Chapter 4

Measurements of $\alpha$-particle multiplicities in heavy-ion fission reactions

4.1 Introduction

In heavy-ion induced fusion-fission reactions, neutron and charged-particle (mainly proton and $\alpha$-particle) emission takes place from various stages, namely from the fissioning compound nucleus (prescission) and from the accelerated fission fragments (postscission) [96, 97]. Prescission neutron and charged particle emission spectra and multiplicities provide important information on the statistical and dynamical aspects of the fusion-fission process [96, 97]. In the case of $\alpha$-particle emission, it is observed that particles are also emitted very near the neck region in the fission process just before scission, akin to the ternary fission events in low energy fission [129–133]. This part of prescission $\alpha$-particles emitted near the neck region is termed as near scission emission (NSE). Moving-source analysis is employed in heavy-ion-induced fission to disentangle the contributions of different sources to the inclusive $\alpha$-particle multiplicity. Although there have been many studies on prescission $\alpha$-particle emission in many heavy-ion induced fusion-fission reactions [96–98, 129–132], a global systematics is yet to be developed. Similarly, there are no systematic studies so far for the NSE over a large fissility ($x$) range in heavy-ion induced fusion-fission reactions.
In addition, at beam energies near the Coulomb barrier, the transfer induced fission cross section becomes significant [199–201]. In the case of $\alpha$-cluster projectiles (such as $^6$Li, $^6$He, and $^{12}$C), a portion of coincident $\alpha$ particles may also originate from transfer-induced fission events. In such cases, the projectile like fragment (PLF) can be an $\alpha$-particle itself or it can decay subsequently to an $\alpha$-particle. The $\alpha$ particles produced from transfer events exhibit a bell-shaped angular distribution having a maximum near the grazing angle. Thus, depending on entrance channel parameters of the heavy-ion reaction, the transfer processes can also contribute to the inclusive $\alpha$-particle multiplicity, adding to the complexity of the analysis of experimental data.

In the present work, we have carried out measurements of $\alpha$-particle energy spectra in coincidence with fission fragments for $^{11}$B (62 MeV) + $^{232}$Th ($Z^2/A = 37.14$) and $^{12}$C (69 MeV) + $^{232}$Th ($Z^2/A = 37.77$) systems in a wide range of relative angles between fission fragments and $\alpha$ particles. The $\alpha$-particle multiplicity spectra for each system at various relative angles have been fitted simultaneously with the moving-source model calculations to extract the components of multiplicity corresponding to different emission stages of the fusion-fission process. The obtained results for both the systems are compared with each other. In case of $^{12}$C induced fission, significantly large value of $\alpha_{\text{nse}}$ is observed as compared with $^{11}$B + $^{232}$Th system, indicating that due to $\alpha$-cluster structure of $^{12}$C there may be an admixture of some other source of $\alpha$-particle emission to the NSE component in the $^{12}$C + $^{232}$Th reaction apart from earlier mentioned four conventional sources involved in the fusion-fission process.

The data obtained for $^{11}$B + $^{232}$Th system are first analyzed along with data from literature over a wide range of excitation energy and fissility of the compound system to develop systematic features of pre- and near-scission emission as a function of $\alpha$-particle emission $Q$-value and $Z^2/A$ of compound systems. The anomalously large value of $\alpha_{\text{nse}}$ in case of $^{12}$C + $^{232}$Th reaction is then compared with above mentioned systematics, providing a strong clue to understand the $^{12}$C + $^{232}$Th reaction data.
Figure 4.1: A photograph of the first experimental setup where a 32-strip Si-detector was used for fission fragment detection.

