Chapter 3

Fusion Measurement of $^7\text{Li} + ^{28}\text{Si}$

In order to experimentally explore the fusion behaviour for $^7\text{Li} + ^{28}\text{Si}$, starting from the sub barrier region to well above (up to $\sim 3V_\pi$) the barrier, separate experiments using different techniques were performed. The fusion cross section of $^7\text{Li} + ^{28}\text{Si}$ at above barrier energies was measured by two different experimental techniques, viz., (i) characteristic $\gamma$-ray method and (ii) evaporation $\alpha$ method. However, the sub-barrier fusion was measured only by the characteristic $\gamma$-ray method. The range of bombarding energies was covered by doing separate experiments. The above barrier fusion measurement by characteristic $\gamma$-ray method was done at the BARC-TIFR Pelletron facility in Mumbai (INDIA). The above barrier fusion measurement by evaporation $\alpha$ method was carried out at the IUAC Pelletron facility in New-Delhi (INDIA). The fusion measurements at sub-barrier energies were done at the Pelletron facility of IOP, Bhubaneswar (INDIA). The details of the three experiments, the analysis of the data, the model calculation, results and discussion are elaborated in the following sections.
3.1 Above barrier fusion cross section for $^7\text{Li}+^{28}\text{Si}$

by characteristic $\gamma$-ray method

3.1.1 Experimental details

The total fusion excitation function of the system $^7\text{Li}+^{28}\text{Si}$ was measured using the characteristic $\gamma$-ray method. Experiment was carried out at the BARC-TIFR 14 UD Pelletron (Mumbai) with $^7\text{Li}$ (3$^+$) beam at energies $E_{lab}=11.5, 12.5, 14, 16, 18, 20, 22, 24$ and $26$ MeV. Beam intensity was of the order of 5–20 pnA. A small thin walled aluminium chamber (80 mm diameter) in the 30° S beam line was used to house the target. The chamber had a provision to put only one target at a time. The vacuum of the chamber was achieved to $\sim 10^{-6}$ torr. The target consisted of 192 $\mu g/cm^2$ natural silicon sandwiched between two thin gold layers (40 $\mu g/cm^2$ and 100 $\mu g/cm^2$) in order to prevent oxidation and was prepared using vacuum evaporation technique. Details of the procedure for preparation of targets are discussed in a later section. The characteristic $\gamma$-rays emitted from the evaporation residues were detected using a Compton suppressed Clover detector placed at 55° with respect to the beam direction. The active volume of the detector was $\sim 470$ cm$^3$. The distance of the Clover detector (front face of Ge crystal) from the target (chamber centre) was about $\sim 25$ cm. The number of incident beam particles were estimated from the charge accumulation in the Faraday cup consisting of a 30 cm long tube insulated from the chamber and connected with Current Integrator. A schematic diagram of the experimental setup is shown in Fig. 3.1. The energy calibration and efficiency of the detector was obtained with standard radioactive sources like $^{152}\text{Eu}$, $^{133}\text{Ba}$, $^{207}\text{Bi}$, $^{60}\text{Co}$. The absolute efficiency in the add-back mode of the detector was measured with $^{152}\text{Eu}$, $^{133}\text{Ba}$ standard radioactive calibrated sources placed exactly at the target position. Target thickness was measured by $\alpha$-energy loss method with a 3-line $\alpha$-source. Background runs were taken at each energy with and without
beam using a blank tantalum frame in place of the target. These data were used to subtract or correct for background \( \gamma \)-rays and also for \( \gamma \)-rays arising out of beam impingement (if any) on the slit, beam line etc. As the target consisted of natural silicon (92.23\%\(^{28}\)Si, 4.68\%\(^{29}\)Si, 3.1\%\(^{30}\)Si), we verified that the contributions of \(^{29}\)Si and \(^{30}\)Si in fusion of \(^{7}\)Li+\(^{28}\)Si was negligible from the yield of the \( \gamma \)-rays of the reaction \(^{7}\)Li+\(^{28}\)Si, \(^{30}\)Si.

### 3.1.2 Electronics circuit diagram

The block diagram for processing the pulse output from the various modules is shown in Fig. 3.2. The \( \gamma \)-rays are detected by a Clover detector (from Eurisys Mesures) which has the standard geometry [54]. It consists of four co-axial N type Germanium detectors, arranged like a four leaf clover. The detector is inserted in a BGO (from Crismatec) shield, serving as Compton suppressor for the reduction of background
due to Compton events.

Timing pulses taken from outputs of separate preamplifiers connected with the four crystals of the Clover detector were amplified with timing filter amplifiers TFA (ORTEC-474). The four output pulses are then fed to a constant fraction discriminator OCTAL CFD (ORTEC CF 8000), threshold of which were set above the noise level and gives output of a OR logic gate pulse. The logic pulse then goes to a gate and delay generator GDG (ORTEC GG 8010) which generates a output (A) with proper delay and width. Similarly the timing pulse of BGO was amplified and logic pulse (B) is generated using TFA (ORTEC-474) and CFD (CF 8000). Anticoincidence between the Clover and BGO detectors is achieved with a 4 Fold 4 Input Logic Unit (CO 4020) and this stage gives a logic output $X (A\overline{B})$. Using Clover and BGO in anti-coincidence mode significant improvements in the peak to background ratio is achieved. A master gate is generated after appropriate delay via another gate and delay generator GDG (ORTEC GG 8010) which produced a TTL output.

Preamplifier energy pulses from the four crystals of the Clover detector are amplified by separate Amplifiers (ORTEC-672) and then go to a Linear Gate and Stretcher LGS (Tennelec TC 310) for proper delay matching. Finally the individual pulses are fed to a Quad 8k ADC (CAMAC AD 413A) which is triggered by the master gate which overlaps with the energy pulses of the four crystals from the amplifier.

Current signals from the Faraday cup (FC) was connected to a current integrator (Cl) for accurate measurement of charge; this unit is connected to a Rate Meter (showing current). Subsequently, this signal is processed through a 16 channel Scalar module (CAEN C 257). The NIM output of master gate from GDG was used for triggering of the Scalar module. Finally, the signal from the ADC and Scalar module (using CAMAC crate) are ready to be used for the multi-parameter data acquisition system.
Figure 3.2: Circuit diagram for the experiment performed at TIFR.
3.1.3 Preparation of target

The thin target of silicon was prepared in our target laboratory at SINP. The target consisted of natural silicon sandwiched between two thin gold layers in order to prevent oxidation. The target was prepared by the electron gun evaporation technique. In this method the target sample (Si/Au) was placed in the crucible. A beam of electron is allowed to fall on the sample placed in the crucible by a magnetic field thereby following a circular path. The electron energy is converted into heat on stopping in the crucible material, the sample material evaporates and gets deposited uniformly on glass slides placed on a bridge inside a hemispherical chamber with the crucible at the centre. The thickness of the deposition can be determined by a quartz monitor.

As thin gold (Au) layer was used to sandwich the target it was first evaporated putting the sample material in the Molybdenum crucible. The evaporated Au was then deposited on glass slides kept at ~12-13 cm above the crucible. After the desired deposition of Au is completed, the target is floated in water and placed on a tantalum frame to mount the target. The gold deposition was measured by the α-energy displacement method with three line α source ($^{239}$Pu, $^{241}$Am, $^{244}$Cm). The exact thickness of Au (layer 1) measured is about 100 $\mu$g/cm$^2$ and is placed again on the top of the crucible. A normalisation of thickness between quartz monitor and α-energy loss method is thus established. Subsequently evaporation of natural silicon was done and again a second layer of Au was evaporated (layer 2) of thickness 40 $\mu$g/cm$^2$ using the above normalisation. The thickness of Si was measured by α-energy loss method using the known thickness of the two thin Au layers.

