Chapter 7

Mass Dependence of Neutron Multiplicities In $^{19}$F + $^{209}$Bi Reaction

The mass distributions of fission fragments measured in heavy ion induced fusion-fission reactions are generally symmetric in shape because the compound nucleus (CN) is generally formed with large excitation energy ($E^*$) well above the barrier. In heavy ion induced reactions, contribution of shell effects is washed out due to the high excitation energy and large angular momentum of the fissioning composite nucleus. The width of mass distribution observed in such reactions is found to be increasing with the increase in the excitation energy of the fissioning nucleus [1-4].

Earlier studies have shown that the mass distributions of fission fragments in heavy ion induced fission may provide information on the reaction mechanism involved in the fission process, due to admixture of fully equilibrated CN events and non-compound nuclear (NCN) reactions, such as, quasi-fission, fast fission and pre-equilibrium fission, etc. [2,6] Mass distributions from the reactions having contribution from above mentioned processes would be expected to be broader, than the one from normal fusion-fission reactions because non compound fission reactions are expected to have more asymmetric component arising due to incomplete equilibration in mass degree of freedom.

Pant et al., has studied the mass dependence of neutron multiplicities at 108 MeV of lab energy, where they found different values of pre- and post-scission neutron multiplicities after gating on the different regions (symmetric and asymmetric) of fragment mass distribution. Pre-scission neutron yield was found to be higher for asymmetric mass splits as compared to symmetric mass splits, which could be due to strong variation in
the fragment mass distribution at different stages in multiple chance fission at medium excitation energies [5]. However, similar measurements on $^{36}$Ar + $^{169}$Tm by Rossner et al. [7], and $^{20}$Ne + $^{159}$Tb, $^{169}$Tm by Keutgen et al. [8], does not show any significant fragment mass dependence of pre-scission neutrons.

In the present experiment, we have measured the fission fragment mass distribution, neutron multiplicities and the mass dependence of neutron multiplicities from the fission of $^{238}$U populated using $^{19}$F + $^{209}$Bi reaction at various lab energies. The details of the energies and corresponding critical angular momentum values ($l_c$) encountered in the present study are listed in Table 7.1. The variance of mass distributions obtained from the present measurement is found to be smaller than already reported by Pant et al. [10], at the overlapping energies. Amongst the lab energies listed in Table 7.1, mass dependence on neutron yield was studied only at three lab energies, i.e., 100, 108 and 116 MeV.

<table>
<thead>
<tr>
<th>$E_{lab}$</th>
<th>$E_{cm}$</th>
<th>$E^*$</th>
<th>$l_c$</th>
</tr>
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</tr>
<tr>
<td>104</td>
<td>95.3</td>
<td>46.3</td>
<td>31.7</td>
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<tr>
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<td>50.0</td>
<td>37.3</td>
</tr>
<tr>
<td>112</td>
<td>102.6</td>
<td>53.7</td>
<td>44.2</td>
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<tr>
<td>116</td>
<td>106.3</td>
<td>57.4</td>
<td>48.1</td>
</tr>
</tbody>
</table>
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7.1.1 Mass Distribution

Fission fragment mass distributions were studied at energies well above the barrier. The component of NCN fission was found to be negligible at all energies chosen in the present study. The measured folding angle distributions and Gaussian fits at all energies are shown in Fig. 7.1. It is observed that the folding angle distributions are essentially single peaked and events are almost entirely from the fission following complete fusion. The peak of the measured distribution matches with the calculated folding angle using Viola’s systematics [9] for symmetric fission.

The mass distributions extracted from the experiment following the procedure discussed in chapter 4, at different CN excitation energies are shown in Fig. 7.2. It is observed that mass distributions are in general symmetric in shape and the peak of the distributions is around $A_{CN}/2$ where $A_{CN}$ is the mass number of the compound nucleus. The width of mass distributions were determined by fitting the spectra with Gaussian distribution. The value of measured variance of mass distributions $\sigma_{m}^2$ at different lab energies is tabulated in Table 7.2. The variation of the variance of the mass distributions as a function

<table>
<thead>
<tr>
<th>$E_{lab}$</th>
<th>$E_{cm}$</th>
<th>$E_{cm}/V_b$</th>
<th>$E^*$</th>
<th>$\sigma_{m}^2 (\sigma^2)$</th>
</tr>
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<td>42.7</td>
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<td>99.0</td>
<td>1.16</td>
<td>50.0</td>
<td>233.9</td>
</tr>
<tr>
<td>112</td>
<td>102.6</td>
<td>1.21</td>
<td>53.7</td>
<td>259.4</td>
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<tr>
<td>116</td>
<td>106.3</td>
<td>1.25</td>
<td>57.4</td>
<td>259.3</td>
</tr>
</tbody>
</table>

Table 7.2: Variance of mass distributions for $^{19}$F + $^{209}$Bi reaction
7.1 Results and Discussion

Figure 7.1: Folding angle distributions for $^{19}$F + $^{209}$Bi reaction at various lab energy. The Gaussian fits are shown by red lines.