4.2 Experimental details

Experiments were performed using $^{11}$B (62 MeV) and $^{12}$C (69 MeV) beams from the BARC-TIFR 14-MV Pelletron accelerator facility at Mumbai. A self-supporting thin metallic foil of $^{232}$Th with thickness 1.6 mg/cm$^2$ was used as a target. Measurements were carried out in two separate experiments. In the first experiment, the fission fragments were detected using a position sensitive 32-strip silicon detector (SSD) having delay line read-out [202] with an angular opening of $\sim$32$^\circ$ and centered at 150$^\circ$ with respect to the beam direction. In the second experiment, a position sensitive gridded gas ionization chamber consisting of $\Delta E_{\text{gas}}$ and $E_{\text{gas}}$ elements [156] was used to detect the fission fragments. The detector was centered at 145$^\circ$ with respect to beam direction and covered an angular opening of 30$^\circ$. In both the experiments, $\alpha$ particles were detected by three collimated CsI(Tl)-Si(PIN) detectors [142] with an angular opening of $\pm 3.5^\circ$. Photographs of experimental setups for the first and second set of
the experiments are shown in the Figs. 4.1 and 4.2, respectively.

4.2.1 CsI(Tl) detector response and energy calibration

The charged particle measurement for $^{11}$B + $^{232}$Th system was carried out in the first as well as the second set of the experiments, whereas for $^{12}$C + $^{232}$Th systems it was only the second set. In the first set of experiments, the CsI(Tl) detectors were placed at the back angles in the range of 115° to 155° on either side of the beam direction. In the second set of the experiments, the CsI(Tl) detectors were placed at angles of 70°, 105°, and 130° with respect to the beam direction in case of $^{11}$B + $^{232}$Th reactions, whereas in the case of $^{12}$C + $^{232}$Th reaction these angles were 75°, 100°, and 135°. The particle identification in CsI(Tl) detectors was achieved using a pulse shape discrimination (zero crossover) technique. The γ rays, light charged particles (p, d, t, and α), and PLFs were well separated in the two-dimensional plot of zero crossover (ZCT) versus pulse height.
Figure 4.3: Typical two-dimensional plots of zero crossover (ZCT) versus energy from CsI(Tl) detectors at laboratory angles of 100° (in panel (a)) and 135° (in panel (b)) for different particles produced in $^{11}$B + $^{232}$Th reaction.

as shown in Figs. 4.3(a) and (b) typically at two laboratory angles of 100° and 135°, respectively for $^{11}$B + $^{232}$Th system. The energy threshold for $\alpha$-particle identification was $\sim 9.5$ MeV (and $\sim 5$ MeV in second experiment). The higher threshold in the first experiment is due to a 14.9-$\mu$m aluminum foil used to stop the fission fragments.

The CsI(Tl) detectors were energy calibrated for $\alpha$-particles using $^{228,229}$Th source and in-beam energy calibration runs. In the first experiment, the in-beam calibration made use of the discrete $\alpha$-particle peaks corresponding to $^{15}$N* states from the reactions $^{12}$C ($^7$Li, $\alpha$) $^{15}$N* at a $^7$Li beam-energy of 15 MeV. In the second experiment the discrete states of $^{20}$Ne* from the $^{12}$C ($^{12}$C, $\alpha$) $^{20}$Ne* reaction at $^{12}$C beam energies of 25 and 40 MeV, were used. In the present work, however, we did not analyze the proton spectra, but the CsI(Tl) detectors were energy calibrated for protons also. For this purpose, elastically scattered protons from thin $^{12}$C, $^{197}$Au, and $^{232}$Th targets and recoil protons from the $^{12}$C beam-bombardment on mylar, were used. The measured light yield as a function of energy of $\alpha$ particles and protons are shown in Figs. 4.4(a) and (b), respectively for three CsI(Tl)-detectors; C1, C2, and C3 having different electronic gain settings. The light yield varies almost linearly for protons, whereas for $\alpha$
Figure 4.4: The light yield measured in the second set of the experiments as a function of energy of α particles (a) and protons (b) for three CsI(Tl)-detectors, C1, C2, and C3 having different electronic gain settings. (c) The light output ratio of proton to α-particle as a function of their energy deposited in the CsI(Tl) crystal.

