}Pb$, $^{19}F+^{181}Ta \rightarrow ^{200}Pb$ and $^{19}F+^{232}Th \rightarrow ^{251}Es$ has been measured by Newton *et al.*[19], for $^{19}F+^{184}W \rightarrow ^{203}Bi$ by Mukul *et al.*[20], $^{16}O + ^{181}Ta \rightarrow ^{197}Tl$ by Singh *et al.*[14], and for the reactions $^{11}B+^{232}Np \rightarrow ^{243}Cf$, $^{12}C+^{232}Th \rightarrow ^{244}Cm$ $^{16}O+^{232}Th \rightarrow ^{248}Cf$ by Saxena *et al.*[21]. The detailed of the chosen reactions and their relevant parameters are given in the Table 1.

2 Experimental Data

The experimental pre-scission neutron multiplicities (M_{pre}) for the mass ~ 200 region of CNs in different reactions are shown in Fig. 1. The pre-scission neutron multiplicities increase with an increase in excitation energy for all the reactions, except for $^{19}F + ^{184}W \rightarrow ^{203}Bi$. For reaction $^{19}F + ^{184}W$, data from fission of ^{203}Bi shows non-monotonous behaviour. Initially, it increases with an increase in excitation energy from E* ~ 63 – 75 MeV, and then it decreases with a further increase in excitation energy above 75 MeV. This behaviour is unexpected, as pre-scission neutron multiplicity is expected to increase with increasing excitation energy. This expectation is also consistent with the observed trend in the literature as well as the pre-scission neutron multiplicity calculated using systematics proposed by Itkis *et al.*[22]. Measured values of neutron multiplicity at E* = 64.8 and 73.9 MeV are consistent with the M_{pre} values (2.37 and 2.80, respectively) calculated from Itkis systematics, whereas at the highest studied excitation energy (82.9 MeV) measured value of M_{pre} is less than the calculated value (M_{pre}^{cal} = 3.23). Furthermore, the comparison of the four systems, within the energy range of E*= 55 - 75 MeV shows that the pre-scission neutron yield is higher for higher-mass compound nuclei.

From Fig. 1, it is observed that the measured pre-scission neutron multiplicities, in general, show an increasing behavior with an increase in excitation energy for all these reaction systems. Further, it is also observed that the measured pre-scission neuron multiplicity increases with an increase in the mass number of the CN at lower excitation energy, *i.e.*, the pre-scission neutron multiplicity increases in going from CN ^{197}Tl to ^{203}Bi at comparable lower excitation energies however, at higher excitation energy, it follows the reverse trend, i.e., the pre-scission neutron multiplicity decreases when going from ^{197}Tl to ^{203}Bi. The reaction $^{16}O + ^{181}Ta \rightarrow ^{197}Tl$ with $\alpha > \alpha_{BG}$ has a pre-scission neutron multiplicity value comparable to the reaction with $\alpha < \alpha_{BG}$ in lower excitation energy range. But at higher excitation energy, it has a comparatively higher value of pre-scission neutron multiplicity. For the $^{16}O + ^{181}Ta \rightarrow ^{197}Tl$ reaction,

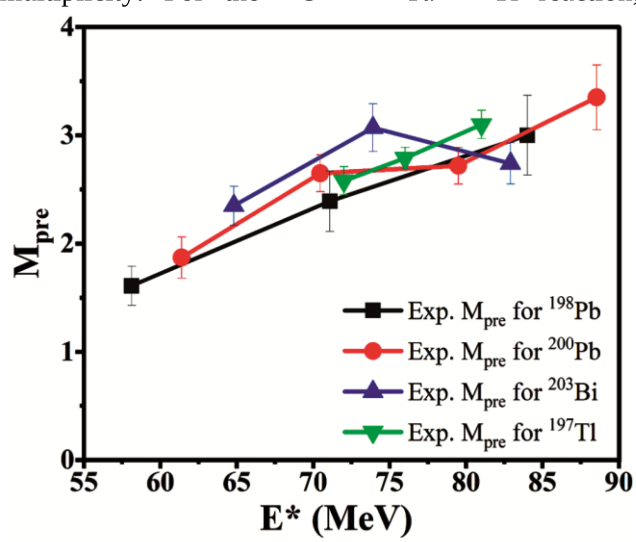

Fig. 1 — Pre-scission neutron multiplicities (M_{pre}) as a function of excitation energy (E*) for mass ~ 200 region.