The Gaussian fit of $E_{cm}/V_b$, where $V_b$ ($= 85$ MeV) is the Coulomb barrier in c.m. frame, is shown in Fig. 7.3. The variation in variance of mass distributions is found to be almost linear.

The measured variance by Ghosh et al. [2] (solid circles) and by Pant et al. [10] (solid triangles) is also shown in Fig. 7.3. It is pertinent to mention here that the measurements of Pant et al. were performed using $\Delta E - E$ technique. Thus fission fragment ma
distributions were derived from the measured kinetic energies of the fission fragment.

It is clear from this figure that our results are matching with the measurements of Ghaf
al. for the overlapping energy and the linear variation in variance of mass distribi
supports the conclusion of absence of any NCN fission events at all projectile en
used in the present study.
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Figure 7.3: The measured variance of mass distributions $\sigma_m^2$ as a function of $E_{cm}/V_b$ for the system $^{19}$F + $^{209}$Bi (solid squares) along with the other measurements. Lines are drawn to guide the eye.

7.1.2 Experimental Neutron Multiplicities

The pre- and post-scission components of neutron multiplicities were derived by carrying out the moving source fits to the observed neutron energy spectra using Watt expression [11] at various angles. As discussed in chapter 4 (section 1.2.1), in case of symmetric fission, energies of the two fragments were determined using Viola’s [9] systematics for the total kinetic energy release,

$$TKE = \left[ 0.0189 \frac{Z^2}{A^{1/3}} + 7.3 \right] \text{MeV}, \quad (7.1)$$

where, $Z$ and $A$ are charge number and mass number of the compound nucleus. In case of asymmetric mass splits, the mean fragment energies were calculated using a different expression [9] for the total kinetic energy, which is dependent on the charge and mass of the two fragments, $Z_1$, $Z_2$, $A_1$ and $A_2$ and is given as,

$$TKE = \left[ 0.755 \frac{Z_1 Z_2}{(A_1^{1/3} + A_2^{1/3})} + 7.3 \right] \text{MeV}, \quad (7.2)$$
The post-scission parameter of neutron multiplicity was taken to be proportional to the ratio of the fragment masses for asymmetric splits. The measured neutron energy spectra along with the fits for pre-scission, post-scission and total neutron multiplicities at various angles for $^{19}$F + $^{209}$Bi reaction at 108 MeV of lab energy is shown in Fig. 7.4. The variation of pre-scission neutron multiplicity with the excitation energy of the CN is shown in Fig. 7.5. The experimental pre-scission neutron yield increases with the excitation energy. The calculated values of neutron yield using
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Figure 7.5: Experimental pre-scission neutron multiplicity from $^{19}$F + $^{209}$Bi (filled squares) reaction plotted as a function of excitation energy. Dotted line shows the pre-scission neutron yield calculated with PACE4 using level density parameter $a_n = A/10\text{MeV}^{-1}$ and $a_f/a_n = 1.0$.

PACE4 are also shown in this Fig. The comparison of measured and calculated values clearly shows that statistical model underestimate the pre-fission neutron yield at all the energies studied in the present experiment. The excess pre-scission neutrons were used to estimate the dynamical fusion-fission delay using the expression,

$$\tau_{\text{fission}} = \sum_{i=1}^{n} \frac{n}{\Gamma_n(E_i)}$$

(7.3)

where, $\Gamma_n$ is the neutron decay width and $n$ is the total excess number of pre-scission neutrons over the calculated value at a given excitation energy. The value of $\tau_{\text{fission}}$ as deduced from this analysis is $80 \pm 5 \times 10^{-21} \text{s}$ for the level density parameter $a_n = A/10\text{MeV}^{-1}$ and $a_f/a_n = 1.0$. The variation of post-scission and total neutron multiplicities with excitation energy is shown in Figs. 7.6 and 7.7. Post-scission neutron yield does not show any significant dependence on the excitation energy as most of the excess energy is being carried away by the pre-fission neutrons and fragments are left with moderate excitation energy at scission. Total neutron yield measured by Pant et al. [5] at 108 MeV
Figure 7.6: Experimental post-scission neutron multiplicity from $^{19}\text{F} + ^{209}\text{Bi}$ (filled squares) reaction. Line is drawn to guide the eye.

Figure 7.7: Experimental total neutron multiplicity from $^{19}\text{F} + ^{209}\text{Bi}$ (filled squares) reaction. Measured value of total neutron yield by Pant et al., at $E_{\text{lab}} = 108$ MeV is shown with filled circle. Line is drawn to guide the eye.
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of lab energy is also shown in Fig. 7.7.