particles, it is nonlinear. The $Z$ and $E$ dependent light yield shown in Figs. 4.4(a) and (b) was fitted with the following functional form:

$$L(Z, E) = a_e Z^b E^c + d_o,$$

(4.1)

where the constant $a_e$ and $d_o$ are related to electronics gain settings, while ‘$b$’ and ‘$c$’ depend on particle type and their response within the crystal, respectively. The value of the constant ‘$c$’ obtained for α-particle and proton are 1.3 and 1.0, respectively. The value of the constant ‘$c$’ was observed to be independent of the value of ‘$b$’. By varying the constant ‘$b$’, the parameter $a_e$ varies accordingly but the value of ‘$c$’ remains constant which is consistent with the earlier reported results [164]. In Figs. 4.4(a) and (b) solid lines show the fit to the light output data using the Eq. (4.1). The ratio of light output for proton to α-particle was obtained as a function of their energy, as shown in Fig. 4.4 (c). For a given energy deposited in the CsI(Tl) crystal, the light yield for proton is more than the α-particle and this difference decreases with increasing energy. The differences in light yield [4.4(a) and (b)] as well as the rise time [Fig. 4.3(a) and (b)] for α-particle and proton are attributed to their specific energy loss behavior (−d$E$/dx) in the crystal [142] as discussed in the chapter-2.
Table 4.1: Main features of the Si-strip detector [202].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitive area</td>
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</tr>
<tr>
<td>Thickness</td>
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</tr>
<tr>
<td>Number of strips</td>
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</tr>
<tr>
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</tr>
<tr>
<td>Inter-strip distance</td>
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</tr>
<tr>
<td>Working voltage</td>
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</tr>
<tr>
<td>Breakdown voltage</td>
<td>&gt;300 V</td>
</tr>
<tr>
<td>Thickness of upper dead layer</td>
<td>5 μm</td>
</tr>
<tr>
<td>Thickness of lower dead layer</td>
<td>5 μm</td>
</tr>
</tbody>
</table>

4.2.2 Measurement of FF: 32-strip Si-detector

In the first set of the experiments [Fig. 4.1], a position sensitive 32-strip silicon detector (SSD) with delay line read-out [202] was used for the fission fragment detection. The detector was centered at 150° with respect to the beam direction and covered an angular opening of ~32°. The Si-strip detector was fabricated at Bharat Electronics Laboratory, Bengaluru, India in collaboration with Electronics Division of BARC, Mumbai, India using an n-Si substratum with resistivity of 25 kΩ cm. The p⁺ n⁻ junctions were made with implanted boron using planar technology. The major specifications of the detector are shown in the Table 4.1. However, the active area of the detector was 60×60 mm², but during the experiment it was masked to 48×42 mm².

The position information is obtained by using the delay line method. Unlike coupling the detector strip and delay-line tap directly, a two-stage AC coupled common source FET amplifier is used in between each detector strip and delay-line tap. The delay-line circuit is essentially a low-pass filter made from LC cells. In the present circuit the value of inductor (L) is 36 μH and capacitance (C) is 4.7 pF. Thus, the
calculated value of characteristic impedance \( Z_o = \sqrt{L/C} \) is \( \sim 2.7 \) k\( \Omega \) and per cell delay \( \tau_d = \sqrt{L \times C} \) comes to be \( \sim 13 \) ns. Each tap of delay-line is made up of two cells (interleaving one cell in between). Thus, calculated value of per tap delay becomes \( \sim 26 \) ns but we get practical value \( \sim 30 \) ns due to stray capacitance of the tracks of printed circuit board (PCB). In total 16 such amplifiers and above mentioned LC delay-line circuit were assembled on a small printed circuit board which was mounted on the rear side of 32-strip Si-detector. Surface mounted devices (SMD) resistors, capacitors and inductors were used to reduce the size of the PCB. The gain of each amplifier was adjusted in the range of 2 - 5 by changing the value of bypass capacitance in the source FET circuit, thus, compensating against higher attenuation suffered by the position signal of the strip facing higher delay. In this way, we have made the amplitude of position signal of all strips almost equal and thereby, achieving reduction in the broadening of position signal peaks. A photograph of the detector along with the delay line electronics is depicted in the Fig. 4.5. The 32-strip silicon detector is seen in the front and the PCB consisting of two sets of 16-tap delay-line and 16 units
Figure 4.6: A typical two-dimensional fission fragment position versus energy spectrum in $^{11}\text{B} + ^{232}\text{Th}$ reaction obtained from one set of 16 strips. In the right-hand-side, strip positions are marked, where '1' and '16' correspond to the central region and the extreme right-end of the detector.

