Chapter 4

Result: Fragment emission in $^{12}\text{C} + ^{28}\text{Si}$, $^{12}\text{C} + ^{27}\text{Al}$, $^{11}\text{B} + ^{28}\text{Si}$ reactions

The complex fragment emission from the reactions 77 MeV $^{12}\text{C} + ^{28}\text{Si}$, 73 MeV $^{12}\text{C} + ^{27}\text{Al}$, 64 MeV $^{11}\text{B} + ^{28}\text{Si}$ have been studied at the excitation energy of $\sim 67$ MeV. The main aim of this study is to compare the emission mechanism of the fragments form $\alpha$-cluster system, $^{40}\text{Ca}^*$, produced in $^{12}\text{C} + ^{28}\text{Si}$ and nearby non $\alpha$-cluster system $^{39}\text{K}^*$ produced via two different reactions, $^{12}\text{C} + ^{27}\text{Al}$ and $^{11}\text{B} + ^{28}\text{Si}$. The last two reactions have been chosen to cross check the equilibrium decay nature (absence of entrance channel dependence) of the energy damped binary fragment yield in the decay of $^{39}\text{K}^*$.

The typical energy spectra of the fragments Li, Be and B emitted in these reactions have been shown in Fig. 4.1. It is evident from the figure that there are significant differences in the shapes of the spectra obtained in the three reactions. This is mainly due to the variation of the relative contributions of different reaction processes to the fragment yield. It is known from theoretical [17, 50, 51, 52, 53, 54, 55, 56] and experimental [12, 26, 29, 31, 32, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85] studies of complex fragment emission in low and intermediate energy nucleus-nucleus collision that, the origin of
complex fragments is broadly due to fusion-fission (FF) and non-fusion (deep inelastic collision, deep inelastic orbiting, quasi elastic, breakup, etc.) processes. The quasi-elastic process contributes to the yields of fragments around the entrance channel only and has a strongly forward peaked (around grazing angle) angular distribution. On the other hand, in deep inelastic (DI) collision, mass and angular distributions are much broader, particularly for the lighter systems considered here. So, there is strong overlap in the elemental distributions of the fragments originating from FF and DI processes in

![Figure 4.1: Typical energy spectra of the fragments measured for the reactions $^{12}$C + $^{28}$Si (a - c), $^{12}$C + $^{27}$Al (d - f) and $^{11}$B + $^{28}$Si (g - i) at $\theta_{\text{lab}} = 17.5^\circ$ (a - h) and $30^\circ$ (i). The blue dash-dotted, the black dotted, and the red solid curves represent the contributions of the FF, the DI, and the sum (FF + DI), respectively. The left and the right arrows correspond to the centroids of FF and DI components of energy distributions, respectively.](image)

the light systems, which make it very difficult to separate the contributions of DI and FF processes from the total spectrum. In addition, since in the present study, one of the systems ($^{12}$C + $^{28}$Si) under study is an $\alpha$-cluster system, there is a possibility of the
contribution of deep inelastic orbiting (DIO) in the total fragment yield. As the exper-
imental signatures of both FF and DIO are same, DIO contribution will be automatically
mixed up (if any) with FF yield. To separate out the contributions of FF and DI from
the total yield, the procedure given in the Ref. [21, 94] has been followed and the same
has been explained in Fig. 4.2. The contributions of FF and DI processes have been
represented by two separate Gaussian functions. The centroid of the Gaussian repre-
senting the FF yield has been obtained from Viola systematics [116], duly corrected

Figure 4.2: The typical extraction procedure of FF and DI components from the total energy
spectrum of Be fragment measured in the reaction $^{12}$C + $^{27}$Al at $\theta_{lab} = 17.5^0$. Detail of the
extraction procedure is given in the text. The arrow at low and higher energy indicates the FF
and DI peaks, respectively.

for the asymmetric factor [44], and the width of the Gaussian (blue dash-dot curve)
has been obtained by fitting the lower energy tail of the spectrum. The area under this
Gaussian gives the yield from FF. In the next step, this Gaussian has been subtracted
from the total energy spectra, as shown by pink color curve. This subtracted spectrum
has then been fitted with another Gaussian (black dotted curve) which represents DI
contribution. The contributions of FF and DI components thus obtained for each frag-
ment from each reaction have been displayed in the Fig. 4.1. Besides the FF and DI
components, there are some other contribution in the yield of fragments B and/or Be
in all systems which are seen as sharps peaks in Fig. 4.1. These peaks are due to one
nucleon transfer for B ($C + Si$, $C + Al$) and Be ($B + Si$). In case of B fragment emitted
in the reaction $B + Si$, sharp peaks are due to elastic and inelastic scattering. But all these peaks are excluded in extraction of FF and DI component by proper fitting of the corresponding Gaussians.