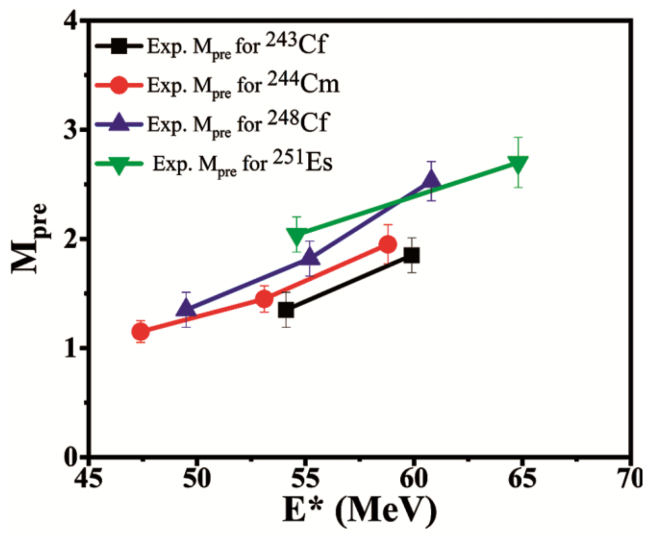

Fig. 2 — Pre-scission neutron multiplicities (M_{pre}) as a function of excitation energy (E*) for mass ~ 250 region.

though $\alpha > \alpha_{BG}$ but their values are not significantly different. Moreover, α_{BG} also has angular momentum dependence and this could lead to an expected trend of neutron multiplicity at higher excitation energies.

The experimental pre-scission neutron multiplicities for the chosen reactions in ~ 250 mass region are shown in Fig. 2. It is evident that the experimental pre-scission neutron multiplicities show a gradual increase with an increase in excitation energy of the compound nucleus for all the systems. It has also been observed that within the overlapping energy range, experimental pre-scission neutron multiplicity increases with an increase in the mass number of the CN, *i.e.*, the pre-scission neutron multiplicity increases in going from CN ^{243}Cf to ^{251}Es at comparable excitation energies. In the reactions ^{12}C+^{232}Th→^{244}Cm and ^{11}B+^{232}Np→^{243}Cf, where pre-scission neutron multiplicities are found to be lower compared to the ^{16}O+^{232}Th→^{248}Cf and ^{19}F+^{232}Th→^{251}Es where $\alpha < \alpha_{BG}$ signifying the role of entrance channel in fusion–fission reactions.

3 Statistical Model Calculations without the inclusion of shell correction in level density and CELD effect

3.1 Model calculations using Bohr-Wheeler fission width

The experimental neutron multiplicity as a function of excitation energy is analyzed using the code VECSTAT[23]. In this code, the simulation of the decay of the compound nucleus is given by Monte-Carlo technique. The various type of decay widths of the compound nucleus is used for the simulation. The emission of neutrons, light charge particles, γ rays and fission are considered as the decay modes of the compound nucleus. Particle and GDR γ emission width are given by the Weisskopf formula[24]. In order to estimate the fission time scale and quantify the amount of dissipation involved in the fission of such reactions, we have performed the statistical model calculations. Initially, the pre-scission neutron multiplicities are calculated using the Bohr-Wheeler fission width without incorporating any dissipation in the fission channel[25].

$$\Gamma_{BW} = \frac{1}{2\pi\rho_g(E_i)} \int_0^{E_i - V_B} \rho_s(E_i - V_B - \varepsilon)\,d\varepsilon\,, \qquad \ldots (1)$$

Where,
E_i = energy of the initial state,
ρ_g = level density at the initial state,
ρ_s = level density at the saddle point,
V_B= the spin dependent fission barrier[26] given as,

$$V_B = B_f^{FRLDM}(l) - (\delta_g - \delta_s) \qquad \ldots (2)$$

Where, $B_f^{FRLDM}(l)$ is the angular momentum-dependent FRLDM fission barrier. δ_g and δ_s are the shell correction energies for ground-state and saddle configurations respectively[27]. The level density parameter taken is given by[28]

$$a(E^*) = \tilde{a}\left(1 + \frac{f(E^*)}{E^*}\delta\right) \qquad \ldots (3)$$

With $f(E^*) = 1 - e^{-E^*/E_D}$ … (4)

Where $\tilde{a}$ is the asymptotic level density parameter and E_D is a parameter that decides the rate at which the shell effects disappear with an increase in the intrinsic excitation energy E*[29]. The experimental pre-scission neutron multiplicities along with statistical model calculation using Bohr-Wheeler fission width in mass ~ 200 region of CNs, for different reactions are shown in Fig. 3.