3.1.4 Analysis

The data were recorded in the list mode in the data acquisition system LAMPS (Linux Advanced Multi Parameter System) [55] with scalar counts of Current Inte-
The off line analysis was also done using LAMPS. The Clover detector was operated in the addback mode, which yields time correlated sum of four crystals. The addback contribution gives enhanced total full energy peak detection efficiency data compared to time uncorrelated sum of four crystals data. We have generated pseudo addback spectra from the 4 singles spectra with accurate gain matching among the four crystals which is extremely crucial. For this, full energy peaks of the crystals 1, 3, 4 was matched with the channel numbers of corresponding peaks in crystal 2. The energy calibration of the addback spectrum was done with radio active sources. The yield $Y_\gamma$ of $\gamma$-rays, which come from residues due to fusion reaction was taken from the addback spectra. The $\gamma$-ray cross section is given by

$$\sigma_\gamma = \frac{Y_\gamma}{N_B N_T \varepsilon_\gamma}$$

where the essential parameters are number of incident beam particles ($N_B$), number of target nuclei per unit area ($N_T$), absolute efficiency of the detector ($\varepsilon_\gamma$). These parameters are described in the following subsections:

**Target thickness**:

The thin target of silicon sandwiched between two gold layers was prepared by the electron gun evaporation technique as described in the previous section 3.1.3. The thickness of the deposition of Au (layer 1) was determined first by the $\alpha$-energy loss method. Then evaporation of Si was done and again Au evaporated to make a thin layer (layer 2). Finally the thickness of the Si was measured by $\alpha$-energy loss method knowing the thickness of two Au layers.

In the $\alpha$-energy loss method, the Surface Barrier (SB) detector (E: 60$\mu$m) was used for the detection of $\alpha$ energies 5.155, 5.447, 5.805 MeV ($E_\alpha$) decaying spontaneously from the sources $^{239}$Pu, $^{241}$Am and $^{244}$Cm respectively. When target is placed between the source and detector the incident $\alpha$ particles will lose energy in the target. This loss of energy suffered by the $\alpha$ particles on getting transmitted
through the target material will be directly proportional to the target thickness. The detected peaks are thus shifted to the lower energy \((E_f)\) side. Target thickness is then calculated from the relation \(\rho t = (E_t - E_f)/\frac{dE}{dz}\), where the value \(\frac{dE}{dz}\) (keV/\(\mu\)g/cm\(^2\)) was taken from the stopping power calculation using the code SRIM2003 [56]. The measured target thickness \((\rho t)\) of Au layer 1 was about 100 \(\mu\)g/cm\(^2\). The thickness of Au layer 2 was about 40 \(\mu\)g/cm\(^2\) using the normalisation method. Finally the thickness \((\rho t)\) of Si was measured by the \(\alpha\)-energy loss method, considering the energy loss due to known target thickness of two Au layers, and its value was about 192 \(\mu\)g/cm\(^2\). The number of target nuclei/cm\(^2\) was then estimated using the relation,

\[
N_T = \frac{\rho t}{A} \times 6.023 \times 10^{23}.
\]

As natural silicon has contaminants \(^{29}\)Si (4.68%) and \(^{30}\)Si (3.08%), the uncertainty of the thickness was estimated including the effects of contaminants and found to be ~ 4.5-5%.

**Beam current:**

In any nuclear reaction experiment it is a well known fact that practically all of the projectile beam gets transmitted through the target without suffering any nuclear interaction. It is only a statistically insignificant number of beam particles per second that interacts with the target nuclei. Consequently, if we measure correctly the total charge \((Q)\) in an experiment, it will give a measure of the number of beam particles \((N_B)\). Total charge was measured in a specially designed Faraday Cup (FC). Basically it is made up of two concentric cylindrical metallic tubes separated from each other by using teflon ring so that FC is completely insulated from the chamber. Faraday cup was operated in an electron suppressed mode by applying a negative voltage of 200 Volts, in order to scatter the secondary electrons coming from the wall of the Faraday cup. The FC was connected with a current integrator (CI) and a scalar module. The number of incident beam particles \((N_B)\) impinging
on the target was estimated from the charge accumulated in the Faraday cup (FC) and it was estimated from the relation \( N \eta = Q/\bar{Z}e \) where \( Q \) is the total accumulated charge in Coulombs and \( \bar{Z} \) is the equivalent charge state of projectile nuclei. The estimated uncertainty was found to be \( \sim 5\% \).

**Detector efficiency:**

The detector relative efficiency was measured for the add-back mode of the Clover detector with the relation, \( \epsilon_{\text{rel}} = Y_\gamma/I_\gamma \), where \( Y_\gamma \) is the yield of the \( \gamma \)-ray peak and \( I_\gamma \) represent \( \gamma \)-ray relative intensity. \( Y_\gamma \) was measured from the generated \( \gamma \)-ray addback (8k) spectra from the 4 single crystal spectra of the Clover detector. Efficiency runs were taken both at the beginning and at the end of the main experiment with a number standard sources \(^{152}\text{Eu}, ^{133}\text{Ba}, ^{207}\text{Bi}, ^{60}\text{Co}\) spanning the energy range 85-1770 keV. Fig. 3.3 shows the detector relative efficiency as a function of \( \gamma \)-ray energy in keV. The detector resolution achieved was better than 2.8 keV for 1408 keV \( \gamma \)-line of \(^{152}\text{Eu}\) and 2 keV for 1332.5 keV \( \gamma \)-line of \(^{60}\text{Co}\). The estimated error of the efficiency was found about \( \sim 3\% \). Here the solid line represents the third order polynomial fit to the data. The relative efficiency data were fitted because most of the observed \( \gamma \)-ray energies lies in the higher energy region. The relative efficiency data was then normalised to the absolute scale \( \epsilon_{\text{abs}} = \epsilon_{\text{rel}} \times 0.01825 \times 10^{-4} \) using the standard radioactive calibrated sources like \(^{152}\text{Eu}, ^{133}\text{Ba}\) placed exactly at the target position. The strength and Ref. date of manufacture and half life \( T_{1/2} \) of the calibrated sources are,

\( ^{152}\text{Eu}: \) Strength = \( 1.2351 \times 10^{-6} \) Ci, Ref. date = 1/12/93, \( T_{1/2} = 13 \) yrs,

\( ^{133}\text{Ba}: \) Strength = \( 0.9432 \times 10^{-6} \) Ci, Ref. date = 1/12/93, \( T_{1/2} = 10.54 \) yrs.

The absolute efficiency for 1332 keV \( \gamma \)-line of \(^{60}\text{Co}\) was estimated to be about \( 16.0 \times 10^{-4} \), where the detector distance was about 25 cm from the target position. This is almost similar to the value obtained by G. Duchêne et al. [54].
Figure 3.3: Measured Relative-efficiency ($\epsilon_{\text{rel}}$) of clover detector vs $\gamma$-ray energy in keV of the standard sources ie., $^{152}$Eu, $^{133}$Ba, $^{207}$Bi. The solid line represents the third order polynomial fit to the data.

**\(\gamma\)- cross section:**

The residues of the system $^7\text{Li}^+\text{Si}^{28}$ at above barrier energies ($E_{\text{lab}}=11.5-26$ MeV) were detected through identification and analysis of the $\gamma$-ray spectrum which characterize the particular residue. A typical $\gamma$-ray "add-back" 8k spectrum at the projectile energy $E_{\text{lab}}=22$ MeV is displayed in Fig. 3.4. The identified $\gamma$-rays originating from residues and "background" $\gamma$-ray peaks originating from surrounding material, radioactivity, inelastic neutron scattering of Ge detector as described in Ref. [30], are also shown in Fig. 3.4. Some of the identified residues were $^{20}\text{Si}$, $^{30}\text{Si}$, $^{32}\text{S}$, $^{33}\text{S}$, $^{30}\text{P}$ and $^{33}\text{P}$. The contributions of these observed channels are found to be 89-75% of the total fusion cross section, as estimated by the code CASCADE [46].
for $^7\text{Li}+^{28}\text{Si}$ system, in the energy region $E_{\text{lab}}=11.5-26$ MeV, respectively. Some of the prominent identified $\gamma$-rays are 2.028 MeV ($2.028\rightarrow 0$ of $^{29}\text{Si}$), 1.273+1.263 MeV ($1.273\rightarrow 0$ of $^{29}\text{Si}+1.263\rightarrow 0$ of $^{30}\text{Si}$), 2.235 + 2.230 MeV ($2.235\rightarrow 0$ of $^{30}\text{Si}+2.230\rightarrow 0$ of $^{32}\text{Si}$), 1.967 MeV ($1.967\rightarrow 0$ of $^{33}\text{S}$), 0.677 MeV ($0.677\rightarrow 0$ of $^{30}\text{P}$), 1.847 MeV ($1.847\rightarrow 0$ of $^{33}\text{P}$). We observed Doppler shifted $\gamma$-ray peaks at the higher energies. Due to the thin Au backing of the $^{28}\text{Si}$ target the residues did not stop at the target layers and yielded Doppler shifted $\gamma$-ray peaks. The Doppler shift $(E - E_0) = E_0 \left(\beta \cos \theta\right)$ of the corresponding residue $^{29}\text{Si}$ at $E_{\text{lab}}=22$ MeV was estimated, the value of $\beta \cos \theta$ was found to be about $\sim 0.008$, where $\theta = 55^\circ$. The $\gamma$-rays 1.014 and 2.218 MeV of the residue $^{27}\text{Al}$ and 0.078 MeV of $^{32}\text{P}$ could not be distinguished from the contaminant background lines. Consequently the residues $^{27}\text{Al}$ and $^{32}\text{P}$ are missing.
residues whose contribution is found to be 10-25% according to CASCADE in the energy region $E_{lab} = 11.5-26$ MeV. The $\gamma$-rays 0.841, 0.968 and 2.968 MeV of the residue $^{33}$S were also merged with background lines and not considered. Only the contribution of 1.967 MeV $\gamma$-ray of $^{33}$S was taken in the fusion measurement.