### 4.1 Study of fusion-fission fragments

#### 4.1.1 Angular distribution

The angular distribution of differential cross section, $\left(\frac{d\sigma}{d\Omega}\right)_{lab}$ (in laboratory frame), of the fragments of FF origin has been obtained by integrating the area under the corresponding Gaussian ($1^{st}$) extracted from energy spectrum at each angle. The obtained

![Figure 4.3](image)

**Figure 4.3:** The c.m. angular distributions of the fragments Li (a), Be (b) and B (c). Solid circles (red), triangles (blue) and inverted triangles (black) correspond to the experimental data for the reactions $^{11}B + ^{28}Si$, $^{12}C + ^{27}Al$ and $^{12}C + ^{28}Si$, respectively. Solid curves are fit to the data with the function $f(\theta_{c.m.}) \propto \frac{1}{\sin\theta_{c.m.}}$. 

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value of \( \frac{d\sigma}{d\Omega} \) has been converted to c.m. frame by using Eq. 2.11, assuming two-body kinematics averaged over total kinetic energy distribution and the corresponding angle, \( \theta_{\text{lab}} \) in laboratory frame, has been transformed by using Eq. 2.13. The c.m. angular distributions \( d\sigma/d\Omega_{FF} \) so obtained for the fragments (Li, Be and B) have been shown in Fig. 4.3 for all three reactions. Each experimental angular distribution data has been fitted with a function \( f(\theta_{c.m.}) = C/sin\theta_{c.m.} \), where \( C \) is constant parameter and the fitted curve is shown by solid lines. It is evident from the figure that the angular distributions of all FF fragments follow \( \sim 1/sin\theta_{c.m.} \) dependence which is characteristic of the fission-like decay of an equilibrated composite system. It is also observed from the figure that the yields of Li and Be are almost same at all angles for \(^{11}\text{B} + ^{28}\text{Si} \) and \(^{12}\text{C} + ^{27}\text{Al} \) reactions. It has further been found that the yield of the fragment Boron in \(^{11}\text{B} + ^{28}\text{Si} \) reaction is more than the same in \(^{12}\text{C} + ^{27}\text{Al} \) reaction. It has also been observed that the fragment angular yields for the reactions \(^{11}\text{B} + ^{28}\text{Si} \) and \(^{12}\text{C} + ^{27}\text{Al} \) are a little higher (though nearly comparable in magnitude) than those obtained in \(^{12}\text{C} + ^{28}\text{Si} \) reaction at the same excitation energy.

**Figure 4.4:** Average \( Q \)-values of the FF fragments Li, Be and B represented by inverted green triangle, pink triangle and blue circle, respectively for reactions (a) \( \text{B} + \text{Si} \), (b) \( \text{C} + \text{Al} \) and (c) \( \text{C} + \text{Si} \).
4.1.2 Angular distribution of $Q$-value

In the present study of fragment emission, it has been observed that $\langle Q \rangle$ are nearly constant for all the FF fragments emitted from $^{11}\text{B} + ^{28}\text{Si}$, $^{12}\text{C} + ^{27}\text{Al}$ and $^{12}\text{C} + ^{28}\text{Si}$ as shown in Fig. 4.4. The independence of $\langle Q \rangle$ with respect of emission angles suggest that, the fragments are emitted from a completely energy equilibrated system at all beam energies.

