CHAPTER-3

RESULTS AND DISCUSSION

3.0 RESULTS AND DISCUSSION

This chapter is devoted to the results of calculations of fusion excitation functions of various projectile-target combinations around near barrier energies and their interpretation. The comparison of calculated results with the corresponding experimental data and the conclusions drawn on the basis of this comparison are also discussed in detail. As mentioned earlier we have performed calculations by using quantum diffusion model and proximity potential. This chapter is divided into four sections. In first section, calculations of fusion excitation functions of systems involving projectiles with one neutron halo structure that is $^{11}\text{Be} + ^{209}\text{Bi}$ and $^{15}\text{C} + ^{232}\text{Th}$, and that involving projectile with one proton halo structure that is $^{8}\text{B} + ^{58}\text{Ni}$ as well as system involving stable weakly bound projectile $^{9}\text{Be} + ^{89}\text{Y}$ are discussed. The second section deals with the interplay of deformation and neutron transfer effects in fusion reactions induced by $^6\text{He}$ and $^{11}\text{Li}$, two neutrons halo nuclei, on various targets. As the effects arising because of the breakup of weakly bound nuclei strongly influence all the reactions induced by these nuclei, in section 3 we have presented the results of our study regarding the effects of breakup on fusion cross section of reactions induced by $^6\text{Li}$ and $^6\text{He}$ projectiles. In fourth section, breakup following neutron transfer effects are discussed in fusion reactions involving stable weakly bound nucleus $^{9}\text{Be}$ as projectile on various targets.

3.1 FUSION EXCITATION FUNCTION

The nuclei $^{11}\text{Be}$ and $^{15}\text{C}$ being representatives of well-established one neutron halo system has attracted a significant attention since from the beginning of the era of Radioactive Ion Beam facilities [1]. The fusion of these nuclei with heavy targets offers a very good opportunity to study the peculiar behavior of fusion reactions involving weakly bound nuclei, so in the present work we have studied the fusion of $^{11}\text{Be} + ^{208}\text{Bi}$ and $^{15}\text{C} + ^{232}\text{Th}$ systems at near barrier energy region within the framework of quantum diffusion approach [2-13]. In this approach, cross section mainly depends upon capture
probability, $P_{\text{cap}}$, which in turn depends upon various fixed and system dependent parameters. The value of renormalized frequency, $\omega_0$, is obtained by using

$$\omega_0^2 = \omega^2 \left[ 1 - \hbar \lambda \frac{\gamma}{\mu(s_1 + \gamma)(s_2 + \gamma)} \right]$$

with $\tilde{\lambda} = 2 \mu \omega \lambda / \hbar$ and $\hbar \omega$ as the barrier curvature for a given projectile-target combination. The friction coefficient ($\hbar \lambda$) and the internal excitation width ($\hbar \gamma$) are kept fixed at 2 MeV and 15 MeV, respectively throughout the calculations.

For the calculation of capture probability and hence the capture cross section, the parameter $R_0$ is very crucial and strongly depends on the separation of the region of pure Coulomb interaction and that of Coulomb nuclear interference. We here propose a very simple expression for its determination which takes into account the spatial extension of the nucleus through $R_{\text{int}}$. If the value of $r_{\text{ex}}$, the position of external turning point, is larger than the interaction radius $R_{\text{int}}$, we take $R_0 = R_{\text{int}} \left( \exp \left( - \frac{(E_{\text{c.m.}} - E_{\text{int}})/V_0}{r_{\text{ex}}/V_0} \right) \right)$ and $P_0 = 0$ while for $r_{\text{ex}} < R_{\text{int}}$ we take $R_0 = R_{\text{int}}$ and $P_0$ is equal to the kinetic energy at that point. The quantity $E_{\text{int}}$ corresponds to the incident energy for which the $r_{\text{ex}}$ and $R_{\text{int}}$ coincides.

It is quite intuitive that the quantity $R_0$ strongly depends on the incident energy. In Figs. 3.1.1 and 3.1.2, the variation of $R_0$ with the incident beam energy in the centre of mass system is shown for $^{11}\text{Be} + ^{209}\text{Bi}$ and $^{15}\text{C} + ^{232}\text{Th}$ systems respectively. The $R_0$ decreases with the increasing energy as the two nuclei come more and more close to each other at high energies. The interaction radius $R_{\text{int}}$ is considered here as the upper limit for the value of relative separation at $t=0$. Since for events with $R_0$ larger than $R_{\text{int}}$ the two nuclei do not interact with each other and hence fusion does not occur.