7.1.3 Mass Dependence of Neutron Multiplicities

We have looked into the mass dependence of neutron multiplicities at 100, 108 and 116 MeV of lab energies. A mass bin of 20 u was used at different places in the mass distribution in order to look for the effect of different mass splits on the neutron multiplicity. Fig. 7.8 shows the neutron energy spectra along with the fits for the pre-scission, post-scission and total neutron multiplicity for three different mass bins centered at 114 u (symmetric mass bin) and at 94 u and 134 u both asymmetric mass bins. The mass gated values of neutron multiplicities are tabulated in Table 7.3. The variation of pre-scission, post-scission, total neutron multiplicities and temperatures with the mass of fission fragment \( \langle A_{F1} \rangle \) is shown in Figs. 7.9, 7.10 and 7.11. It is evident from the Fig. 7.9, that pre-scission neutron yield does not show any noticeable dependence on the mass distribution of fission fragments. Similar conclusion has been drawn from other measurements by several groups [7, 8, 12]. However, mass gated neutron multiplicity measurement for \( ^{19}\text{F} + ^{209}\text{Bi} \) reaction by Pant et al. does not support the above conclusion as they found the pre-scission neutron yield to be more for asymmetric mass splits as compared to the symmetric mass splits and they have attributed this to the variations in the fragment mass distribution at different stages in multiple chance fission at medium excitation energies.

Post-scission multiplicity increases almost linearly with fragment mass. As shown in Fig. 7.11, the effective pre- and post-scission temperatures do not show any significant dependence on the fission fragment mass distribution. The linear dependence of the post-scission multiplicity is consistent with a mass partition independent effective temperature for post-scission emissions. Assuming initial fragment excitation energy \( E_{F1} \) proportional to the square of the effective temperature,

\[
E_{F1} \propto a_n (T_n^{F1})^2 = \frac{A_{F1}}{a_0} (T_n^{F1})^2, \tag{7.4}
\]

where \( a_n \) is the level density parameter and \( a_0 \), the level density constant. As temperature is mass partition independent and neutron multiplicity is roughly proportional to \( E_{F1} \), then this multiplicity becomes approximately proportional to \( A_{F1} \) [8].

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Figure 7.8: Mass gated neutron multiplicity spectra (filled squares) for the $^{19}$F + $^{209}$Bi reaction at $E_{\text{lab}} = 108$ 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.
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Figure 7.9: Mass dependence of pre- (solid squares) and post-scission (solid circles) neutron multiplicities for $^{19}$F + $^{209}$Bi reaction. Lines are to guide the eye.

Figure 7.9: Mass dependence of pre- (solid squares) and post-scission (solid circles) neutron multiplicities for $^{19}$F + $^{209}$Bi reaction. Lines are to guide the eye.
Figure 7.10: Mass gated total neutron multiplicity values (filled squares) at 100, 108 and 116 MeV of lab energies. Lines are to guide the eye.
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Figure 7.11: Mass dependence of pre-scission (filled squares) and post-scission (filled circles) temperatures. Lines are to guide the eye.
Mass Dependence of Neutron Multiplicities In $^{19}$F + $^{209}$Bi Reaction

Table 7.3: Mass gated neutron multiplicity values for $^{19}$F + $^{209}$Bi reaction

<table>
<thead>
<tr>
<th>$E_{lab}$</th>
<th>Mass bin (u)</th>
<th>$M_n^{pre}$</th>
<th>$M_n^{post}$</th>
<th>$M_n^{total}$</th>
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<tr>
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<td>3.96 ± 0.20</td>
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</tr>
<tr>
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</tr>
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<tr>
<td>116</td>
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<td></td>
</tr>
<tr>
<td>124 - 144</td>
<td>3.34 ± 0.19</td>
<td>3.57 ± 0.26</td>
<td>6.91 ± 0.21</td>
<td></td>
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</table>
7.2 Conclusion

In the present work we have measured the fission fragment mass distributions, multiplicities of pre- and post-scission neutrons and fission fragment mass dependence of neutron multiplicities from the fission of $^{238}$U compound system populated at various excitation energies using the reaction $^{19}$F + $^{209}$Bi. The measured folding angle and fragment mass distributions at all the lab energies do not show any contribution of NCN fission events. The measured variance of mass distribution was found to be in agreement with the work already reported in literature at overlapping energies using similar experimental setup. The measured yield of pre-scission neutron multiplicity was compared with the statistical model calculation and the excess in pre-scission yield over the statistical model predictions has been used to calculate the dynamical fusion-fission time for the $^{238}$U compound system. Using a level density parameter $a_n = A/10 \ MeV^{-1}$ and $a_f/a_n = 1.0$, the fusion-fission dynamical time has been measured as $80 \pm 5 \times 10^{-21}$ s. Pre-scission neutron yield as well as pre- and post-scission temperatures does not show any significant dependence on the mass distribution of fission fragments whereas post-scission neutron yield increases almost linearly with fragment mass, which is expected if the fission fragments, in all mass partitions, have a common temperature.
Bibliography


BIBLIOGRAPHY