From Fig. 3, it is evident that though the experimental pre-scission neutron multiplicity is reproducible with the statistical model calculations at lower excitation energies for all systems, but model calculations underpredict the neutron multiplicity at higher excitation energies, for all reactions in ~ 200 mass region. The calculated neutron multiplicity shows a nearly flat behavior for all the reaction systems under consideration, within the studied energy domain, whereas, the experimental data exhibits an increasing trend. Therefore, fission width calculated using Bohr-Wheeler formulation is unable to reproduce the data of pre-scission neutron multiplicity.

The experimental pre-scission neutron multiplicity along with statistical model calculation using Bohr-Wheeler fission width for different reaction systems populating CNs in ~ 250 mass region are shown in Fig. 4.

In this mass region, again, statistical model calculations underpredicted the pre-scission neutron multiplicity for all the chosen reactions. These observations indicate that the pre-scission neutron multiplicities calculated using the statistical model with Bohr-Wheeler fission width are unable to reproduce the experimental data, for all the chosen reactions in both mass regions. Therefore, in order to account for the dissipation in the fission channel, we used the Kramers modified fission width as,

$$\Gamma_k = \frac{\hbar\omega_g}{2\Pi} e^{-\frac{V_B}{T}} \left(\sqrt{1 + \left(\frac{\beta}{2\omega_s}\right)^2} - \frac{\beta}{2\omega_s} \right) \quad \dots (5)$$

Where β (10^{21} s^{-1}) is the reduced dissipation coefficient, ω_g and ω_s are the frequencies of the harmonic oscillator at the ground state and saddle configurations respectively[30].

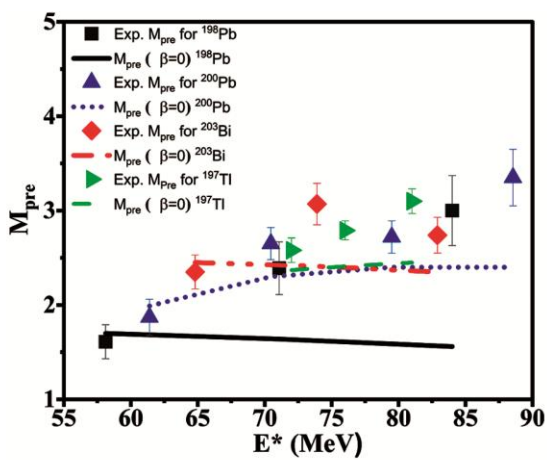

Fig. 3 — Experimental Pre-scission neutron multiplicities (M_{pre}) with statistical model calculations (β =0) as a function of excitation energy (E*) for A ~ 200.

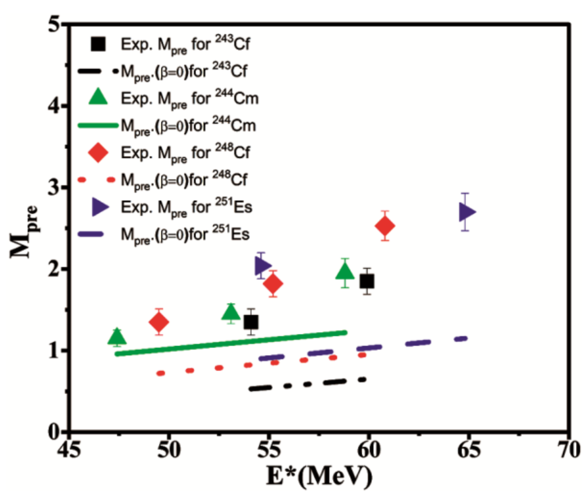

Fig. 4 — Experimental Pre-scission neutron multiplicity (M_{pre}) with statistical model calculation (β = 0) as a function of excitation energies (E*) for mass ~ 250 region of CN.