Using this energy variation of $R_0$, we have calculated the fusion excitation functions of $^{11}\text{Be} + ^{209}\text{Bi}$ and $^{15}\text{C} + ^{232}\text{Th}$ systems in the near barrier energy region. In Figs. 3.1.3 and 3.1.4, the calculated results are compared with the corresponding data taken from Ref. [14] for $^{11}\text{Be} + ^{209}\text{Bi}$ and from Ref. [15] for $^{15}\text{C} + ^{232}\text{Th}$ system. Further, the fusion excitation functions of $^{11}\text{Be} + ^{209}\text{Bi}$ and $^{15}\text{C} + ^{232}\text{Th}$ systems are also compared with the neighboring systems that is $^{10}\text{Be} + ^{209}\text{Bi}$ and $^{12}\text{C} + ^{232}\text{Th}$ systems, respectively.
Fig. 3.1.1 Variation of average separation at $t = 0$ ($R_0$) between the colliding nuclei $^{11}\text{Be}$ and $^{209}\text{Bi}$ is shown as a function of incident beam energy $E_{\text{c.m.}}$ in centre of mass system.
Fig. 3.1.2  Same as Fig. 3.1.1 but for $^{15}$C + $^{232}$Th system.
Fig. 3.1.3 The fusion excitation function of $^{11}\text{Be} + ^{209}\text{Bi}$ system (solid line) is compared with the experimental data (solid square) taken from Ref. [14] as well as with the fusion excitation function of $^{10}\text{Be} + ^{209}\text{Bi}$ (dotted line).
Fig. 3.1.4 Same as Fig. 3.1.3 but for $^{15}$C + $^{232}$Th and $^{12}$C + $^{232}$Th system. Experimental data (solid square) are taken from Ref. [15].
In both the cases, there is a small enhancement in fusion cross-section for weakly-bound nuclei in comparison to their stable counterpart. This enhancement may be attributed to the static effects arising because of large spatial extension of halo nuclei.

As far as the comparison with the experimental data is concerned, it may be clearly observed from these figures that in the deep sub-barrier energy region the predictions of quantum diffusion approach overestimate the measured fusion cross-section, while in the above barrier energy region the data are slightly underestimated. The energy variation of fusion cross-section in quantum diffusion approach is primarily governed through the energy variation of various parameters appearing in the formulation. Here \( R_0 \) varies exponentially with the energy and hence dominates over other energy dependent parameters. As energy increases, \( R_0 \) decreases and hence the argument of the complimentary error function also decreases, which in turn results in larger value of capture probability. Although in the deep sub-barrier energy region \( R_0 \) grows, but because of dominance of channel coupling effects in this region there is a substantial enhancement in the calculated fusion cross-section with respect to the experimental data. These results that is enhancement in the sub-barrier region and suppression at the above-barrier region are in accordance with the results obtained through dynamical polarization potential approach [16]. The below barrier enhancement is ascribed to coupling of various channels to elastic channels which is taken into account in the present approach through the fluctuation and dissipation.

Since, the proton halo structure due to the presence of Coulomb interaction between the valance proton and the remaining core is more complex than its neutron counterpart it is quite tempting to investigate the static and dynamic effects on the fusion of proton halo nuclei. In Fig. 3.1.5, variation of \( R_0 \) with \( E_{\text{c.m.}} \) is shown, which clearly displays that \( R_0 \) decreases with energy.

The comparison of calculated fusion excitation function with the experimental data taken from Ref. [17] is shown in Fig. 3.1.6. The results of calculations made by using Wong formula with 20.8 MeV, 9.2 fm and 4.0 MeV as barrier height, radius and curvature respectively are also included in this figure [18].
Fig. 3.1.5 Same as Fig. 3.1.1 but for $^8\text{B} + ^{58}\text{Ni}$ system.
Fig. 3.1.6 Comparison of the fusion excitation function of $^8\text{B} + ^{58}\text{Ni}$ system with the experimental data taken from Ref. [17] and with Wong Model.
It may be clearly observed from this figure that in the sub barrier energy region, the predictions of quantum diffusion approach overestimate the measured fusion cross section while that of Wong formula underestimate it. In the above barrier energy region the data and the result of quantum diffusion approach and of Wong formula are almost similar since at energies higher than the barrier energy the channel coupling effects are negligibly small. However slight overestimation of data points by quantum diffusion approach may be removed by using more realistic model parameters. In order to understand the discrepancy between data and predictions of quantum diffusion approach in the sub barrier region, the effects of halo structure and of high probability of breakup of $^7$Be into $\alpha + t$ with $S_\alpha = 1.587$ MeV, produced after one proton transfer from $^8$B to target at sub barrier energies on various parameters involved in the approach are needed to be properly incorporated.