The $\gamma$-cross sections at different projectile energies were obtained in the manner described in [30] using eq. (3.1). The measured $\gamma$-ray cross sections from the yield of the $\gamma$-ray from de-exciting residues are plotted against projectile energy ($E_{lab}$), in Fig. 3.5, where the solid curves shows the estimation of statistical model code CASCADE. However, the main contributions to fusion come from $od+^{28}$Si, $pn+^{33}$S, $\alpha p+^{30}$Si, $dn+^{32}$S channels. Small contribution was also observed from $dp+^{33}$P, $\alpha n+^{30}$P channels. The contribution of the residues i.e., $^{29}$Si, $^{30}$Si and $^{33}$S according to CASCADE estimation are found to be 2-23%, 25-19% and 37-15% respectively, of the total fusion cross section at $E_{lab}=11.5$ to 16 MeV; however at
higher energies, \( E_{\text{th}} = 16 \) to 26 MeV these contributions are accordingly 32-51%, 16-6% and 9-1%. At lower energies, from 11.5 to 16 MeV, the contribution of the 1.967 MeV \( \gamma \)-ray (\(^{33}\text{S}\)) was observed to be larger than that of 1.273+1.263 MeV \( \gamma \)-ray (\(^{29}\text{Si}+^{30}\text{Si}\)). But at higher energies (18-26 MeV) the contribution of 1.273+1.263 MeV \( \gamma \)-ray was more compared to that of 1.967 MeV \( \gamma \)-ray. A substantial contribution of 2.235+2.230 MeV \( \gamma \)-ray (\(^{30}\text{Si}+^{32}\text{S}\)) was observed throughout the energy region explored, however \(^{32}\text{S}\) is less populated channel (3-9%) in this energy range 11.5-26 MeV, according to CASCADE. The weak \( \gamma \)-rays observed are 0.677 MeV and 1.847 MeV and CASCADE also predict 16-5% and 6-2% contribution of \(^{30}\text{P}\) and \(^{33}\text{P}\).
Figure 3.5: Measured \( \gamma \)-ray cross section from \( \gamma \) yield of the de-exciting nuclei for the system \( ^7\text{Li} + ^{28}\text{Si} \) as a function of \( E_{\text{lab}} \) and solid curves represent theoretical estimation using the code CASCADE.

**Fusion cross section:**

We could not measure individual residue cross section due to overlapping \( \gamma \)-rays from different residues. At lower energy contribution of 2.028 MeV \( \gamma \)-ray is so small that we could not measure individual \( ^{29}\text{Si} \) residue cross section. So the total \( \gamma \)-ray cross section was obtained by summing over all the above mentioned \( \gamma \)-ray cross sections \((\sum \sigma^\text{exp}_\gamma)\). The total fusion cross section \( (\sigma_{\text{fus}} = \frac{\sum \sigma^\text{exp}_\gamma}{F_\gamma}) \) was then extracted as the ratio of the above total \( \gamma \)-ray cross sections and the branching factor \( F_\gamma \) following a procedure used in Refs. [33, 57]. \( F_\gamma \) was estimated theoretically \((\frac{\sum \sigma^\text{theo}_\gamma}{\sigma_F})\) as the ratio of the total theoretical \( \gamma \)-ray cross sections and the corresponding theoretical
fusion cross section, both obtained from a statistical model calculation using the code CASCADE. The fusion cross section ($\sigma_F$) is an input in the code CASCADE and was estimated from 1D BPM using code CCFULL in the no coupling mode, as discussed below. The correction due to direct feeding of the population to the ground state of the residues were also taken into account. Though experimentally it is not possible to measure the ground state contribution, but the ground state population is included in the fusion cross section ($\sigma_F$). In this way, the above method of extraction of $F_\gamma$ also incorporates the ground state contribution of residues.

The factor $F_\gamma$ was estimated considering the relative population of different bound states of the nuclei under consideration, their branching ratios and the known de-excitation schemes [51] in a detailed statistical model calculation using CASCADE as discussed in Chapter 2. The calculated value of $F_\gamma$ is shown in Fig. 3.6, which varies from 30% to 48% in the energy region under review. It is also found
Table 3.1: Measured fusion cross section of $^7\text{Li}+^{28}\text{Si}$ as a function of energy with error.

<table>
<thead>
<tr>
<th>$E_{\text{lab}}$ (MeV)</th>
<th>$E_{\text{c.m.}}$ (MeV)</th>
<th>$\sigma_{\text{fus}}$ (mb)</th>
<th>Error ($\pm$ mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.5</td>
<td>9.2</td>
<td>492.7</td>
<td>71.6</td>
</tr>
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<td>12.5</td>
<td>10</td>
<td>605.5</td>
<td>83.4</td>
</tr>
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<td>14</td>
<td>11.2</td>
<td>775.5</td>
<td>93</td>
</tr>
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<td>12.8</td>
<td>865.6</td>
<td>128.6</td>
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<tr>
<td>18</td>
<td>14.4</td>
<td>962.4</td>
<td>139.3</td>
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<td>16</td>
<td>973.5</td>
<td>144.7</td>
</tr>
<tr>
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<td>17.6</td>
<td>906.1</td>
<td>117.8</td>
</tr>
<tr>
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<td>19.2</td>
<td>1003.8</td>
<td>135.5</td>
</tr>
<tr>
<td>26</td>
<td>20.8</td>
<td>974.3</td>
<td>144.8</td>
</tr>
</tbody>
</table>

that $F_\gamma$ is not so sensitive to small parameter changes and the estimated uncertainty of the $F_\gamma$ was found to be $\leq 10\%$. As natural silicon has contaminants $^{29}\text{Si}$ and $^{30}\text{Si}$, their contributions were estimated using CASCADE and this yielded an overall maximum error of about 5% in the total fusion cross section. This is taken into account in estimation of total uncertainty in fusion cross section. Finally the total uncertainty of fusion cross section has been estimated to be about 12-15% considering statistical $\gamma$-ray yield, absolute efficiency of the detectors, systematic error in target thickness measurement and incident beam current and $F_\gamma$ (all added in quadrature). The measured total fusion cross section ($\sigma_{fus}$) are given in the tabulated form in Table 3.1 and is displayed in Fig 3.9.
3.1.5 Estimation of 1D BPM from CCFULL

