Chapter 5

Neutron Multiplicities From $^{16}$O + $^{181}$Ta & $^{19}$F + $^{178}$Hf Reactions

The dynamics of fusion-fission processes in nucleus-nucleus collisions has been extensively investigated, both experimentally and theoretically, in recent years. The most commonly used experimental probe for such studies is the measurement of pre-scission neutrons. The emission of a pre-scission neutron can take place at different stages starting from the formation of a compound nucleus (CN) till it reaches the scission configuration. Initially, the di-nuclear system in the entrance channel requires a time interval ($t_{\text{form}}$) in order to form a fully equilibrated CN [1]. Neutron emission can take place during $t_{\text{form}}$ and it would contribute to the measured pre-scission multiplicity. After the CN is formed, its dynamical evolution can be considered as a quasi stationary diffusion process over the fission barrier. Most of the pre-scission neutrons are emitted during this stage. Beyond the saddle point, neutron emission from the CN can still continue till it reaches the scission point and it would make an additional contribution to the multiplicity of pre-scission neutrons.

In heavy ion induced fusion-fission reactions, it is possible to create the same CN at the same excitation energy through different entrance channels by choosing proper combinations of the target and projectile nuclei and appropriate beam energies of the projectiles. For such compound nuclei formed through different entrance channels, the average number of pre-scission neutrons emitted after formation of the CN are expected to be the same. However, the number of neutrons emitted during the formation time $t_{\text{form}}$, in different reactions could be different depending upon the dynamical evolution of
the respective entrance channels.

The pre- and post-scission neutron multiplicities were measured from the fission of $^{197}$Tl compound nucleus (CN). This CN was populated at various excitation energies using the reactions $^{160}O + ^{181}$Ta and $^{19}F + ^{178}$Hf. The entrance channel mass asymmetry ($\alpha$) values for the two reactions are 0.837 and 0.807 respectively. These reactions were chosen so that the $\alpha$ of these two entrance channels lie on two sides of the critical Businaro-Gallone mass asymmetry ($\alpha_{BG}$), which is 0.814 for the $^{197}$Tl compound system. As discussed in the first chapter, fusion mechanism is entirely different on two sides of the BG point. For $\alpha > \alpha_{BG}$, system prefers more asymmetric shapes, so the target nucleus sucks the projectile nucleus to form the CN whereas, for $\alpha < \alpha_{BG}$ system prefers more symmetric shapes and, a large mass transfer takes place from the target nucleus to the projectile nucleus. Hence fusion takes place on a faster time scale for the reaction with $\alpha > \alpha_{BG}$ as compared the reaction lying on other side of the BG point.

The above discussion implies that the formation time of a CN is expected to be different on two sides of the BG mountain [1–3]. It is more for the reaction where $\alpha < \alpha_{BG}$ as compared to the reaction lying on other side of the Businaro-Gallone point. In the present study, $\alpha > \alpha_{BG}$ for $^{16}O + ^{181}$Ta whereas $\alpha < \alpha_{BG}$ for $^{19}F + ^{178}$Hf. Therefore, formation time and consequently neutrons emitted during the formation phase of $^{19}F + ^{178}$Hf would be more as compared to that of $^{16}O + ^{181}$Ta reaction.

We have looked into the contribution of neutrons emitted during the formation phase of a CN to the total pre-scission neutron multiplicity from the fission of $^{197}$Tl. A detailed comparison was made between the measured values and the statistical model predictions. Dissipation strength ($\gamma$) was calculated after reproducing the measured pre-scission neutron yield by varying the $\gamma$ value in the statistical model code.
5.1 Results and Discussion

5.1.1 Excitation Energies and Critical Angular Momentum ($l_c$) Values

The critical angular momentum ($l_c$) values were calculated using the expression,

$$\sigma(l) = \frac{\pi}{k^2} \frac{2l + 1}{1 + \exp\left(\frac{l - l_c}{\delta l}\right)}$$

(5.1)

the parameters ($l_c$ and $\delta l$) of which were fixed by fitting the experimental fusion cross-sections [4]. Using the above expression, the calculated critical angular momentum values along with the energies for both the reactions are tabulated in Table 5.1. It is clear from the above Table that, for all the incident energies of both the projectiles, the compound system is populated with almost similar spins through the two channels.