3.2 Statistical Model Calculations using Kramers fission width

Statistical model calculations are performed using the Kramers fission width to reproduce the pre-scission neutron multiplicity data for both mass regions and the same are plotted in Figs. 5 & 6. From these Figs, it is evident that dissipation strength increases with an increase in excitation energy of the compound nucleus in both the mass regions except for

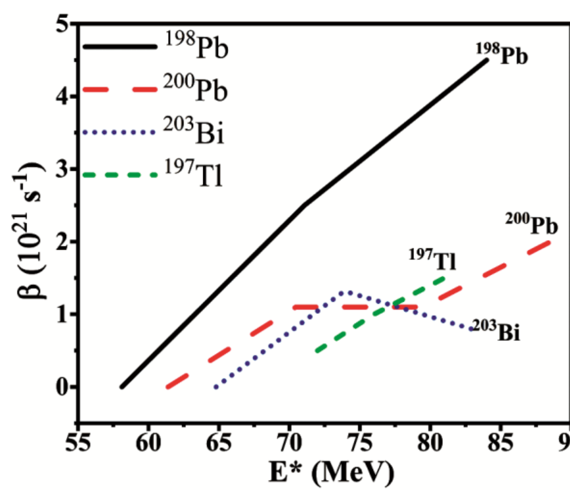

Fig. 5 — Dissipation strength (β) as a function of excitation energy (E*) for mass ~ 200 region.

Table 1 — Reactions considered for the analysis and their different parameters.

S.No.	Reactions	CN	α	$\alpha_{B.G.}$	χ	Ref.
1	^{16}O+^{181}Ta	^{197}Tl	0.837	0.832	0.693	[14]
2	^{28}Si+^{170}Er	^{198}Pb	0.710	0.839	0.704	[19]
3	^{19}F+^{181}Ta	^{200}Pb	0.810	0.837	0.701	[19]
4	^{19}F+^{184}W	^{203}Bi	0.812	0.842	0.708	[20]
5	^{11}B+^{232}Np	^{243}Cf	0.909	0.899	0.832	[21]
6	^{12}C+^{232}Th	^{244}Cm	0.901	0.889	0.807	[21]
7	^{16}O+^{232}Th	^{248}Cf	0.870	0.896	0.825	[21]
8	^{19}F+ ^{232}Th	^{251}Es	0.848	0.899	0.833	[19]

the reaction ^{19}F + ^{184}W in mass ~ 200 region, which shows the non-monotonous behaviour. The dissipation strength required to reproduce the experimental pre-scission neutron multiplicity is highest for the fission of ^{198}Pb among the chosen reactions in the overlapping excitation energy range, whereas, strength for the other reactions is comparable. This difference could again be possible as having ^{16}O + ^{181}Ta reaction, all the other reactions have $\alpha < \alpha_{BG}$ with a significant difference in their values for $^{28}Si+^{170}Er \rightarrow ^{198}Pb$ reaction.

From the Fig. 5, it is also observed that the reaction $^{16}O + ^{181}Ta \rightarrow ^{197}Tl$ with $\alpha > \alpha_{BG}$ has a lower value of dissipation strength as compared to other reactions with $\alpha < \alpha_{BG}$, at excitation energy ~ 70 – 75 MeV, however, the dissipation strength is comparable in higher energy range. Further, for reaction $^{28}Si+^{170}Er\rightarrow^{198}Pb$ with $\alpha < \alpha_{BG}$ we obtained the highest dissipation strength which might be due to entrance channel dynamics.

From Fig. 6, it can be observed that dissipation strength obtained for the reactions $^{12}C+^{232}Th \rightarrow ^{244}Cm$ with $\alpha > \alpha_{BG,}$ is found to be significantly lower as compared to the reactions with $\alpha < \alpha_{BG,}$ at comparable excitation energies. Among the reaction systems with $\alpha < \alpha_{BG,}$ the dissipation strength is found to be large for the reaction $^{16}O+^{232}Th \rightarrow ^{248}Cf$, in ~ 250 mass region. The possible reason for the large dissipation strength at overlapping excitation energy in $^{16}O+^{232}Th \rightarrow ^{248}Cf$, results from larger dynamical time during formation of the compound nucleus.