In order to compare the fusion results with 1D BPM predictions we used the code CCFULL [50] in the no coupling mode. In the code CCFULL to estimate 1D BPM calculation in the no coupling mode, we need to incorporate the optical model parameters. The potential parameters \( V_0, r_0 \) and \( a_0 \) were found out by fitting the high energy experimental fusion data (Fig. 3.7) of the nearest tightly bound projectile-target system \( ^{11}\text{B} + ^{27}\text{Al} \) [58]. Complementarily to the above OM potential parameters, we have also derived Akyüz Winther (AW) [59] potential parameters for the system \( ^{11}\text{B} + ^{27}\text{Al} \) and \( ^{7}\text{Li} + ^{28}\text{Si} \); they are \( V_0 = 40.58 \text{ MeV}, r_0 = 1.11 \text{ fm}, a_0 = 0.60 \text{ fm} \) and \( V_0 = 36.5 \text{ MeV}, r_0 = 1.11 \text{ fm}, a_0 = 0.59 \text{ fm} \) respectively. CCFULL calculation with the AW (bare) shallow potential gives oscillation at high energies, so we have chosen deeper potential. The value of the best fit potential parameters were \( V_0 = 130 \text{ MeV}, r_0 = 0.97 \text{ fm} \) and \( a_0 = 0.63 \text{ fm} \). The same parameters were used for 1D BPM estimation of the system \( ^{7}\text{Li} + ^{28}\text{Si} \). Here we consider Wood Saxon type of potential and we have checked the sensitivity of the 1D BPM estimation to changes of optical model parameters. For the system \( ^{7}\text{Li} + ^{28}\text{Si} \), the diffuseness parameter \( a_0 \) and \( r_0 \) are allowed to vary (by \( \sim \pm 20\% \)) keeping \( V_0 \) fixed in order to achieve best fit, which is shown in Fig. 3.8. If diffuseness parameter \( a_0 \) is decreased then \( r_0 \) has to be increased accordingly, but it results in a poor fit. If \( a_0 \) is further increased, then \( r_0 \) gets decreased which leads to oscillation, especially at high energies. The maximum change in fusion cross sections above \( 2V_b \) is seen to be marginal. The value of diffuseness parameter \( a_0 = 0.63 \text{ fm} \) has also been previously used for the systems \( ^{6,7}\text{Li} + ^{209}\text{Bi} \) [15]. The CCFULL calculation yielded a value for the barrier as \( V_b = 6.79 \text{ MeV} \), produced by the best fit potential parameters i.e., \( V_0 = 130 \text{ MeV}, r_0 = 0.97 \text{ fm} \) and \( a_0 = 0.63 \text{ fm} \). The experimental results are compared with 1D BPM in Fig. 3.9.
Figure 3.7: The fit of the measured fusion data $^{11}$B+$^{27}$Al [58], denoted in the figure by solid stars, using CCFULL at high energy region with OM parameters $V_0=130$ MeV, $r_0=0.97$ fm, $a_0=0.63$ fm, $R_b=8.21$ fm.

### 3.1.6 Results and discussion

The $\gamma$-measurement usually yields the total fusion cross section (TF) consisting of CF and ICF components. We could not experimentally distinguish between CF and ICF events (occurring from breakup/transfer followed by fusion) because there will be overlapping residual nuclei produced in CF and ICF. The transfer process is negligible at the above barrier regions. The residues $^{29}$Si, $^{30}$Si, $^{30}$P, $^{27}$Al and $^{31}$P may be produced by incomplete fusion with evaporation of $n$, $p$, $d$ and $\alpha$ as predicted by CASCADE/PACE2 (assuming that the breakup components $t$ and $\alpha$ are moving with beam velocity) as shown below

(i) $t+^{28}$Si $\rightarrow$ $^{30}$P+$n$, $^{30}$Si+$p$, $^{29}$Si+$d$, $^{27}$Al+$\alpha$
Figure 3.8: Estimation of 1D BPM in CCFULL with varying $r_0$ and $a_0$ keeping $V_0=130$ MeV and $V_6.79$ MeV fixed.

(ii) $\alpha^{+28}\text{Si} \rightarrow ^{31}\text{P}+p$.

PACE2 predicts that for $t$-ICF, $^{28}\text{Si}$ is the most dominating channel at higher energies, i.e., $E_{lab}=16-26$ MeV, which contribute 37-68% of the $t$-incomplete fusion process. However in the lower energy region at $E_{lab}=11.5-14$ MeV contribution of $^{30}\text{P}$ is large, about 47-36%. Other channel contributions are $^{30}\text{Si}$ (26-7%) and $^{27}\text{Al}$ (13-14%) throughout the energies $E_{lab}=11.5-26$ MeV. PACE2 have shown that for $\alpha$-ICF, $^{31}\text{P}$ is the most dominating channel. The residue $^{31}\text{P}$ accounts for 99-73% of the $\alpha$-incomplete fusion process in the energy range $E_{lab}=11.5-26$ MeV. Though in our measurement we did not observe $^{31}\text{P}$ and we found weak contribution of
0.677 MeV γ line of $^{30}$P. However substantial contribution of 1.273+1.263 MeV γ-ray ($^{28}$Si+$^{30}$Si) and 2.235+2.230 MeV γ-ray ($^{30}$Si+$^{32}$S) were found. We can say that contribution of α-ICF is negligible compared to t-ICF, which occurs with higher probability as it faces a lower Coulomb barrier than the former. This is consistent with the observation of a large α yield compared to t for the system $^7$Li+$^{165}$Ho by V. Tripathi et al. [21].

From Fig. 3.9 it is clear that the 1D BPM prediction describes well the experimental fusion data on the lower energy side, up to twice the barrier ($2V_b$) energy. But it over predicts the data beyond $2V_b$ region. This overprediction was found to be about 15-20% of the experimental data. Most of the existing data with the neighbouring target projectile combinations are reported to agree with the 1D BPM
model (with widely varying OM parameters) at near barrier energies. However Kovar et al. [60] reported similar type of observations for the fusion of $^{12}\text{C}$ and $^{16}\text{O}$ projectiles with targets in the mass range $12 \leq A \leq 19$ and also by Takahashi et al. [29] for the systems $^6$Li+$^9$Be. The theoretical CDCC calculation of fusion cross section for $^6$Li+$^{59}$Co by Diaz-Torres et al. [61] has also overestimated the experimental values at energies well above the barrier. Our result is also similar to the results obtained by Figueira et al. [27] for the system $^9$Be+$^{28}$Si. In this region it seems fusion behaviour is no longer dominated by interaction barrier. To further investigate the fusion mechanism beyond $2V_b$ region, we undertook another experiment with the same target-projectile system using evaporation $\alpha$ method.

3.2 Measurement of above barrier fusion cross section for $^7\text{Li}+^{28}\text{Si}$ by evaporation $\alpha$ method

3.2.1 Experimental details

Experiment was performed at the 15 UD Pelletron facility of Inter University Accelerator Centre (IUAC), New Delhi for the measurement of fusion cross section by detecting evaporation charged particle i.e., $\alpha$ detection technique for the system $^7\text{Li}+^{28}\text{Si}$ at energies $E_{lab} = 16, 21$ and $26$ MeV. During the experiment the beam ($^7\text{Li}^{3+}$) current was varied from 1 to 4 pnA. We used Si target (150 $\mu g/cm^2$) sandwiched between two Au thin layers (95 $\mu g/cm^2$, 30 $\mu g/cm^2$) to avoid oxidation. The preparation of target using vacuum evaporation technique and measurement of target thickness using $\alpha$-energy loss method are same as described in the previous Section 3.1. The target was placed on the target ladder at the centre of 150 cm diameter large scattering chamber known as General Purpose Scattering Chamber (GPSC). The target ladder was made of stainless steel and can house 8 targets at a time. The ladder has a provision to rotate about its own axis and different vertical
heights can be adjusted from outside the chamber. The proper alignment of the incident beam upon the target was fine tuned by illuminating a quartz by the beam placed at the target position. The online picture of the glowing quartz was viewed through a CCTV camera and proper positioning and focusing of the beam on the target was fixed. This ensures that the beam is passing through the centre of target, which can also be verified by the symmetrically placed monitor ratio. The vacuum of the chamber was about $\sim 1.6 \times 10^{-6}$ torr during the experiment.

Two silicon (SB) telescopes detectors (T1, T2: $\Delta E$: 25 $\mu$m, E: 300 $\mu$m) were used for heavy ion (Li, $\alpha$) particles detection. The telescope detectors (T1 and T2) were placed on one of the rotational arms (lower arm $\rightarrow$ L.A) of the scattering chamber, with angular separation of 12°. The arms of the chamber can be rotated over a wide angular range in the reaction plane. The detectors T1 and T2 with a slit, diameter
of 7.9 and 8 mm and thickness of 8.2 mm in front of it, were kept at a distance about 64.8 and 60.8 cm, respectively from the target centre. Two monitor detectors (M1, M2: 300 μm) placed at ± 9.8° (fixed to the wall of the chamber) with respect to beam axis at the same distance from centre of the chamber, were used to monitor the beam axis and also for beam normalization purposes. The two monitors were kept at a distance 69.5 cm from the target centre with a thin slit of diameter 2 mm. A schematic diagram of the experimental arrangement is shown in Fig. 3.10.