4.1.3 Total fragment yield

The total yields of the FF fragments have been shown in Fig. 4.5. These total FF fragment yield has been obtained by integrating the angular distribution, $d\sigma/d\Omega_{FF} = C/\sin\theta_{c.m.}$, over the whole angular range. The yields of the fragments Li and Be in $^{11}\text{B} + ^{28}\text{Si}$ and $^{12}\text{C} + ^{27}\text{Al}$ reactions are found to be nearly the same which confirms their compound nuclear origin. It has also been observed that the yields of these

![Figure 4.5](image_url)

*Figure 4.5: The total FF fragment cross sections (c.m.) for the three reactions. The solid circles (red), triangles (blue), and inverted triangles (black) correspond to the experimental data for $^{11}\text{B} + ^{28}\text{Si}$, $^{12}\text{C} + ^{27}\text{Al}$, and $^{12}\text{C} + ^{28}\text{Si}$ reactions, respectively. The solid (red), dashed (blue) and dotted (black) lines are the corresponding theoretical predictions.*
fragments are comparable to those obtained in $^{12}$C + $^{28}$Si reaction. The yield of B in the reaction $^{11}$B + $^{28}$Si has been found to be slightly more than that obtained in the other two reactions, which might be due to the contamination from the beam-like channels in the former case, where B was the projectile. The experimental FF fragment yields have been compared with the theoretical estimates of the same obtained from the extended Hauser-Feshbach model (EHFM) [18]. The values of the critical angular momenta have been obtained from the experimental fusion cross section data, wherever available [117, 118]; otherwise, they have been obtained from the dynamical trajectory model calculations with realistic nucleus-nucleus interaction and the dissipative forces generated self-consistently through stochastic nucleon exchanges [98]. The values of the critical angular momentum, $\ell_{cr}$, for all the three systems, have been the same (27ℏ). The calculated fragment emission cross sections have been shown in Fig. 4.5. It is seen from the figure that in all three cases, the theoretical predictions are nearly the same and are in fair agreement with the experimental results.

4.2 Study of DI fragments

4.2.1 Angular distribution

The angular distribution of DI component of the fragment-yield has been obtained by integrating the respective Gaussian ($2^{nd}$) extracted from the energy distribution. The obtained angular distributions ($d\sigma/d\Omega_{ab}$) have been converted to c.m. frame, $d\sigma/d\Omega_{DI}$, using the same procedure discussed in Sec. 4.1.1 and have been displayed in Fig. 4.6. It is observed that $d\sigma/d\Omega_{DI}$ forward peaked and falls off with $\theta_{c.m.}$ much faster than $\sim 1/\sin \theta_{c.m.}$ distribution. This is an indication of the non-equilibrium nature of the emission. To reproduce the angular distribution of the fragments originating from DI, several models are available in the literature. For example, it can be explained, classically, in terms of the evolution of a viscous or rigidly rotating dinuclear system [119, 24, 25, 26] as discussed in Sec. 1.2.1.3 and the angular distribution can
be expressed by Eq. 1.22. When $\tau \gg 2\pi/\omega$ (dinucleus rotation period), the angular distribution takes the form

$$(d\sigma/d\Omega)_{c.m.} = C/\sin\theta_{c.m.}$$

(4.1)

which is expected in case of fusion as seen in Sec. 4.1.1. So, angular distribution of DI fragments falls (Eq. 1.22) faster than the same of FF fragments. This faster fall indicates shorter lifetime of the composite system. Such a shorter lifetime (less than the time period of dinuclear rotation) is not sufficient for the formation of an equilibrated compound nucleus, but may still cause significant energy damping within
Table 4.1: Emission time scale of different DI fragments for all three reactions.