<table>
<thead>
<tr>
<th>$^{16}$O + $^{181}$Ta</th>
<th>$^{19}$F + $^{178}$Hf</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{lab}$</td>
<td>$E_{cm}$</td>
</tr>
<tr>
<td>105</td>
<td>96.5</td>
</tr>
<tr>
<td>110</td>
<td>101.0</td>
</tr>
<tr>
<td>115</td>
<td>105.7</td>
</tr>
</tbody>
</table>

5.1.2 Experimental Neutron Multiplicities

The pre- and post-scission neutron multiplicities were derived from the neutron energy spectra using the least squares fitting procedure to Watt expression [5], as discussed in chapter 4. The fits to the double differential neutron multiplicity spectra at various angles for both the reactions are shown in Figs. 5.1 and 5.2. The measured values of pre-scission,
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Figure 5.1: Neutron multiplicity spectra (filled squares) for the $^{16}$O + $^{181}$Ta reaction at $E_{\text{lab}} = 110$ MeV along with the fits for the pre-scission (dotted curve), post-scission from one fragment (dashed curve) and that from the other (dot dashed curve). The solid curve represents the total contribution.

Post-scission & total neutron multiplicities from both the reactions are tabulated in Table 5.2 and are plotted against the excitation energies of the CN in Figs. 5.3, 5.4 and 5.5, respectively. The pre-scission neutron multiplicity, as shown in Fig. 5.3, is found to be higher for the system with entrance channel mass asymmetry $\alpha < \alpha_{BG}$ as compared to the system with $\alpha < \alpha_{BG}$. This difference in pre-scission multiplicities for the two cases increases with the excitation energy of the CN.
Figure 5.2: Neutron multiplicity spectra (filled squares) for $^{19}$F + $^{178}$Hf at $E_{\text{lab}} = 113$ MeV along with fits for pre-scission (dotted curve), post-scission: fragment 1 (dashed curve), fragment 2 (dot dashed curve). Solid curve represents the total contribution.

Post-scission yield of neutrons does not show any noticeable dependence on characteristic $\alpha$, as well as, on excitation energy of the CN, for both the reactions, as most of the excess in excitation energy of CN is being carried away by the pre-scission neutrons (Fig. 5.4).

The major contribution to the increase in total neutron multiplicity with excitation energy of the CN comes from the pre-scission neutrons as post-scission component is not having any remarkable dependence on the excitation energy of the CN.
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Figure 5.3: Experimental pre-scission neutron multiplicities from $^{16}$O + $^{181}$Ta (filled squares) and $^{19}$F + $^{178}$Hf (filled circles) reactions. The lines are drawn to guide the eye.

Figure 5.4: Experimental post-scission neutron multiplicities from $^{16}$O + $^{181}$Ta (filled squares) and $^{19}$F + $^{178}$Hf (filled circles) reactions. The lines are drawn to guide the eye.
Table 5.2: Values of neutron multiplicities from the reactions $^{16}O + ^{181}Ta$ & $^{19}F + ^{178}Hf$

<table>
<thead>
<tr>
<th>$E^*$</th>
<th>$M^\text{pre}_n$</th>
<th>$2 \times M^\text{post}_n$</th>
<th>$M^\text{total}_n$</th>
<th>$M^\text{pre}_n$</th>
<th>$2 \times M^\text{post}_n$</th>
<th>$M^\text{total}_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>72.0</td>
<td>2.58 ± 0.13</td>
<td>2.95 ± 0.15</td>
<td>5.58 ± 0.20</td>
<td>2.75 ± 0.16</td>
<td>2.84 ± 0.12</td>
<td>5.59 ± 0.20</td>
</tr>
<tr>
<td>76.0</td>
<td>2.79 ± 0.10</td>
<td>3.00 ± 0.12</td>
<td>5.79 ± 0.15</td>
<td>3.07 ± 0.13</td>
<td>3.05 ± 0.14</td>
<td>6.12 ± 0.19</td>
</tr>
<tr>
<td>81.0</td>
<td>3.10 ± 0.13</td>
<td>3.18 ± 0.11</td>
<td>6.28 ± 0.17</td>
<td>3.57 ± 0.12</td>
<td>3.15 ± 0.11</td>
<td>6.72 ± 0.16</td>
</tr>
</tbody>
</table>

Figure 5.5: Total neutron multiplicities from $^{16}O + ^{181}Ta$ (filled squares) and $^{19}F + ^{178}Hf$ (filled circles) reactions. The lines are drawn to guide the eye.