Further, we have analyzed the complete fusion excitation function data of $^9$Be + $^{89}$Y system in near barrier energy region by quantum diffusion approach. Here the choice of target nucleus $^{89}$Y, which is a neutron magic nucleus is important because fusion of $^{89}$Y with $^9$Be forms the compound nucleus (CN) $^{98}$Tc and this isotope of technetium has great importance in industrial and medical applications. Because of simplicity and wider acceptability for fusion process, we have adopted here the proximity potential to calculate the nuclear interaction between the two nuclei [19-24]. All the input parameters have been taken as prescribed earlier in this section. The barrier height and position have been calculated by using proximity potential which comes out to be 22.10MeV and 9.35fm respectively. The parameter $R_0$ with respect to energy of centre of mass is plotted in Fig. 3.1.7. The comparison of the calculated complete fusion excitation function for $^9$Be + $^{89}$Y system in the near barrier energy region with the corresponding experimental complete fusion data taken from Ref. [25] is shown in Fig. 3.1.8. It is found that at sub barrier energies the data are underestimated at sub barrier energies while at above barrier energies the data are overestimated by the calculations. The discrepancy between the theoretical predictions and data at sub barrier energies may be due to various dynamical effects like coupling to continuum, coupling to neutron transfer channel etc. which are not accounted here.
Fig. 3.1.7 Same as Fig. 3.1.1 but for $^9$Be + $^{89}$Y system.
Fig. 3.1.8 Comparison of the complete fusion excitation function of $^{9}$Be + $^{89}$Y system with the experimental complete fusion data taken from Ref. [25].
The overestimation of data at above barrier energies may be ascribed to significant contribution of ICF channel since in this energy region a significant flux is lost in incomplete fusion channel.

3.2 INTERPLAY OF DEFORMATION AND NEUTRON TRANSFER EFFECTS

In the present work we have studied the fusion of \( ^6\text{He} + ^{64}\text{Zn} \), \( ^6\text{He} + ^{68}\text{Zn} \), \( ^6\text{He} + ^{206}\text{Pb} \), \( ^6\text{He} + ^{209}\text{Bi} \) and \( ^6\text{He} + ^{238}\text{U} \) systems at near barrier energy region within the framework of quantum diffusion approach with a special emphasis on the interplay of the effects of deformation and neutron transfer process. Various system dependent parameters needed in the calculations are listed in Table 3.2.1.

In Fig. 3.2.1, the fusion excitation function of \( ^6\text{He} + ^{64}\text{Zn} \) system is compared with the corresponding data taken from Ref. [26]. In order to investigate the effects of two neutrons transfer, with positive \( Q_{2n} \) value, from \( ^6\text{He} \) to \( ^{64}\text{Zn} \) it is assumed that the neutrons transfer occurs before the capture leading to the fusion of \( ^4\text{He} + ^{66}\text{Zn} \) system. The nucleus \( ^4\text{He} \), being a doubly magic nucleus, is spherical in shape with \( \beta_2 = 0.0 \) and here \( ^6\text{He} \) is also considered to be a spherical nucleus. After two neutrons transfer the mass numbers and deformations of the target change from 64 to 66 and \( \beta_2 = 0.219 \) to \( \beta_2 = -0.215 \) respectively which in turn affect the height and shape of Coulomb barrier and hence the fusion cross section. It may be noticed quite clearly from Fig. 3.2.1 that there is suppression in fusion cross section in the vicinity of Coulomb barrier when the neutrons transfer is taken into account. As a result the data point lying in the sub barrier energy region is now well reproduced by the calculations. The suppression may be ascribed to the change in shape of target nucleus from prolate to oblate which results in raising the barrier. The explanation is quite straightforward and is based on the fact that the Coulomb field on the tips of deformed nucleus is lower than on its sides. However the inverse effects that is enhancement of fusion cross section are found for \( ^6\text{He} + ^{68}\text{Zn} \) system in which the target nucleus changes from oblate (\( \beta_2 = -0.156 \)) to prolate (\( \beta_2 = 0.045 \)) shape after the neutrons transfer [See Fig. 3.2.2]. Such a change in shape leads to the lowering of barrier and hence the enhancements in the fusion cross section.
Table 3.2.1 The values of barrier height ($V_b$), barrier position ($R_b$), mass asymmetry ($\eta$), the parameter ($s_1$) and the renormalized frequency ($\omega_0$) for different projectile-target combinations considered in the present work.