<table>
<thead>
<tr>
<th>System</th>
<th>Frag.</th>
<th>C</th>
<th>$\omega \tau_{\text{DI}}^{c_r}$</th>
<th>$\tau_{\text{DI}}^{c_r} \times 10^{-22}$ s</th>
<th>Err.</th>
</tr>
</thead>
<tbody>
<tr>
<td>C + Si</td>
<td>Li</td>
<td>0.49</td>
<td>1.05</td>
<td>22.69</td>
<td>± 3.64</td>
</tr>
<tr>
<td></td>
<td>Be</td>
<td>0.76</td>
<td>0.41</td>
<td>8.94</td>
<td>± 0.70</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>5.17</td>
<td>0.25</td>
<td>5.34</td>
<td>± 2.25</td>
</tr>
<tr>
<td>C + Al</td>
<td>Li</td>
<td>1.22</td>
<td>0.92</td>
<td>20.14</td>
<td>± 2.94</td>
</tr>
<tr>
<td></td>
<td>Be</td>
<td>1.30</td>
<td>0.51</td>
<td>11.28</td>
<td>± 1.35</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>5.52</td>
<td>0.45</td>
<td>9.89</td>
<td>± 1.34</td>
</tr>
<tr>
<td>B + Si</td>
<td>Li</td>
<td>5.23</td>
<td>0.43</td>
<td>9.77</td>
<td>± 0.96</td>
</tr>
<tr>
<td></td>
<td>Be</td>
<td>2.07</td>
<td>0.36</td>
<td>8.17</td>
<td>± 1.15</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>16.32</td>
<td>0.27</td>
<td>6.14</td>
<td>± 0.39</td>
</tr>
</tbody>
</table>

the deep-inelastic collision mechanism. In Fig. 4.6, the solid lines represent the fit to the experimental data using Eq. 1.22 \([d\sigma/d\Omega]_{c.m.} = (C/sin\theta_{c.m.})e^{-\theta_{c.m.}/\omega}\). From this fitting, the lifetime of the intermediate dinuclear complex has been estimated. The time scales for different DI fragments (Li, Be and B) thus obtained (for angular momentum $\ell = \ell_{cr}$) have been compared in Fig. 4.7 and also in Table 4.1. It is seen that, in all reactions, the time scale decreases as the fragment charge increases, which agrees with a previous study by Mikumo et al. [25]. This is expected because the heavier fragments (nearer to the projectile) require less nucleon exchange and therefore less time; on the other hand, the emission of lighter fragments requires more nucleon exchange and therefore longer times. The emission time scales of the fragments are related to the number of nucleons exchanged on the average. This explains why the emission time scales of $^{12}\text{C} + ^{27}\text{Al}$ and $^{12}\text{C} + ^{28}\text{Si}$ reactions are nearly the same for all fragments. On the other hand, in the case of $^{11}\text{B} + ^{28}\text{Si}$ reaction, net nucleon exchange is one less to reach any particular fragment; so the corresponding time scales are less. For example, in terms of net nucleon exchange, the emission time scale of Li (Be) from $^{11}\text{B} + ^{28}\text{Si}$ should be comparable to that of Be (B) from $^{12}\text{C} + ^{27}\text{Al}$ and $^{12}\text{C} + ^{28}\text{Si}$ reactions, which is actually the case (Fig. 4.7).
4.2.2 Average Q-value

The average Q-values ($< Q_{DI} >$) of the DI fragments, estimated from the corresponding fragment kinetic energies assuming two-body kinematics, have been displayed in Fig. 4.8 as a function of the c.m. angle. It is found that, for all fragments, the $< Q_{DI} >$ values tend to decrease with the increase of angle for $\theta_{c.m.} \lesssim 40^\circ$, and then gradually become nearly constant. It implies that, up to $\theta_{c.m.} \lesssim 40^\circ$, kinetic energy dissipation is incomplete, whereas beyond this point, the kinetic energy is fully damped and dynamic equilibrium has been established before the scission of the di-nuclear composite takes place.

4.2.3 Total fragment yield

The experimental angle integrated yields of the DI fragments for all the reactions are shown in Fig. 4.9. The total DI yields have been obtained by integrating fitted Eq. 1.22 over the full range of angles. It is found that the DI yields of all fragments emitted in $B + Si$ reaction are slightly higher than those obtained in $C + Al$ and $C + Si$ reactions. This may be due to the variation of the probability of net nucleon exchange.
Figure 4.8: The average $Q$-values, $<Q_{DI}>$, plotted as function of $\theta_{c.m.}$ for Li (green inverted triangle), Be (pink triangle), and B (blue solid circle) emitted in (a) $^{11}B + ^{28}Si$, (b) $^{12}C + ^{27}Al$, and (c) $^{12}C + ^{28}Si$ reactions. Solid lines are plotted to guide the eye.

Figure 4.9: Total DI cross sections of the fragments obtained in three different reactions.

In addition, the DI fragment yield in C + Si reaction tends to be lower than that for C + Al reaction.