Two time-to-amplitude converters (TACs) were used to generate the position signals where start signal was derived from common electrode (cathode) of detector and the stop signals were derived from position (anode-strip) side after delay line read-out through all 32 strips. The common energy signal after energy pre-amplifier was shaped through a shaping amplifier. A typical two-dimensional position versus energy spectrum obtained from one set of 16 strips in $^{11}\text{B} + ^{232}\text{Th}$ reaction, is shown in the Fig. 4.6. In the right-hand-side of the Fig. 4.6, strip positions are marked, where '1' and '16' correspond to the central region and the extreme right-end of the detector. The higher strip position correspond to the large angle with respect to the beam direction.
4.2.3 Measurement of FF: Position sensitive gas ionization chamber

In the second experiment, a position sensitive gridded gas ionization chamber consisting of $\Delta E_{gas}$ and $E_{gas}$ elements [156] was used to detect the fission fragments. The detector was centered at 145° with respect to beam direction and covered an angular opening of 30°. A photograph of this position sensitive gas telescope is depicted in the Fig. 4.7. Basic characteristics of the detector are discussed earlier in the chapter-2.

The detector was filled with P-10 (90% Ar + 10% CH₄ mixture) gas and kept at a constant pressure of 150 mbar in a gas-flow mode throughout the experiments. The cathode was kept at -100 V and positive voltages applied to the grid (+125 V) and anode (+250 V). The $\Delta E$ anode segment is further split into two segments as shown in the Fig. 4.7, in such a way that the average $dE/dx$ is almost equal in both the regions for the FFs entering the central line of the detector. FFs, passing at any other angle will lose energies proportional to the path lengths in $\Delta E_1$ and $\Delta E_2$ regions. A
Figure 4.8: Two-dimensional plots of $\Delta E_1$ vs. $\Delta E_2$ [in panel (a)] and $\Delta E_1 + K_g \Delta E_2$ vs. residual energy loss $E_R$ [in panel (b)] of the fission fragments produced in $^{12}$C + $^{232}$Th reaction. $K_g$ is the gain matching factor between $\Delta E_1$ and $\Delta E_2$ (see text).

typical $\Delta E_2$ vs. $\Delta E_1$ plot is shown in the Fig. 4.8(a), where FFs are clearly separated from projectile like fragments (PLFs) produced in $^{12}$C + $^{232}$Th reaction. The Fig. 4.8 (b) shows the $(\Delta E_1 + K_g \Delta E_2)$ vs. $E_R$ plot, where $E_R$ is the residual energy deposited by the FFs in the E-segment of the anode. $K_g$ is a ratio of electronic gains of $\Delta E_1$ to $\Delta E_2$, and was measured to be 2.2 using the pulse generator. The position information was obtained using the charge division method. Position parameter is defined as:

$$x = \frac{\Delta E_1 - K_g \Delta E_2}{\Delta E_1 + K_g \Delta E_2}. \quad (4.2)$$

A typical position spectrum obtained from the gas ionization telescope in $^{12}$C + $^{232}$Th reaction, is shown in the Fig. 4.9. The total width of the position spectrum corresponds to the detector angle opening of $30^\circ$. Thus, gas ionization chamber in the $\Delta E$ vs. $E$ arrangement, provides angle information of the FFs with respect to the beam direction as well as a clear disentangling between FFs and the PLFs.

### 4.2.4 Electronics configuration for coincidence measurements

The linear energy outputs from all the detectors were fed to analog-to-digital converters (ADCs) after suitable amplification through spectroscopy amplifiers. The ZCT outputs
from the CsI(Tl) detectors and the two position TAC-outputs from the 32-strip detector were also fed to the ADCs. The event trigger for data collection was generated with the fission events from the FF-detector via a combination of timing filter amplifier (TFA), constant fraction discriminator (CFD). In case of the gas detector, the timing signal was obtained from the cathode. Schematic layout of the electronics used for charged particle and fission fragment coincidence measurements is given in Fig. 4.10. The ‘PSD BLOCKS’ in the Fig. 4.10 refer to the electronics configuration of pulse shape discrimination which has been discussed in detail in the chapter-2.