<table>
<thead>
<tr>
<th>Projectile + Target</th>
<th>Before Neutron transfer</th>
<th>After neutron transfer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$V_b$</td>
<td>$R_b$</td>
</tr>
<tr>
<td>$^{6}$He$^{+64}$Zn</td>
<td>8.222</td>
<td>9.7</td>
</tr>
<tr>
<td>$^{6}$He$^{+68}$Zn</td>
<td>8.411</td>
<td>9.46</td>
</tr>
<tr>
<td>$^{6}$He$^{+206}$Pb</td>
<td>20.687</td>
<td>12.01</td>
</tr>
<tr>
<td>$^{6}$He$^{+209}$Bi</td>
<td>19.818</td>
<td>11.26</td>
</tr>
<tr>
<td>$^{6}$He$^{+238}$U</td>
<td>21.432</td>
<td>11.56</td>
</tr>
<tr>
<td>$^{11}$Li$^{+208}$Pb</td>
<td>27.591</td>
<td>12.07</td>
</tr>
</tbody>
</table>
Fig. 3.2.1 The fusion excitation function of $^6\text{He} + ^{64}\text{Zn}$ system calculated by using quantum diffusion approach without neutron transfer (solid line) and with neutron transfer (dotted line) are compared with the experimental data (solid square) taken from Ref. [26].
Fig. 3.2.2 Same as Fig. 3.2.1, but for $^6$He + $^{68}$Zn system.
Fig. 3.2.3 Same as Fig. 3.2.1 but for $^6$He + $^{206}$Pb system. The experimental data (solid square) are taken from Ref. [27].
Next we have considered $^6\text{He} + ^{206}\text{Pb}$ fusion reaction for which all the measured data points lie in the sub barrier region. In this case, the calculations made without considering the role of neutrons transfer substantially overestimate the data as shown in Fig. 3.2.3. On the other hand when neutrons transfer effects are taken into consideration the matching between the data and prediction improves to a great extent which indicates that the neutron transfer process plays an important role in the description of sub barrier fusion cross section. The sub barrier fusion suppression may be attributed to the fact that after the 2n transfer, $^6\text{He} + ^{206}\text{Pb} (\beta_2 = -0.008) \rightarrow ^4\text{He} + ^{208}\text{Pb} (\beta_2 = 0.0)$, the slightly oblate target nucleus $^{206}\text{Pb}$ changes into doubly magic spherical nucleus $^{208}\text{Pb}$. As a consequence of this decrease in the value of deformation parameter, the Coulomb barrier height increases and hence the capture probability decreases which eventually results in a decrease in fusion cross section after two neutrons transfer.

Further we have also considered $^6\text{He} + ^{209}\text{Bi} (\beta_2 = -0.008) \rightarrow ^4\text{He} + ^{211}\text{Bi} (\beta_2 = -0.018)$ and $^6\text{He} + ^{238}\text{U} (\beta_2 = 0.215) \rightarrow ^4\text{He} + ^{240}\text{U} (\beta_2 = 0.224)$ systems for which the change in absolute value of deformation parameter is almost same and there is no change in shape after two neutrons transfer. For these cases it was found that there is an enhancement in the sub barrier cross section when neutron transfer effects are considered [See Figs. 3.2.4 and 3.2.5]. For the former reaction the data points lying slightly above the barrier are explained very well by taking the two neutrons transfer into account. For the later reaction the data measured at well below and well above the barrier are reasonably reproduced but there is a large discrepancy between the data and predictions in the vicinity of barrier. Since there is no noticeable change in the deformation and shape, the 2n transfer reactions with positive $Q_{2n}$ value are of particular interest for these reactions induced by neutron halo nucleus $^6\text{He}$. The neutrons being insensitive to the Coulomb barrier may be transferred at a large separation much before the fusion. Intuitively the neutron transfer tends to lower the barrier and hence enhance the fusion cross section. However in general after 2n transfer and before fusion, there occurs change in deformation and mass asymmetry of participating nuclei, which may result in either enhancement or suppression of sub barrier fusion cross section.
Fig. 3.2.4 Same as Fig. 3.2.1, but for $^6$He + $^{209}$Bi system. The experimental data (solid square) are taken from Ref. [28].
Fig. 3.2.5 Same as Fig. 3.2.1 but for $^6\text{He} + ^{238}\text{U}$ system. The experimental data (solid square) are taken from Ref. [29].
Fig. 3.2.6 Same as Fig. 3.2.1 but for $^{11}$Li + $^{208}$Pb system. The experimental data (solid square) are taken from Ref. [30].
It is the overall effect of all these factors which is responsible for sub barrier fusion enhancement or suppression. For $^6\text{He} + ^{209}\text{Bi}$ and $^6\text{He} + ^{238}\text{U}$ reactions, the enhancement is attributed predominantly to the neutron transfer channel as the influence of factors related to shape is negligibly small.

In Fig. 3.2.6, the fusion excitation function of $^{11}\text{Li} + ^{208}\text{Pb}$ system is compared with the corresponding data taken from Ref. [30]. The nucleus $^{208}\text{Pb}$, being a doubly magic nucleus, is spherical in shape with $\beta_2=0.0$ and here $^{210}\text{Pb}$ is also considered to be a spherical nucleus. After two neutrons transfer the mass numbers and deformations of the projectile change from 11 to 9 and $\beta_2=0.58$ to $\beta_2=0.805$ respectively which in turn affect the height and shape of Coulomb barrier and hence the fusion cross section. As the deformation increases, barrier height decreases and hence the fusion cross section increases after neutron transfer. It may be noticed quite clearly from Fig. 3.2.6 that there is enhancement in fusion cross section in the vicinity of Coulomb barrier when the neutrons transfer is taken into account. There is a reasonably good agreement between the data and predictions in the deep sub barrier energy region as well as at energies above the barrier. The agreement at sub barrier region shows that neutron transfer process plays a major role in sub barrier energy region. However, the calculations at energy around 32MeV considerably over predict the data which needs further investigations.