5.1.3 Comparison With The Statistical Model Predictions

The excitation function of pre-scission neutron multiplicity was calculated for different values of the dissipation strength for both the reactions using the Kramers [6] modified
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Bohr-Wheeler fission width,

\[ \Gamma_j^{Kramers} = \Gamma_j^{BW} \left[ (1 + \gamma^2)^{1/2} - \gamma \right], \tag{5.2} \]

where \( \gamma \) represents the strength of nuclear dissipation and was treated as a free parameter in the calculations. The results of the statistical model calculations were compared with the experimental values in Fig. 5.6. The comparison of the calculated post-scission neutron multiplicities with the experimental values is shown in Fig. 5.7. It may be noted that the post-scission multiplicity also depends upon \( \gamma \) since the available excitation energy of the fission fragments is determined by the number of pre-scission neutrons. We find that a value of 0.4 for \( \gamma \) gives a reasonable fit to the experimental post-scission neutron multiplicity for the \(^{16}\text{O} + ^{181}\text{Ta}\) system at all the three energies while a value of 0.3 is required in the case of the \(^{19}\text{F} + ^{179}\text{Hf}\) system.

The comparison of calculated pre-scission neutron multiplicities with the experimental values clearly shows that the predictions using the statistical model fission width (for
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Figure 5.7: Experimental post-scission neutron multiplicities (filled squares) along with the statistical model calculation results for $\gamma = 0$ (solid line), $\gamma = 0.2$ (dotted line), $\gamma = 0.3$ (dashed line), $\gamma = 0.4$ (dash dotted line), $\gamma = 0.5$ (dash double dotted line), $\gamma = 0.6$ (short dashed line), and $\gamma = 0.7$ (short dash dotted line).

$\gamma = 0$ considerably underestimate the pre-scission neutron multiplicity at all the three energies and the discrepancy increases with excitation energy. It is also observed that for each system, the experimental values at all the three energies cannot be reproduced by a single value of $\gamma$. The best fit values of $\gamma$ for $^{16}$O+$^{181}$Ta at the three excitation energies are 0.2, 0.5 & 0.7 respectively and the same for $^{19}$F+$^{178}$Hf are 0.3, 0.7 & 1.2 respectively. The experimental pre-scission neutron multiplicities along with the fitted values of dissipation strength are shown in Fig. 5.8.

The role of neutrons emitted during saddle-to-scission transition was explored in order to account for the systematic difference in the pre-scission multiplicity values for the two reactions under consideration. Since the saddle-to-scission transition time depends on the CN spin and the spin distributions in the CN $^{197}$Tl formed in the two reactions are different, the number of neutrons emitted during saddle-to-scission transition in the two reactions could be different. The calculated neutron multiplicities during saddle-
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Figure 5.8: The experimental pre-scission neutron multiplicities from the reactions $^{19}$F+$^{178}$Hf (solid circle) and $^{16}$O+$^{181}$Ta (solid square) along with the fitted values from the statistical model calculation (solid line). The calculated multiplicities of neutrons emitted during saddle-to-scission transition for both the reactions are not distinguishable and are shown by the dotted line.

To-scission transition are also shown in Fig. 5.8. We find from the statistical model calculations that the saddle-to-scission contributions are almost the same for both the systems while they account for a small fraction of the total pre-scission neutrons. It was therefore concluded that the observed difference in the pre-scission multiplicities can not be attributed to the neutrons emitted during saddle-to-scission transition.