The α angular distribution was measured from the α spectra using telescope T1 and T2 at different angles, varying from $\theta_{lab} = 15.5°$-159.5°. However, fusion cross section was estimated from experimental α angular distribution at backward angles ($\theta_{lab} = 103.5°$-159.5°) at the three different projectile energies. The elastically scattered 7Li projectile was also detected by the same telescopes T1 and T2 in the angular range $\theta_{lab} = 15.5°$-159.5°, for energy calibration purposes. The solid angle subtended by the telescopes (T1, T2) and monitor (M1, M2) detectors at the target centre was respectively $1.18 \times 10^{-4} sr$ ($\Omega_T$), $1.36 \times 10^{-4} sr$ ($\Omega_T$) and $6.5 \times 10^{-6} sr$ ($\Omega_M$). Angular resolution ($\Delta \theta$) of each telescope detector was about $\sim 0.7°$.

### 3.2.2 Electronics circuit diagram

Fig. 3.11 shows a simplified block diagram for processing the pulse output from the various modules of the associated electronics setup during experiment. Each telescope detector consists of two silicon surface barrier (S.B) detectors, one of transmission type, used for ΔE, and another of stop detector type used for E. The signals from ΔE1, E1, ΔE2, E2 of telescope 1 and 2 were first pre-amplified by charge sensitive pre-amplifiers (ORTEC 142 IH). The energy signal from the preamplifiers were amplified by spectroscopic amplifiers (ORTEC 572/571). The amplified signals of ΔE1, E1 and ΔE2, E2 were digitised by a 16 Channel ADC (CANBERA 8075) connected to the CAMAC bus. The ΔE detector was in coincidence with E detector and timing signal was taken from the ΔE detector. In order to setup the
Figure 3.11: Circuit diagram for the experiment performed at IUAC
time circuit we have taken another separate amplified signal of $\Delta E_1$ and $\Delta E_2$ which are fed to a TSCA (ORTEC 455/551) module for generation of gate signal. Both the energy signals from $\Delta E_1$, $\Delta E_2$ were taken in coincidence and subsequently processed through a Universal Coincidence Unit (ORTEC 418A). The coincidence pulse with proper delay in GDG (ORTEC 416A) as TTL output used as the master gate for triggering ADC. The energy signals from the monitor detectors (M1 and M2) were also similarly processed through pre-amplifier (CANBERA), amplifier (ORTEC 672), ADC and were recorded as Histograms in the CAMAC data acquisition system. Finally, the signals from histograms for Monitors (M1, M2) and the ADC are connected in the data acquisition system. The multi-parameter data acquisition system was controlled by a standard control software, called "FREEDOM".

3.2.3 Analysis

The data was stored in the list mode and the off line analysis was done with the data acquisition software "FREEDOM". From the 2D ($E$ vs $\Delta E$) spectra we generated $E$ vs $E+\Delta E$ spectra (Fig. 3.12) after proper gain matching of the detectors. Fig. 3.12 shows well separated $^7$Li (scattered from Si and Au) and $\alpha$ band with projectile energy $E_{lab}=16$ MeV at an detector angle $\theta_{lab}=125.5^\circ$. The X-axis projection of the $\alpha$ band in Fig. 3.12 is shown in Fig. 3.13. The energy calibration of the X-axis of $\alpha$ spectra (Fig. 3.13) was done with elastic scattering data of $^7$Li from $^{28}$Si and $^{197}$Au targets using the code KINACEM, considering energy loss in the target. The energy resolution of the detectors (T1, T2) was found to be about $\sim$ 180-220 keV. The lower energy cut-off $\alpha$ was found $\sim$ 5 MeV. The differential cross section $\frac{d^2\sigma}{d\Omega dE}$ (mb/sr MeV) was extracted using measured monitor yield ($Y_M$) [eq. (3.3)] and $\alpha$ yield ($Y_\alpha$) at successive one MeV energy bins for a particular bombarding energy ($E_{lab}$) of $^7$Li and at a particular angle ($\theta_{lab}$) of the detector (T)

$$\frac{d^2\sigma}{d\Omega dE} = \frac{Y_\alpha d\Omega_M}{Y_M d\Omega_T} \frac{d\sigma_{M}}{d\epsilon_M}$$ (3.3)
Figure 3.12: Two dim. (E vs E+ ΔE) gain matched spectrum showing α and Li-bands, at an angle $\theta_{lab} = 125.5^\circ$ and for projectile energy $E_{lab} = 16$ MeV.

Figure 3.13: X-projection of evaporation α-particles obtained from 2D-spectrum (Fig. 3.12) for projectile energy $E_{lab} = 16$ MeV at an angle $\theta_{lab} = 125.5^\circ$. 
This cross sections were measured from $\alpha$ spectra at three different bombarding energies of the projectile at different angles and were analysed with the statistical model code PACE2 [47].

### 3.2.4 Analysis with PACE2

In the code PACE2, the essential input parameters are $l$-diffuseness ($\Delta$) and level density ($a$). The $l$-diffuseness was obtained from the CCFULL estimate of $\sigma_l$ vs $l$ plot, for a fixed energy. The empirical formula of fusion cross section is given by partial wave summation:

$$\sigma_{cf} = \pi \chi^2 \sum_{l=0}^{l_{cr}} (2l + 1)T_l(E).$$

(3.4)

Here value of $T_l$, given by eq. (3.5), is calculated from eq. (3.4) and plotted in Fig. 3.14 (solid circle-line curve) as a function of $l$:

$$T_l = \frac{\sigma_l}{\pi \chi^2 (2l + 1)}.$$

(3.5)

Another expression (empirical) of penetrability is given by

$$T_l = \frac{1}{1 + exp \frac{l - l_{max}}{\Delta}}.$$

(3.6)

The values of $T_l$ were found also taken from eq. (3.6) with different values of $\Delta$. The value of $l_{max}$ was taken as that corresponding to the value of $T_l = 1/2$. The variation of $T_l$ with different values of $\Delta$ are shown in the same Fig. 3.14 (solid line). Finally considering the quality of fit in Fig. 3.14, we obtain the best fit value of $l$-diffuseness ($\Delta$) = 0.60 fm. The value of level density parameter used is $\lambda/8$, most acceptable in the previous work in the near light mass region [36].

In our analysis with PACE2, we treat the fusion cross sections, measured from $\gamma$-ray method as described in Section 3.1, as an input fusion parameter and then it was varied $\pm (5 - 10)\%$ so that the theoretical $\alpha$-cross section per 1 MeV energy
Figure 3.14: $T_l$ vs $l$ plot. The solid circle represent $T_l$ values calculated from CCFULL estimation, using eq. (3.5), and solid line represent $T_l$ estimation using eq. (3.6). See details in text.

Figure 3.14: $T_l$ vs $l$ plot. The solid circle represent $T_l$ values calculated from CCFULL estimation, using eq. (3.5), and solid line represent $T_l$ estimation using eq. (3.6). See details in text.

bin (considering 5 MeV $\alpha$ onward) gives best fit to the corresponding experimental $\alpha$- cross section $[d^2\sigma/d\Omega dB$ (mb/sr MeV)]. Fig. 3.15 shows the measured $\alpha$- cross section $[d^2\sigma/d\Omega dB$ at some selected angles, as a function of $E_{lab}$ along with PACE2 estimations with varying fusion cross sections. The best fit values of fusion cross section obtained by PACE2, at energies $E_{lab} = 16, 21, 26$ MeV are 900, 980, 1050 mb respectively and the $\alpha$ multiplicity with these best fit parameters at the above energies was found to be 63%, 76% and 89% respectively.
Figure 3.15: $\alpha$ energy distributions at three projectile energies. Experimental values (solid rectangles) are compared with PACE2 (solid lines) with varying fusion cross section as an input parameter.
Figure 3.16: $\alpha$ energy distributions at three projectile energies. Experimental values (solid rectangles) are compared with best fit PACE2 estimates (solid lines).
Typical experimental $\alpha$ cross section (mb/sr MeV) at some selected backward angles along with theoretical estimation (with above mentioned fusion values, $l$-diffuseness ($\Delta$) = 0.60 fm and level density parameter= $A/8$) at three higher projectile energies are shown in Fig. 3.16. It is apparent that the experimental values of $\alpha$ energy distributions are matching the statistical model predictions (from code PACE2) quite well. The energy integrated measured $\alpha$ cross section $d\sigma/d\Omega$ (mb/sr) at different angles i.e., $\alpha$ angular distributions are given in Table 3.2 and are compared with the theoretical best fit estimates from PACE2 in Fig. 3.17. In this graph the experimental values are in good agreement with the theoretical estimation.
Table 3.2: Measured fusion cross section of $^7$Li+$^{28}$Si as a function of centre of mass energy with error.