3.3 Statistical Model Calculations with the inclusion of shell correction in level density and CELD effect

It was well known that the shell correction in level density and CELD plays a significant role in statistical model calculations. The parameter (E_D), given in Equation (4), decides the rate at which the shell effects disappear with an increase in the intrinsic excitation energy E* and nuclear collective motion (rotational and vibrational) enhances the nuclear level density with respect to the intrinsic level density of nucleus. So, it may be effective to include the above-mentioned parameters in statistical model calculations. By using the CELD, the total level density $\rho(E_{th})$ is represented as

$$\rho(E_{th}) = K_{coll}(E_{th})\rho_{intr}(E_{th}) \quad \dots (6)$$

Here, $K_{coll}(E_{th})$ is the collective enhancement factor due to vibrations (K_{vib}) and rotations (K_{rot}) of the nucleus. The enhancement factor for collective rotation and vibration was obtained from the work of Ignatyuk *et al.*[31].

In Figs. 7 & 8, it is observed that the pre-scission multiplicities calculated with Bohr-Wheeler fission width with the inclusion of shell correction in level density and CELD for both mass regions are highly under estimated. For both mass regions, the calculated pre-scission neutron multiplicities for (β = 0) are relatively more when calculated without the inclusion of the shell correction in level density and the CELD effect.

Further, we did the calculations using Kramers fission width with inclusion of shell correction in level density and CELD. The dissipations strength obtained for both mass regions is plotted in Figs. 9 & 10.

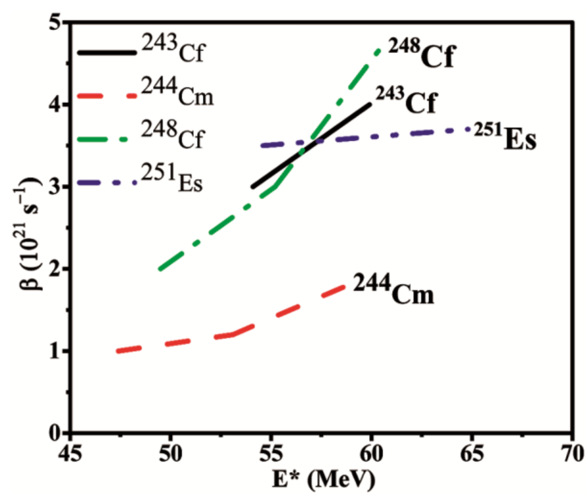

Fig. 6 — Dissipation strength (β) as a function of excitation energy (E*) for mass ~ 250 region.

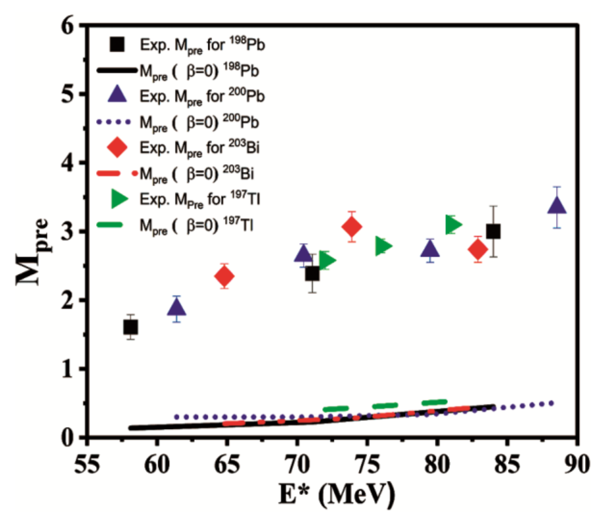

Fig. 7 — Experimental Pre-scission neutron multiplicities (M_{pre}) with statistical model calculations (β =0) with inclusion of shell correction in level density and CELD as a function of excitation energy (E*) for A ~ 200.