The best fit values of dissipation strength from the two reactions are plotted as a function of excitation energy in Fig. 5.9. The statistical error associated with an experimental multiplicity gives rise to an error on the corresponding fitted value of $\gamma$ and it is also shown in this figure. It is observed that starting with values which are very close for both the systems at the lowest excitation energy, $\gamma$ increases faster with excitation energy for the $^{19}$F+$^{178}$Hf system than the $^{16}$O+$^{181}$Ta system. In order to understand the above systematic behaviour of $\gamma$ qualitatively, we first note that though $\gamma$ is introduced in the present calculation as the strength of the dissipative force in the
fission dynamics of the CN, its value obtained from fitting the experimental data has to account for the total number of neutrons emitted before scission including those emitted during the formation time of the CN. Since the survival probability of a CN decreases fast with increasing excitation energy, the formation time would be a larger fraction of the total time available for pre-scission neutron emission at a higher excitation energy. One would therefore expect that the fraction of pre-scission neutrons emitted during the formation time to increase with excitation energy. A larger value of $\gamma$ is thus required to fit the experimental multiplicities at higher excitation energies in order to account for the larger number of pre-scission neutrons emitted during the formation time.

It may further be noted that the formation time, and hence the number of neutrons emitted during the formation time, would be different for two different systems leading to the same CN since the dynamics of their entrance channels are different. We would however expect that the number of neutrons emitted after the fully equilibrated CN is formed to be the same for both the systems considered in the present study since the same CN nucleus is formed at the same excitation energies. Consequently, the $\gamma$ values
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extracted for the two systems at each excitation energy would be different on account of the difference in the formation time. This difference would grow with increasing excitation energy reflecting the fact that the two systems have different formation time. In fact, we find in fig. 5.9 that $\gamma$ increases faster with excitation energy for the $^{19}$F+$^{178}$Hf system than the $^{16}$O+$^{181}$Ta system. This indicates that the formation time for the more symmetric $^{19}$F+$^{178}$Hf system is larger than that of $^{16}$O+$^{181}$Ta.

It may be mentioned at this point that microscopic theories of nuclear dissipation such as that of two body viscosity can give rise to an excitation energy dependence of $\gamma$. It is therefore not the excitation energy dependence of $\gamma$ in itself, but the difference in the excitation energy dependence of $\gamma$ between the two systems that is considered here as a signature of entrance channel effect on the multiplicity of pre-scission neutrons.

Since the entrance channel dynamics critically depends upon the entrance channel mass asymmetry with respect to the Businaro-Gallone point, we have examined how this point moves with increasing angular momentum of the di-nuclear system using the formalism of Abe [15] (discussed in chapter 2). Fig. 5.10 shows the angular momentum dependence of the Businaro-Gallone point. The largest value of the critical angular momentum encountered in the present study is also shown in this figure. The maximum angular momentum which leads to fusion is also indicated in fig. 5.10. It is observed that, the $^{16}$O+$^{181}$Ta and $^{19}$F+$^{178}$Hf systems are on opposite sides of the Businaro-Gallone line for the entire range of angular momentum accessible in the present study. Entrance channel effects are therefore expected to persist at all the three beam energies considered in this work. However, it is also observed that both the systems can be found on the same side of the Businaro-Gallone line at higher values of angular momentum in the range of 60$h$ to 75$h$. One can therefore speculate that a reduction in the entrance channel effects may be experimentally observed at higher beam energies.

We have next performed statistical model calculations using a temperature dependent level density parameter. Since our conclusion regarding the entrance channel effect as discussed above relies on the excitation energy dependence of $\gamma$, it is important to verify whether the same conclusion holds when a temperature dependent level density parameter is used in the calculation. The excitation energy dependence as given in Eq.(2.10)
is relatively weak since it merely accounts for the smoothing away of the nuclear shell structure. However, the temperature dependence may be much stronger as was indicated by the Thomas-Fermi calculations [16]. Finally Eq. (2.12) was used to calculate the strength of additional temperature dependence. Using the level density parameter as given in Eq. (2.12), the strength of $\gamma$ was subsequently adjusted to reproduce the experimental pre-scission neutron multiplicity at each excitation energy and the results are shown in Fig. 5.11. The calculated values of the multiplicity of neutrons emitted during saddle-to-scission transition of the CN are also shown in this figure. We find that the number of neutrons emitted during the saddle-to-scission transition does not depend upon the entrance channel and is a small fraction of the total number of pre-scission neutrons, similar to our earlier observation in Fig. 5.8. It is however interesting to note that more neutrons are emitted during saddle-to-scission transition when calculations are performed with $\kappa = 0.8$ ($\kappa$ determines the strength of the additional temperature dependence) compared to those obtained with $\kappa = 0$ (Fig. 5.8). This is due to the fact that
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Figure 5.11: The experimental pre-scission neutron multiplicities from the reactions $^{19}\text{F}+^{178}\text{Hf}$ (solid circle) and $^{16}_0+^{181}\text{Ta}$ (solid square) along with the fitted values from the statistical model calculation (solid line) using a value of $\kappa = 0.8$ for the temperature dependence of the level density parameter (see text). The calculated multiplicities of neutrons emitted during saddle to scission transition for both the reactions are not distinguishable and are shown by the dotted line.