<table>
<thead>
<tr>
<th>$E_{lab}$ (MeV)</th>
<th>$\theta_{lab}$ (degree)</th>
<th>$d\sigma/\Omega$ (mb/sr)</th>
<th>$\sigma_{ fus}$ (mb)</th>
<th>Error ± (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>103.5</td>
<td>27.09</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>115.5</td>
<td>20.93</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>125.5</td>
<td>21.48</td>
<td>923.79</td>
<td>92</td>
</tr>
<tr>
<td></td>
<td>137.5</td>
<td>17.13</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>147.5</td>
<td>19.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>159.5</td>
<td>16.26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>103.5</td>
<td>35.16</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>115.5</td>
<td>26.70</td>
<td>976.33</td>
<td>98</td>
</tr>
<tr>
<td></td>
<td>125.5</td>
<td>26.67</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>137.5</td>
<td>23.42</td>
<td></td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>117.5</td>
<td>34.49</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>123.5</td>
<td>30.71</td>
<td>1041.96</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>129.5</td>
<td>31.31</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>135.5</td>
<td>32.03</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The evaporation α's in the backward angles might arise mainly from two sources, (a) complete fusion (CF) residues and (b) incomplete fusion (ICF) preceded by breakup and or transfer. Now the contribution of α’s from process (b) seemed to be very small at lower energies as per study of Pakou et al. [34]. At higher energies, though there might be appreciable breakup/transfer events, the back angle α contributions of this secondary process (each followed by fusion) will be insignificant. This led us to assume that the α evaporations in the backward hemisphere are mainly coming from complete fusion (CF) events. The fusion cross section was estimated from the angle integrated α-angular distribution, at some selected backward angles.
Table 3.3: Measured values of absolute fusion cross section of $^7\text{Li}+^{28}\text{Si}$ using two different techniques i.e., characteristic $\gamma$-method and evaporation $\alpha$-method.

<table>
<thead>
<tr>
<th>Technique</th>
<th>$E_{\text{lab}}$ (MeV)</th>
<th>$E_{\text{c.m.}}$ (MeV)</th>
<th>$\sigma_{\text{fus}}$ (mb)</th>
<th>Error ($\pm$ mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$-method</td>
<td>16</td>
<td>12.8</td>
<td>865.6</td>
<td>128.6</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>16.0</td>
<td>973.5</td>
<td>144.7</td>
</tr>
<tr>
<td></td>
<td>26</td>
<td>20.8</td>
<td>974.3</td>
<td>144.8</td>
</tr>
<tr>
<td>$\alpha$-method</td>
<td>16</td>
<td>12.8</td>
<td>923.8</td>
<td>92</td>
</tr>
<tr>
<td></td>
<td>21</td>
<td>16.8</td>
<td>976.3</td>
<td>98</td>
</tr>
<tr>
<td></td>
<td>26</td>
<td>20.8</td>
<td>1041.9</td>
<td>100</td>
</tr>
</tbody>
</table>

and are given in Table 3.2 and is also shown in Fig. 3.18. The estimated uncertainty of the above measurement was found to be $\sim$10% throughout the energy range after considering errors in $\alpha$-measurement and that crept in fitting angular distribution obtained from the code PACE2.

3.2.5 Results and discussion

The estimated fusion cross sections thus obtained from the best fit are also shown in Fig. 3.18 (open circle). The measured fusion cross section from two different methods i.e., the characteristic $\gamma$-ray method and the evaporation $\alpha$ measurement, are consistent and agree with each other and have been given in Table 3.3. It is apparent that our fusion measurements with two different experimental techniques [62] yielded almost similar results. The 1D BPM predictions describe the data well up to twice the Coulomb barrier $2V_0$, but at higher energies beyond $2V_0$ region it overestimates the data by about 15 -20%. Our result for $^7\text{Li}+^{28}\text{Si}$ system at higher energies, is similar to the results obtained by Figueira et al. [27] for the system
In Fig. 3.19 we have plotted our measured fusion data with $1/E_{\text{cm}}$. The solid line, Fit. 1 represents a linear fit with the four lowest energy ($E_{\text{lab}} = 11.5 \text{ MeV}$) fusion cross sections and Fit. 2 gives another linear fit with five highest energies ($E_{\text{lab}} = 18 \text{ MeV}$). From Fit. 1 [using eq. (2.10)] we get the value of $V_b$ (I) = 6.73 MeV and $R_b$ (I) = 7.7 fm and Fit. 2 gives $R_{cr}$ (II) = 5.68 fm. In the higher energy region (II) ($>2V_b$) it seems fusion behaviour is no longer dominated by interaction barrier in region (I). The critical value of interaction radius ($R_{cr}$), in the region (II) is smaller than the value ($R_b$), in the region (I). It appears that the projectile at higher energies will penetrate more in the nuclear interaction region and as a result, relative separation is less between target and projectile compared to the low energy.
Though we could not identify any ICF events at our measured energies, one has to keep in mind that several of the residue channels that were populated could have been formed from incomplete fusion and direct processes as well. Though it is expected that breakup would be larger at energies above $2V_b$, but breakup followed by fusion (a second order effect) even if present, would occur with a very small contribution. In fact our experimental findings do corroborate this fact. Considering the above conflicting arguments it is not possible to comment on the quantitative estimate of ICF and their energy dependence from this type of inclusive measurements. Explicit coincident measurement of $^7\text{Li}$ breakup fragments and tagging of residues with transfer components might provide more insight into the fusion behaviour, in this high energy region.

3.3 Measurement of sub-barrier fusion cross section of $^7\text{Li} + ^{28}\text{Si}$ system by characteristic $\gamma$-ray method

3.3.1 Experimental details

The total fusion (TF) cross sections of $^7\text{Li} + ^{28}\text{Si}$ system at near and sub-barrier energies was measured by characteristic $\gamma$-ray method. The experiment was done at the 3 MV Pelletron accelerator of Institute of Physics (IOP), at Bhubaneswar, with $^7\text{Li}$ ($2^+, 3^+$) beam (8 -30 pnA) at energies, $E_{lab}= 7, 8, 8.5, 10,$ and 11.5 MeV. A self-supported thin target of $^{28}\text{Si}$ (175$\mu$g/cm$^2$) was used. A specially designed target chamber of 25 mm inner diameter made of stainless steel was used in the $0^\circ$ beam line to measure the fusion cross section using the characteristic $\gamma$-ray method. The $\gamma$-rays emitted from the evaporation residues were detected using a HPGe detector placed
Figure 3.20: Experimental set-up at IOP

at 125° with respect to the beam direction. The active volume of the detector was ~ 110 cm³. The distance between target and detector was ~ 15 cm. A long insulated metallic cylinder with proper electron suppressor (applying 200 V negative) was used as Faraday cup in the beam line and standard current integrator was employed to measure the incident beam current. The vacuum of the chamber was achieved to ~ 7 × 10⁻⁶ mbar. Efficiency runs were taken both at the beginning and at the end of the main experiment with a number of standard sources like $^{152}$Eu, $^{133}$Ba, $^{207}$Bi spanning the energy range 81-1770 keV. The absolute efficiency of the HPGe detector was measured using calibrated sources $^{152}$Eu and $^{133}$Ba by placing it at the target position. In order to subtract or correct for γ-rays arising out of beam impingement on the slit, beam line or the Faraday cup, one additional spectra was taken with beam using a Ta-frame having a hole in place of target position. The room background run was also taken without beam after each run. The experimental
set-up is shown in Fig. 3.20.