### 3.3 Influence of Breakup of Projectile on Fusion Cross Section

The present theoretical understanding concerning the effect of breakup on the fusion cross section is controversial [31-35]. Some studies [34] predict the fusion cross section enhancement, when compared with the fusion induced by strongly bound nuclei, due to the additional breakup channel. This enhancement is of particular importance at sub-barrier energies, where the coupling effects on the fusion are strong. On the opposite side, some models [31-33] suggest the hindrance of the complete fusion, due to the loss of incident flux in breakup channel. Hagino et al. [35] have predicted fusion cross section enhancement at sub-barrier energies and fusion hindrance at above barrier energies, both effects originating from the breakup process. Thus in the present work we have studied
the fusion reactions induced by $^6$He and $^6$Li projectiles with mass number $A=6$ on various targets in near barrier energy region with a special emphasis on the role of breakup in fusion enhancement or suppression. The effects arising because of the breakup of projectile into constituent fragments are included through the incorporation of survival probability of projectile against breakup in theoretical formalism as described in chapter 2.

The fusion excitation functions of reactions induced by light neutron-rich projectiles, $^6$He and $^6$Li on $^{209}$Bi and $^{64}$Zn targets are calculated in near barrier energy region using the model described in previous chapter. The values of various parameters needed in the calculations are listed in Table 3.3.1 for the projectile-target combinations considered here. The barrier height and the barrier position given in column 2 and 3 respectively are determined by plotting proximity potential as a function of projectile-target relative separation while the barrier curvature values are taken from Refs. [40-41]. The values of barrier curvature, $\hbar \omega$ for a given projectile-target combination are used to determine the value of renormalized frequency $\omega_0$ by employing

$$\omega_0^2 = \omega^2 \left[ 1 - \hbar \tilde{\lambda} \gamma / [ \mu (s_1 + \gamma) (s_2 + \gamma) ] \right]$$

with $\tilde{\lambda} = 2 \mu \alpha \lambda / \hbar$. The friction coefficient ($\hbar \lambda$) and the internal excitation width ($\hbar \gamma$) are kept fixed at 2MeV and 15MeV, respectively throughout the calculations. When the effect of breakup of projectile is taken into account two additional parameters $\alpha$ and $A$ are also needed. As mentioned earlier these parameters are determined to reproduce the measured/ calculated through CDCC values of the projectile breakup probability at two different energies in near barrier energy region. The values of these parameters along with the values of breakup probability used in their determination are given in Table 3.3.2. Besides these, the values of $R_0$, which is very crucial and strongly depends on the separation of the region of pure Coulomb interaction and that of Coulomb nuclear interference, and $P_0$ are determined through the procedure as described in earlier section.
Table 3.3.1 The values of barrier height ($V_b$), barrier position ($R_b$), the parameter ($s_1$) and the renormalized frequency ($\omega_0$) for different projectile–target combinations.

<table>
<thead>
<tr>
<th>Projectile + Target</th>
<th>$V_b$(MeV)</th>
<th>$R_b$(fm)</th>
<th>$\hbar s_1$(MeV)</th>
<th>$\hbar \omega_0$(MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^6\text{He} + ^{209}\text{Bi}$</td>
<td>19.82</td>
<td>11.26</td>
<td>2.59</td>
<td>3.32</td>
</tr>
<tr>
<td>$^6\text{He} + ^{64}\text{Zn}$</td>
<td>8.22</td>
<td>9.70</td>
<td>5.60</td>
<td>6.89</td>
</tr>
<tr>
<td>$^6\text{Li} + ^{209}\text{Bi}$</td>
<td>32.14</td>
<td>11.24</td>
<td>2.56</td>
<td>3.24</td>
</tr>
<tr>
<td>$^6\text{Li} + ^{64}\text{Zn}$</td>
<td>17.21</td>
<td>10.13</td>
<td>5.59</td>
<td>6.87</td>
</tr>
</tbody>
</table>

Table 3.3.2 The values of breakup probability at two different centre of mass energies in MeV ($P_{bu}(E_{c.m.})$), the parameter ($A$) and the parameter ($\alpha$) for different projectile – target combinations.