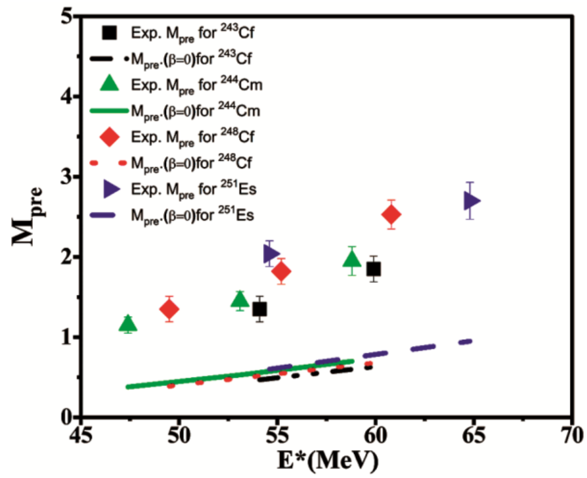

Fig. 8 — Experimental Pre-scission neutron multiplicity (M_{pre}) with statistical model calculation (β = 0) with inclusion of shell correction in level density and CELD as a function of excitation energies (E*) for mass ~ 250 region of CN.

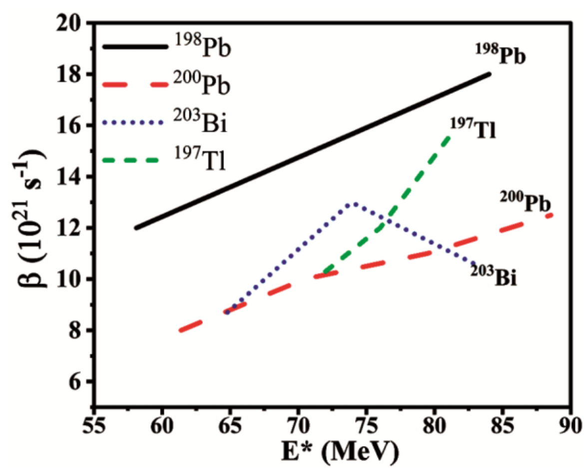

Fig. 9 — Dissipation strength (β) with the inclusion of shell correction in level density and the CELD effect as a function of excitation energy (E*) for mass ~ 200 region.

From Figs. 9 & 10, the dissipation strength is found to be increases with increase in excitation energy except $^{19}F+^{184}W$ system. It is also evident that the dissipation obtained with inclusion of shell correction in level density and CELD effect are found to be higher as compared to the dissipation obtained without the inclusion of shell correction in level density and CELD. This shows that shell correction in level density and CELD effect play an important role in the nuclear dissipation. This colud be due to the fact that shell correction in level density and CELD effect, are related with the neutron and fission widths. The neutron emission probability P_n is given by $P_n = \Gamma_n/(\Gamma_n + \Gamma_f) = (\Gamma_n/\Gamma_f)/[(\Gamma_n/\Gamma_f) + 1]$, where Γ_n and Γ_f are the neutron and fission widths, respectively. The

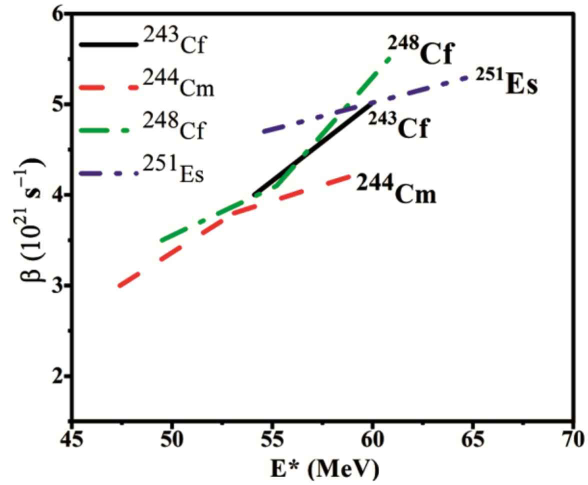

Fig. 10 — Dissipation strength (β) with inclusion of shell correction in level density and CELD as a function of excitation energy (E*) for mass ~ 250 region.

inclusion of shell correction in level density and CELD effect causes a high reduction in Γ_n/Γ_f[15,32-33], which results in higher dissipation strength compared to when no shell correction in level density and CELD effect are not included. Although these parameters strongly influenced the dissipation strength in ~ 200 mass region as compared to ~ 250 mass region.