### 3.3.2 Electronics circuit diagram

A simplified block diagram for processing the pulse output from the various modules of the associated electronics setup during experiment is showing in Fig. 3.21. The energy signals from preamplifier of HPGe detector (from ORTEC) was amplified by Ortec-672 amplifier. The amplified signal is fed to the two channel MCA.

Separate energy signals from the two monitor detectors (M1 and M2) were also similarly processed through pre-amplifiers (142 IH) and amplifiers (CAEN N968). The summing signal was taken using a Dual Sum and Inverter module and output
was connected to MCA. The multi-parameter data acquisition system was controlled by a standard control software, called "MCA-3".

The signals from electron suppressed Faraday Cup due to charge accumulation, was processed through a Current Integrator (CI) which is connected with Rate meter. The digitised pulse was counted with a digital clock "Counter" for each single run of data acquisition in "MCA-3".

### 3.3.3 Analysis

The on-line data was stored in MCA-3 acquisition software as singles 8k spectra. The charge accumulation in the Faraday-cup was measured using a Current Integrator (CI). The off-line analysis was done in the "Nsctsk" software. Fig. 3.23 shows the typical γ-ray spectra at projectile energy 10 MeV. To measure the γ-ray cross section [eq. (3.1)] the essential parameters like, no. of incident beam particle \((N_B)\), no. of target nuclei per unit area \((N_T)\), absolute efficiency of the detector \((\epsilon_r)\) was estimated by similar method, as was discussed earlier in Section 3.1. Apart from the two monitor detectors we also used the CI to estimate \(N_B\) in the present work, similar to our earlier measurement in Section 3.1. The resolution of the detector was found to be 2 keV for the 1408 keV γ-line of \(^{152}\)Eu.

Fig. 3.22 shows the detector relative efficiency vs γ-ray energy in keV. The solid line represent the third order polynomial fit of the data. The relative efficiency data were fitted because most of the observed γ-rays energies lie in the higher energy region. The relative efficiency of the detector was then normalized to the absolute scale \([\epsilon_{abs} = \epsilon_{rel} \times 9.43 \times 10^{-7}]\) with standard radioactive calibrated sources \(^{152}\)Eu, \(^{133}\)Ba placed at the target position. The sources are similar to what we have used in our earlier measurement, as described in Section 3.1. The error in the measurement of efficiency was found to be \(\sim 3\%\).

The self supporting thin target of natural Si (\(^{28}\)Si-92.23%) was prepared very carefully in our target laboratory at SINP by electron gun evaporation technique.
The sample material was placed in the Molybdenum crucible and target mounted on tantalum frame in the same process described earlier in Subsection 3.1.3. The thickness of target was measured by the α-energy displacement method with three line α source (239Pu, 241Am, 244Cm). The exact thickness of 28Si was measured to be about 175 μg/cm². The estimated uncertainty in the thickness was ~ 5%. The contributions of 29Si and 30Si in Silicon target (4.68% 29Si, 3.1% 30Si) present to fusion of 7Li+28Si were found negligible from the yield of the γ-rays of the reaction 7Li+29Si, 30Si.

γ- cross section:

The residues were identified by analysing the γ-ray spectra. The γ-ray 8k spectra at \( E_{\text{lab}} = 10 \) MeV is displayed in Fig. 3.23. The identified γ-rays originating from residues and background γ-ray peaks originating from surrounding material,
radioactivity, inelastic neutron scattering of Ge detector, as described in Ref. [30], are also shown in Fig. 3.23.

The main contributions to fusion come from channels like $pn + ^{33}\text{S}$, $dn + ^{32}\text{S}$, $\alpha p + ^{30}\text{Si}$ for $E \leq 9 \text{ MeV}$ and $pn + ^{33}\text{S}$, $\alpha p + ^{30}\text{Si}$, $\alpha n + ^{32}\text{P}$, $dn + ^{32}\text{S}$ for $E \geq 9 \text{ MeV}$. Some of the prominent identified $\gamma$-rays are 1.263 MeV ($1.263 \rightarrow 0$ of $^{30}\text{Si}$), 2.230 + 2.235 MeV ($2.230 \rightarrow 0$ of $^{32}\text{S}$ + 2.235 $\rightarrow 0$ of $^{30}\text{Si}$), 1.967 MeV ($1.967 \rightarrow 0$ of $^{33}\text{S}$), 0.677 MeV ($0.677 \rightarrow 0$ of $^{30}\text{P}$). The strong contribution of 1.263 MeV $\gamma$-rays of $^{30}\text{Si}$, 2.230+2.235 MeV $\gamma$-rays of $^{32}\text{S}$+$^{30}\text{Si}$ and 1.967 MeV $\gamma$-rays of $^{33}\text{S}$ was observed. However weak contribution of 0.677 MeV $\gamma$-rays of $^{30}\text{P}$ was also found. The contributions of the observed channels are almost about 85 -80% of the total fusion cross section for $^7\text{Li} + ^{28}\text{Si}$ system, in the energy region $E_{lab} = 7$-11.5 MeV respectively, as
estimated by CASCADE. In the low energy region a significant projectile energy loss will occur. So we estimated the projectile energy loss in the half thickness of the target and is about 134 keV at 7 MeV and 125 to 102 keV in the high energy regime 8-11.5 MeV. The intrinsic energy resolution and uncertainty in beam energy calibration yields an error of about 30 keV. These factors were taken into account and the measured γ-ray cross section at different effective energies i.e., σγ vs E_{c.m.} were plotted with the theoretical CASCADE predictions in Fig. 3.24. Good fits with the statistical model are obtained for most of the γ-rays cross section in the whole energy domain, except for the γ-ray 1.263 MeV of 30Si at lower energies, showing under prediction of the data.
Fusion cross section:

As there are overlapping $\gamma$-rays and weak transitions, we could not measure the individual channel cross section. So total fusion cross section was extracted from the sum of the measured $\gamma$-ray cross sections $\sum \sigma_{\gamma}^{\text{exp}}$. The total fusion cross section ($\sigma_{\text{fus}} = \sum \sigma_{\gamma}^{\text{exp}} / F_{\gamma}$) was extracted as the ratio of the total experimentally measured $\gamma$-ray cross sections and the corresponding branching factor $F_{\gamma}$. $F_{\gamma}$ was estimated theoretically ($\frac{\sum \sigma_{\gamma}^{\text{theo}}}{\sigma_F}$), following a procedure used in Refs. [33, 57] as the ratio of the total theoretical $\gamma$-ray cross sections and the corresponding theoretical fusion cross section, both obtained from a statistical model calculation using the code CASCADE. The fusion cross section ($\sigma_F$) is an input in the code CASCADE and its value was estimated from 1D BPM using CCFULL in the no coupling mode and it includes ground state contribution. The ground state transitions may be important at barrier energies. Here also the ground state population is included in the fusion
cross section. In this way, though experimentally it is not possible to measure the ground state contribution, the above method of extraction of $F_\gamma$ includes the ground state contribution of residues. A small variation of $F_\gamma$ with energy was found and is shown in Fig. 3.25. The estimated uncertainty of $F_\gamma$ was found to be within 10% and $F_\gamma$ is also found to be not sensitive to small parameter changes. The uncertainty in the measurement of the total fusion cross section was estimated to be about 16% for all energies, except for the lowest energy, where it was nearly 20%, owing to very poor yield. The error due to statistical $\gamma$-ray yield, absolute efficiency of the detectors, systematic error in target thickness measurement, integrated beam current and $F_\gamma$ were taken into account to estimate total uncertainty in the measurement of the $\sigma_{\text{fus}}$. 

Figure 3.24: Measured $\sigma_\gamma$ vs $E_{\text{c.m.}}$ for the system $^7\text{Li}+^{28}\text{Si}$. Theoretical CASCADE predictions are shown by solid lines.
The total fusion cross sections were plotted as a function of effective projectile energy in Fig. 3.26 with our previous data at above barrier energies (Section 3.1) [62]. The data are also presented in the tabulated form in Table 3.4. The overall resulting uncertainty in projectile energy is also shown. The effective projectile energy values was used in all other figures. Our measured fusion data at $E_{lab}=11.5$ MeV by two different experimental setups, targets and beams from different pelletron facilities are almost similar within the uncertainty which substantiates that the quality of data and analysis is quite good. The one-dimensional barrier penetration model (1D BPM) estimates were found out using the coupled channel code CCFULL [50] in the no coupling mode, and are shown in Fig. 3.26 for comparison. The input optical model parameters ($V_0=130$ MeV, $r_0=0.97$ fm and $a_0=0.63$ fm) were extracted as described in Section 3.1. It is seen that below the nominal barrier [$V_b (c.m.)=6.79$ MeV] the theoretical prediction underestimates the experimental excitation function.
and the difference is more near the barrier, pointing to the effective role of coupling in this region. Sub-barrier enhancement with respect to 1D BPM is apparent and it is more prominent just below the barrier.