The values of $\gamma$ which are obtained with $\kappa = 0.8$ and which reproduce the experimental pre-scission neutron multiplicities are plotted in Fig. 5.12 for both the systems. Evidently, $\gamma$ is lower for $\kappa = 0.8$ than those obtained with $\kappa = 0$ (see Fig. 5.9). This is expected since it is well known that results from statistical model calculations are sensitive to the level density parameter. It is, however, interesting to note that $\gamma$ increases faster with excitation energy for the $^{19}\text{F}+^{178}\text{Hf}$ system than that for the $^{16}_0+^{181}\text{Ta}$ system, similar to our earlier observation in Fig. 5.9. It corresponds to a larger formation

the level density parameter with $\kappa = 0.8$ is smaller than that obtained with $\kappa = 0$ and hence the temperature calculated with $\kappa = 0.8$ is higher than that with $\kappa = 0$. More neutrons are emitted from a CN at a higher temperature than from one at a lower temperature over a given interval of time (saddle-to-scission transition time) and hence the above observation.

The values of $\gamma$ which are obtained with $\kappa = 0.8$ and which reproduce the experimental pre-scission neutron multiplicities are plotted in Fig. 5.12 for both the systems. Evidently, $\gamma$ is lower for $\kappa = 0.8$ than those obtained with $\kappa = 0$ (see Fig. 5.9). This is expected since it is well known that results from statistical model calculations are sensitive to the level density parameter. It is, however, interesting to note that $\gamma$ increases faster with excitation energy for the $^{19}\text{F}+^{178}\text{Hf}$ system than that for the $^{16}_0+^{181}\text{Ta}$ system, similar to our earlier observation in Fig. 5.9. It corresponds to a larger formation
time for the $^{19}$F+$^{178}$Hf system than that of $^{16}$O+$^{181}$Ta. Thus, the distinguishing features of entrance channel effects are retained in the statistical model calculations with different temperature dependences in the level density parameter.

5.2 Conclusion

We have measured the multiplicities of pre- and post-scission neutrons emitted in the fission of $^{197}$Tl compound nucleus. This CN was formed at the same excitation energies in $^{16}$O+$^{181}$Ta and $^{19}$F+$^{178}$Hf reactions using $^{16}$O beam at energies of 105, 110 and 115 MeV and $^{19}$F beam at 108, 113 and 118 MeV, respectively. The pre-scission neutron yield from the two systems lying on either side of the Businaro-Gallone point was found to be different reflecting its dependence on the mass asymmetry in the entrance channel. The experimental neutron multiplicities were compared with the statistical model predictions which included a dissipative force in the fission channel. The strength of the dissipation, $\gamma$, was obtained by comparing the statistical model calculation with experimental data.
The $\gamma$ was found to increase with excitation energy for both the systems though the rate of increase was higher for the $^{19}$F+$^{178}$Hf than the $^{16}$O+$^{181}$Ta system. It was then shown from the statistical model calculation that the number of neutrons emitted during the saddle-to-scission transition were same for both the systems and hence they could not account for the observed difference in the pre-scission multiplicities between the two systems. We, therefore, concluded that the observed difference can be solely attributed to the different entrance channel dynamics of the two systems. Subsequently, we argued that the excitation energy dependence of $\gamma$ should depend on the formation time of the CN. Therefore, the observed difference in the excitation energy dependence of $\gamma$ between the two systems can be considered as an evidence of a larger formation time for a CN formed in a more symmetric entrance channel ($\alpha < a_{BG}$) compared to one formed in the entrance channel with higher asymmetry ($\alpha > a_{BG}$).
Bibliography