4 Results and Discussion

In the present work, Statistical model analysis for pre-scission neutron multiplicity as a function of excitation energy of the CN has been performed with and without the inclusion of the shell correction in level density and the CELD effect for the chosen reactions in two different mass regions. In this analysis, initially, we considered the Bohr- Wheeler fission width to reproduce the experimental data. The statistical model results show that pre-scission neutron multiplicities calculated using Bohr-Wheeler fission width are highly under estimated in both mass regions with and without the inclusion of the shell correction in level density and the CELD effect. Higher under estimation in pre-scission multiplicity was found with inclusion of shell correction in level density and CELD effect as compared to the dissipation obtained without inclusion of above mentioned parameters. These findings suggest that higher dissipation strength is required to reproduce the experimental data with inclusion of these parameters. To address this descriptively, we used the Kramers modified fission width in the calculations to reproduce the experimental pre-scission neutron multiplicities. Dissipation strength, which quantifies the amount of dissipation involved in fission process, shows complementary trends in two different mass regions with and without inclusion of the above mentioned parameters. It is relatively higher for relatively less fissile systems as compared to other reactions in mass ~ 200 region. Whereas, dissipation strength is maximum for more fissile system as compared to others among the chosen reactions in the overlapping energy domain, in ~ 250 mass region. However, in both the mass region the dissipation strength for reactions with $\alpha > \alpha_{BG}$ are found to be lower as compared to reactions with $\alpha < \alpha_{BG}$. Comparison between dissipation strength obtained with and without inclusion of shell correction in level density and CELD effect shows that the dissipation strength required to reproduce the experimental data is higher with inclusion of these parameters. The inclusion of these parameters causes a high reduction in Γ_n/Γ_f that results in higher dissipation.

5 Summary

In the present work, we have calculated pre-scission neutron multiplicity for two different mass regions using the Bohr-Wheeler fission width as well as the Kramers fission width for the chosen reactions with and without the inclusion of shell correction in level density and CELD effect. We found that the measured pre-scission neutron multiplicities increase with the increase in excitation energy of the compound nucleus in both mass regions for all the systems, except for $^{19}F + ^{184}W$. For reaction $^{19}F + ^{184}W$, the pre-scission neutron multiplicity initially increases in excitation energy range of ~ 64.80 – 73.90 MeV and then decreases at 82.90 MeV, which is unexpected and also inconsistent with the observed trend in literature as well as with the Itkis systematics. It is also observed that pre-scission neutron multiplicities calculated with the statistical model using Bohr-Wheeler fission width, with and without the inclusion of above mentioned parameters, without dissipation (*i.e*, for β=0) are highly under estimated as compared to the experimental data. Moreover, a relatively higher degree of under estimation in pre-scission neutron multiplicity is obtained when the shell correction in level density and the CELD effect are used in the calculations. The dissipation strength is found to increase with the increase in excitation energy of the compound nucleus in both the mass region, except for the reaction $^{19}F + ^{184}W$ in the mass ~ 200 region which shows contrary trend. When the effects of shell correction in level density and CELD are incorporated in the calculations, the dissipation strength is found to be higher as compared to that obtained without incorporating these effects. Further, dissipation strenght obtained to reproduce the data is nearly comparable in both mass regions, when the shell correction in the level density and the CELD effect are not incorporeted. Whereas, with the inclusion of these parameters the dissipation obtained is found to be quite higher in cae of ~ 200 mass region.

In mass ~ 200 region, the dissipation strength decreases with increase in mass number of the CN. The lower value of dissipation strength is obtained for the reactions with $\alpha > \alpha_{BG}$. Similarly, for mass ~ 250 region the highest dissipation strength is obtained in case of reaction $^{16}O+^{232}Th \rightarrow ^{248}Cf$ with $\alpha < \alpha_{BG}$ and lowest for the reaction $^{12}C+^{232}Th \rightarrow ^{244}Cm$ with $\alpha > \alpha_{BG,}$ at nearly same excitation energies. The higher dissipation strength in $^{16}O+^{232}Th \rightarrow ^{248}Cf$ can be attributed to a larger dynamical time during the formation of the compound nucleus. In order to gain a better understanding of systematic behaviour and to obtain clear insight data for more reactions at similar excitation energies would be helpful**.**

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