3.3.4 Results and discussion

The experimental results are also compared with Wong’s phenomenological model predictions [49] (discussed in Chapter 2) using the input parameters like barrier and barrier radius from the prescription of Vaz et al. [63] and curvature from Wong parametrization. These values are respectively 6.74 MeV ($V_b$), 8.18 fm ($R_b$) and 3.24 ($\hbar\omega$). As expected, the Wong formulation overestimates the fusion excitation below the barrier owing to the assumption of a parabolic nature of the potential,
Table 3.4: Measured fusion cross section of $^7$Li+$^{28}$Si as a function of centre of mass energy with error in fusion and energy.

<table>
<thead>
<tr>
<th>$E_{lab}$ (MeV)</th>
<th>$E_{c.m.}^{eff}$ (MeV)</th>
<th>$\sigma_{fus}$ (mb)</th>
<th>$Err_{fus}$ (± mb)</th>
<th>$Err_{Energy}$ (± MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>5.49</td>
<td>12.52</td>
<td>2.5</td>
<td>0.134</td>
</tr>
<tr>
<td>8</td>
<td>6.30</td>
<td>91.93</td>
<td>17.5</td>
<td>0.125</td>
</tr>
<tr>
<td>8.5</td>
<td>6.70</td>
<td>137.17</td>
<td>23.3</td>
<td>0.121</td>
</tr>
<tr>
<td>10</td>
<td>7.82</td>
<td>345.07</td>
<td>55.2</td>
<td>0.110</td>
</tr>
<tr>
<td>11.5</td>
<td>9.12</td>
<td>485.70</td>
<td>77.7</td>
<td>0.102</td>
</tr>
</tbody>
</table>

whereas the shape of real nucleus-nucleus potential may be asymmetric and broad at lower energies. Our experimental observations are somewhat similar to the recent findings of Penionzhkevich et al. [64] for $^6$He+$^{208}$Pb having large enhancement and of C. Beck et al. [25] for $^6$Li+$^{59}$Co yielding small enhancement. We have explored the effects of rotational coupling (discussed in Chapter 2) employing the exact coupled channels calculation with CCFULL. The $^{28}$Si nucleus has a large ground state quadrupole deformation $\beta_2 = -0.407$ [65]. The rotational state $2^+$ (1.779 MeV) of $^{28}$Si was coupled to the g.s. The results are shown in Fig. 3.26. Though it yields a reasonable fit to the experimental data at higher energies there is still 25 -40% under prediction in the sub-barrier energy range $E_{c.m.} = 5.6-6.4$ MeV. The effect of the projectile deformation is seen to be small and is not shown. It is possible that other types of coupling, e.g., transfer and/or breakup are responsible for the remaining discrepancy.

We also investigated the nature of the variation of logarithmic derivative of the product of fusion cross section and energy i.e., $\sigma E$ with energy (E) in c.m. for the system $^7$Li+$^{28}$Si at near barrier energy. A recent observation [66] at sub-
barrier energies showed that, the product of the fusion cross section ($\sigma$) and the c.m. energy ($E$) for $^{60}\text{Ni}+^{89}\text{Y}$, falls much faster than the usually accepted exponential falloff. They analyzed this steep falloff in terms of the logarithmic derivative ($L$) of the product $\sigma E$ defined by eq. (3.7).

$$L(E) = \frac{d\ln(\sigma E)}{dE} = \frac{1}{\sigma_E} \frac{d(\sigma E)}{dE}$$  \hspace{1cm} (3.7)

Their results showed a continuous increase with decreasing bombarding energy in contradiction to theoretical prediction with Wong's prescription [49]. This discrepancy was attributed by Hagino et al. [67] to a deviation of the parabolic shape
of potential assumed by Wong [49], from the asymmetric shape of the Coulomb barrier and was explained by using a large diffuseness of the ion-ion potential. To investigate the nature of the fall of $\sigma E$ for our system we have plotted in Fig. 3.27 the experimental values of L obtained from consecutive fusion data points together with the Wong's prediction. Here also we find increasing $L$ with decreasing $E$ below the barrier while the theoretical prediction saturates to a constant value below the barrier. However the increase is not that steep as is observed by Jiang et al. [66].

The $\gamma$-measurement usually yields the total fusion cross section (TF) consisting of CF and ICF components. We could not experimentally distinguish between CF and ICF events (occurring from breakup/transfer followed by fusion) because there will be overlapping residual nuclei produced in CF and ICF similar to the above barrier measurement. The residues $^{30}$P, $^{30}$Si, $^{27}$Al, $^{29}$Si, $^{32}$S and $^{31}$P may be produced by incomplete fusion with evaporation of protons and neutrons predicted by CASCADE/PACE2, assuming that the projectile breakup components $t$ and $\alpha$ are moving with beam velocity after breakup.

PACE2 predict that for $t$-ICF, $^{30}$P is the most dominating channel at lower energies, i.e., $E_{lab}=7$-11.5 MeV, which contributes 51-47% of the $t$-incomplete fusion process. Other residues contribution are 25-27% ($^{30}$Si), 11-14% ($^{27}$Al), 12-13% ($^{29}$Si), in the above energy range. In our measurement the contribution of 0.677 MeV $\gamma$ line of $^{30}$P was found to be poor with good agreement with CASCADE, but was not observed at the lowest two energies (7, 8 MeV). We did not find $\gamma$-rays of $^{27}$Al and $^{29}$Si at these energy range. However, substantial contribution of 2.230+2.235 MeV ($^{32}$S+$^{30}$Si), 1.263 MeV ($^{30}$Si) $\gamma$-ray were observed. Enhanced yield of 1.263 MeV $\gamma$-ray for $^{30}$Si compared to CASCADE prediction was found in the lower energy region $E_{lab}=7$-9 MeV. The 2n-transfer channel produces the same residue $^{30}$Si. But according to Pakou et al. [34] $d$-transfer (which produces $^{30}$P) is the dominant mechanism at near barrier energies in the reaction $^7$Li$^{+28}$Si. So we can argue with some confidence that contribution of $^{30}$Si in $t$-ICF may be more. PACE2 have

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shown that for $\alpha$-ICF, the most dominating channel is $^{32}$S, which accounts for 100% of the $\alpha$-incomplete fusion process in the energies $E_{\text{lab}} = 8.5 - 10$ MeV. However 99% contribution estimated for $^{31}$P at an energy 11.5 MeV. The results are not found satisfactory at the energy 7 or 8 MeV which correspond to $E_\alpha \leq 4.6$ MeV below the Coulomb barrier of $\alpha + ^{28}$Si where PACE2 fails to predict. In our measurement we did not observe $^{31}$P and here also we found that contribution of $\alpha$-ICF is negligible compared to $t$-ICF.

To summarise, we have experimentally determined the excitation function for $^7$Li+$^{28}$Si [68] at near and mostly sub-barrier energies, for the first time, employing the usual characteristic $\gamma$-ray method. Below the barrier our results show some sort of enhancement when compared with 1D BPM prediction. Introduction of coupling to target rotational motion improves the fit with experiment to some extent. Recently Shrivastava et al. [69] have advocated in their work on $^7$Li+$^{68}$Co that neutron transfer is more probable than all other possible direct reactions and hence an n-transfer followed by fusion may be a possibility. Sub-barrier enhancement owing to n-transfer (with positive Q-value) has been shown by Zagrebaev [70] for the fusion of $^6$He with $^{206}$Pb. However Pakou et al. [34] pointed out in their work on direct and compound contribution in the reaction $^7$Li+$^{28}$Si that d-transfer is the dominant mechanism at near barrier energies. These imply that the picture is not yet clear. So it is necessary to do a detailed theoretical analysis (utilizing more realistic coupled reaction channels model) introducing these possible couplings for a better and complete understanding of the phenomenon.