<table>
<thead>
<tr>
<th>Projectile + Target</th>
<th>$P_{bu}(E_{c.m.})$</th>
<th>$P_{bu}(E_{c.m.})$</th>
<th>$A$</th>
<th>$\alpha$(fm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^6\text{He} + ^{209}\text{Bi}$</td>
<td>$5.42 \times 10^{-4}$ (18.51)</td>
<td>$2.91 \times 10^{-4}$ (21.11) [36]</td>
<td>$1.12 \times 10^3$</td>
<td>0.69</td>
</tr>
<tr>
<td>$^6\text{He} + ^{64}\text{Zn}$</td>
<td>$4.43 \times 10^{-2}$ (7.53)</td>
<td>$1.42 \times 10^{-2}$ (9.15) [37]</td>
<td>$1.01 \times 10^3$</td>
<td>0.61</td>
</tr>
<tr>
<td>$^6\text{Li} + ^{209}\text{Bi}$</td>
<td>$5.12 \times 10^{-3}$ (38.88)</td>
<td>$3.31 \times 10^{-3}$ (33.99) [38]</td>
<td>$1.10 \times 10^3$</td>
<td>0.68</td>
</tr>
<tr>
<td>$^6\text{Li} + ^{64}\text{Zn}$</td>
<td>$4.73 \times 10^{-3}$ (18.21)</td>
<td>$1.83 \times 10^{-3}$ (19.93) [39]</td>
<td>$0.57 \times 10^3$</td>
<td>0.88</td>
</tr>
</tbody>
</table>
In Fig. 3.3.1, the fusion excitation function of $^6\text{He} + ^{209}\text{Bi}$ system around barrier energy is compared with the corresponding data taken from Ref. [28]. The solid line is the result of calculations, which take the projectile breakup effect into account while the dashed line corresponds to the results of calculation without breakup effect. It is clearly observed in this figure that the breakup of projectile does not affect the fusion cross section in the energy region considered here. Although there is a very small decrease in the value of fusion cross section in the sub barrier energy region but that too is within the experimental uncertainty. In this case neither suppression nor enhancement arising due to breakup is found. The similar trend prevails for $^6\text{He} + ^{64}\text{Zn}$ system as shown in Fig. 3.3.2.

However for $^6\text{Li} + ^{209}\text{Bi}$ and $^6\text{Li} + ^{64}\text{Zn}$ fusion reactions, as a consequence of projectile breakup significant suppression of fusion cross section is found in below barrier energy region as is evident from Figs. 3.3.3 and 3.3.4. This fusion suppression may be ascribed to the loss of flux in breakup channel. It is very surprising that the breakup effects are more pronounced for reaction induced by $^6\text{Li}$, which has a larger breakup threshold (1.48 MeV) in comparison to that of $^6\text{He}$ (0.973 MeV). In fact, $^6\text{He}$ has a two neutrons Borromean structure wherein the neutron matter is much more extended in space. The wave function of the valance di neutron is very extended in $^6\text{He}$ as there is no Coulomb or centrifugal barrier to overcome. Owing to large spatial extension this neutron matter interacts with the target even when the separation of projectile is quite large from the target. As a result of this attractive interaction between neutrons and the target the potential barrier gets lowered and hence the fusion cross section increases. Further due to small two neutron separation energy the transfer of neutrons from $^6\text{He}$ to target before fusion is possible. Thus the neutrons transfer process also strongly affects the fusion cross section for reactions induced by $^6\text{He}$. The fusion enhancement or suppression, in case of reactions involving $^6\text{He}$ as projectile, is a cumulative effect of large spatial extension, of neutron transfer process and of breakup process. The former two effects dominate over the breakup effects, hence the influence of breakup on the fusion in this case is negligibly small. On the other hand, the nucleus $^6\text{Li}$ is dissociated into $\alpha + d$ fragments with a breakup threshold of 1.48 MeV. Since both the breakup fragments are charged, the barrier lowering does not occur.
Fig. 3.3.1 The fusion excitation function of $^6$He + $^{209}$Bi system calculated by using quantum diffusion approach without breakup effect (dashed line) and with breakup effect (solid line) are compared with the experimental data (solid square) taken from Ref. [28].
Fig. 3.3.2 Same as Fig. 3.3.1 but for $^6\text{He} + ^{64}\text{Zn}$ system. The experimental data (solid square) are taken from Ref. [26].
Fig. 3.3.3 Same as Fig. 3.3.1 but for $^6$Li + $^{209}$Bi system. The experimental data (solid square) are taken from Ref. [42].
Fig. 3.3.4 Same as Fig. 3.3.1 but for $^6\text{Li} + ^{64}\text{Zn}$ system. The experimental data (solid square) are taken from Ref. [39].
In addition in this case the neutron transfer reaction with positive Q value is forbidden. Consequently, in case of fusion induced by $^6$Li the dominant reaction channel which may affect the fusion process is the breakup channel and due to the flux lost in this channel the fusion cross section is suppressed.

### 3.4 Breakup Following Neutron Transfer Effects

We have investigated the role of most likely breakup channel via excited $^8$Be states, produced following the transfer of single neutron to target on fusion cross section of reactions induced by $^9$Be projectile. In particular, the fusion excitation functions of reactions induced by weakly bound nucleus $^9$Be on targets $^{64}$Zn, $^{144}$Sm, $^{186}$W, $^{208}$Pb and $^{209}$Bi are calculated in near barrier energy region. Since the breakup threshold for the process $^9$Be $\rightarrow$ $^8$Be + n is quite low (1.67MeV) and the $Q_{1n}$ values for the one neutron transfer reactions are positive it is plausible to assume that the valance neutron in $^9$Be detaches from the projectile and transfers to the target nucleus much earlier than the fusion. As a result of neutron transfer, deformation and isospin of projectile and the target change and hence barrier parameters. The values of various deformation dependent parameters are listed in Table 3.4.1 for the projectile-target combinations considered here and are obtained by employing the procedure already discussed.

Besides these, when the effect of breakup of $^8$Be into $\alpha + \alpha$ is taken into account two additional parameters $\alpha$ and $A$ are needed. The values of these parameters along with those of breakup probability used in their determination are given in Table 3.4.2.

In order to investigate the role of breakup following neutron transfer in the fusion induced by highly deformed projectile ($\beta_2 = 1$)$^9$Be, we have considered prompt breakup as a dominant process. This breakup mechanism occurs as $^9$Be $\rightarrow$ $^8$Be$^*$ + n and then $^8$Be$^*$ is immediately ($\sim 10^{-22}$sec) dissociated into two alpha particles i.e. $^8$Be$^*$ $\rightarrow$ $\alpha + \alpha$.

In Fig. 3.4.1 the fusion excitation function of $^9$Be+$^{64}$Zn fusion reaction is compared with the corresponding experimental fusion cross section data taken from Ref. [39]. The dotted line represents the result of calculation when neither neutron transfer nor breakup of $^8$Be into $\alpha + \alpha$ is taken into account, while the dashed line represents the
results of calculations when the single neutron transfer from $^9\text{Be}$ to the target is included. The solid curve represents the results obtained by considering breakup of $^8\text{Be}^*$ into two alphas following one neutron transfer from $^9\text{Be}$ to $^{64}\text{Zn}$ target. As a consequence of the dependence of deformation parameter of colliding nuclei on neutron number, there occurs change in deformations after neutron transfer. The change in deformation parameters, mass numbers and the isotopic composition leads to change in Coulomb barrier position and height which in turn affect the fusion cross section.

Table 3.4.1 The values of barrier height ($V_b$), barrier position ($R_b$), asymmetry parameter ($\eta$), the parameter ($s_1$) and the renormalized frequency ($\hbar\omega_0$) before and after neutron transfer for different projectile–target combinations.

<table>
<thead>
<tr>
<th>Projectile + Target</th>
<th>Before neutron transfer</th>
<th>After neutron transfer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$V_b$ (MeV) $R_b$ (fm) $\eta$ $\hbar s_1$ (MeV) $\hbar\omega_0$ (MeV)</td>
<td>$V_b$ (MeV) $R_b$ (fm) $\eta$ $\hbar s_1$ (MeV) $\hbar\omega_0$ (MeV)</td>
</tr>
<tr>
<td>$^9\text{Be} + ^{64}\text{Zn}$</td>
<td>18.63 10.45 0.753 5.52 6.83</td>
<td>18.97 10.37 0.780 5.64 6.97</td>
</tr>
<tr>
<td>$^9\text{Be} + ^{144}\text{Sm}$</td>
<td>31.56 10.62 0.882 4.23 4.41</td>
<td>31.11 10.48 8.895 4.34 4.52</td>
</tr>
<tr>
<td>$^9\text{Be} + ^{186}\text{W}$</td>
<td>38.94 10.92 0.907 3.44 3.72</td>
<td>38.68 10.79 0.917 3.57 3.84</td>
</tr>
<tr>
<td>$^9\text{Be} + ^{208}\text{Pb}$</td>
<td>41.62 11.22 0.917 2.56 2.97</td>
<td>41.20 11.09 0.926 2.64 3.09</td>
</tr>
<tr>
<td>$^9\text{Be} + ^{209}\text{Bi}$</td>
<td>42.37 11.43 0.917 2.42 2.81</td>
<td>41.89 11.51 0.926 2.54 2.96</td>
</tr>
</tbody>
</table>
Table 3.4.2 The values of breakup probability ($P_{bu}$) at two different centre of mass energies ($E_{c.m.}$) in MeV and the corresponding values of the parameter ($A$) and the parameter ($\alpha$) for different projectile – target combinations.

<table>
<thead>
<tr>
<th>Projectile + target</th>
<th>$E_{c.m.}$ (MeV)</th>
<th>$P_{bu}$</th>
<th>$A$</th>
<th>$\alpha$ (fm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^9$Be + $^{64}$Zn [39]</td>
<td>18.98</td>
<td>$3.8 \times 10^{-2}$</td>
<td>$0.62 \times 10^3$</td>
<td>0.890</td>
</tr>
<tr>
<td></td>
<td>19.99</td>
<td>$1.0 \times 10^{-2}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^9$Be + $^{144}$Sm [43]</td>
<td>25.88</td>
<td>$2.1 \times 10^{-2}$</td>
<td>$1.10 \times 10^3$</td>
<td>0.973</td>
</tr>
<tr>
<td></td>
<td>26.53</td>
<td>$2.0 \times 10^{-2}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^9$Be + $^{186}$W [43]</td>
<td>31.80</td>
<td>$5.8 \times 10^{-2}$</td>
<td>$1.22 \times 10^3$</td>
<td>0.912</td>
</tr>
<tr>
<td></td>
<td>32.29</td>
<td>$5.1 \times 10^{-2}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^9$Be + $^{208}$Pb [43]</td>
<td>34.72</td>
<td>$6.1 \times 10^{-2}$</td>
<td>$1.37 \times 10^3$</td>
<td>0.841</td>
</tr>
<tr>
<td></td>
<td>35.24</td>
<td>$5.9 \times 10^{-2}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^9$Be + $^{209}$Bi [54]</td>
<td>34.66</td>
<td>$6.2 \times 10^{-2}$</td>
<td>$1.39 \times 10^5$</td>
<td>0.763</td>
</tr>
<tr>
<td></td>
<td>35.41</td>
<td>$5.5 \times 10^{-2}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fig. 3.4.1 The fusion excitation functions of $^9$Be + $^{64}$Zn system calculated by using quantum diffusion approach without neutron transfer and breakup effect (dotted line), with neutron transfer effect (dashed line) and with breakup following neutron transfer (solid line) are compared with the experimental total fusion cross section data (open circle) taken from Ref. [39].
For $^9\text{Be} + ^{64}\text{Zn}$ system, after one neutron transfer deformation parameter of target nucleus changes from $\beta_2 = 0.219$ to $\beta_2 = -0.264$ while that of projectile remains unchanged. The shape of target nucleus changes from prolate to oblate and hence the barrier height increases which results in suppression of fusion cross section. The increase in barrier height leading to decrease in fusion cross section is ascribed to the fact that the Coulomb field is lower on the tips of a deformed nucleus in comparison to its side. The suppression of fusion cross section in near barrier energy is further amplified when the breakup following one neutron transfer is taken into account. It may be attributed to the flux lost in breakup channel. When both the breakup and one neutron transfer effects are taken into account the sub barrier fusion cross section data are found to be in excellent agreement with the prediction.

In case of $^9\text{Be} + ^{144}\text{Sm}$ system, after one neutron transfer from projectile to target the shape of target changes from spherical ($\beta_2 = 0.0$) to oblate ($\beta_2 = -0.035$). This shape change results in lowering the barrier and hence enhancement in the fusion cross section as shown in Fig. 3.4.2. In the near barrier energy region, the fusion enhancement is reduced when the breakup effects are included in the calculations. As a result, the complete as well as total fusion cross section data are well reproduced when both the transfer and breakup effects are considered. It is also important to mention here that the nearly equal values of experimental total and complete fusion cross section suggests the contribution of ICF is negligibly small in this case.

In Fig. 3.4.3 fusion excitation function of $^9\text{Be} + ^{208}\text{Pb}$ projectile-target combination is compared with the corresponding experimental data taken from Ref. [44]. After one neutron transfer from projectile to the target, the deformation parameter of the target changes from $\beta_2 = 0.0$ to $\beta_2 = -0.008$ leading to an enhancement in fusion cross section. The breakup effect however reduces this enhancement. It is clearly seen in Fig. 3.4.3 that at energies much higher than the barrier height, the complete fusion data are significantly over predicted by the theory but total fusion data are very well explained.
Fig. 3.4.2 Same as Fig. 3.4.1 but for $^9\text{Be} + ^{144}\text{Sm}$ system. The experimental total fusion cross section data (open circle) and complete fusion cross section data (solid square) are taken from Ref. [44].
Fig. 3.4.3 Same as Fig. 3.4.1 but for $^9$Be $+ ^{208}$Pb system. The experimental total fusion cross section (open circle) and complete fusion cross section data (solid square) are taken from Ref. [44].
It may be ascribed to the fact that within the framework of the model used here it is not possible to evaluate complete and incomplete fusion separately only total fusion cross section is evaluated. Further, the larger experimental values of total fusion cross section in comparison to complete fusion cross section at energies much higher than the barrier height indicates that in this energy region a significant flux is lost in incomplete fusion channel. However measurement of total fusion cross section at lower energies is highly desirable to investigate the role of ICF in this energy region.

For $^9\text{Be} + ^{186}\text{W}$ and $^9\text{Be} + ^{209}\text{Bi}$ systems, in spite of a negligible change in deformation parameters of target nuclei i.e. from 0.230 to 0.221 for $^{186}\text{W}$ to $^{187}\text{W}$ and -0.008 to -0.018 for $^{209}\text{Bi}$ to $^{210}\text{Bi}$ there is fusion enhancement after neutron transfer (Figs. 3.4.4 and 3.4.5). When the breakup effects are included this enhancement is decreased leading to an improved matching between measurements and calculations. In fact, the neutron transfer before fusion may cause either enhancement or suppression in fusion cross section. While because of flux lost in breakup channel it always leads to suppression of fusion. As a result of cumulative effects of these processes there may occur either overall enhancement or overall suppression in fusion cross sections for different projectile–target combinations.
Fig. 3.4.4 Same as Fig. 3.4.1 but for $^9$Be + $^{186}$W system. The experimental complete fusion cross section data (solid square) taken from Ref. [45].
Fig. 3.4.5 Same as Fig. 3.4.1 but for $^9$Be + $^{209}$Bi system. The experimental total fusion cross section data (open circle) and complete fusion cross section data (solid square) are taken from Refs. [14] and [46] respectively.
REFERENCES