The time correlations between light particles and FFs were recorded through time-to-amplitude converters (TACs). The coincidence TAC spectra between $\alpha$ particles and FFs obtained in the first set of experiments (for $^{11}$B + $^{232}$Th system) and in the second set (for $^{12}$C + $^{232}$Th system) are shown in the Figs. 4.11(a) and (b), respectively. The coincidence TAC-spectrum is quite sharp in case of the 32-strip Si-detector (width $\sim$70 ns), whereas for the gas detector it is comparatively broader (width $\sim$120 ns). This difference in the widths of TAC spectra obtained from 32-strip Si-detector and the gas detectors is attributed to the larger rise time of the gas detector pulse than that
Figure 4.10: Schematic layout of the electronics used for charged particle and fission fragment coincidence measurements. The ‘PSD-BLOCKS’ refer to the electronics configuration of pulse shape discrimination which has been discussed in detail in the chapter-2.
of Si-detector. The coincidence TACs were used to correct for random coincidences.

The stability of the amplifier gains corresponding to various detectors was monitored using a precision pulser throughout the measurements. The data were recorded in a list-mode using CAMAC based multi-parameter data acquisition system.

4.3 Data Analysis: Moving-source fit

The angular opening of the fission detector in both the experiments was divided into four equal parts. Thus, in case of $^{11}$B + $^{232}$Th reaction, a total number of 24 combinations of $\alpha$-particle spectra each having different relative angles with respect to the beam ($\theta_\alpha$) and fission fragments ($\theta_{\alpha,fd}$), were obtained from the combined geometry of both the experiments. Whereas for $^{12}$C + $^{232}$Th system, a total number of 12 combinations of $\alpha$-particle spectra were obtained from the second set of the experimental geometry.

The inclusive $\alpha$-particle coincidence spectra were projected out from the list-mode data by imposing separate gate conditions: (i) prompt coincidence TAC, (ii) the se-
Figure 4.12: The $\alpha$-particle multiplicity spectra in $^{11}$B + $^{232}$Th reaction along with fits of moving-source model for different combination of laboratory angles of CsI(Tl) detectors with respect to beam direction, $\theta_\alpha$ and detected fission fragments, $\theta_{\alpha\text{fd}}$. The dotted, long-dashed, short-dashed, and dash-dot curves are contributions from compound nucleus, detected fission fragment, complementary fission fragment, and near scission emission, respectively. The solid curve indicates the total contribution from four sources.
Figure 4.13: The α-particle multiplicity spectra in $^{12}$C + $^{232}$Th reaction along with fits of moving-source model for different combination of laboratory angles of CsI(Tl) detectors with respect to beam direction, $\theta_{\alpha}$ and detected fission fragments, $\theta_{\alpha/fd}$. The dotted, long-dashed, short-dashed, and dash-dot curves are contributions from compound nucleus, detected fission fragment, complementary fission fragment, and near scission emission, respectively. The solid curve indicates the total contribution from four sources.
Figure 4.14: Schematic velocity diagram for α-particle emission from different sources such as compound nucleus, fission fragments (FE), and near-scission emission (NSE). The circles represent the most-probable velocities of α particles emitted from compound nucleus (dash-dot), from detected fragment (dotted), and complementary fragment (dashed). The NSE is perpendicular to the scission axis defined by the detected fragment direction.

lection of the fission - fragment angle with respect to the beam, (iii) an appropriate two-dimensional banana-gate to select the fission events; from FF energy versus coincidence TAC in the first set of the experiments and from ΔE vs. E-plot in the second set of the experiments, and (iv) an appropriate two-dimensional banana-gate to select the only α particles from ZCT versus energy plots for each charged particle detector. After correcting for random coincidence, the normalized α-particle multiplicity spectra were obtained by dividing the coincidence spectra with total number of fission single events. Figs. 4.12 and 4.13 show typical normalized α-particle multiplicity spectra for $^{11}$B + $^{232}$Th and $^{12}$C + $^{232}$Th systems, respectively.

The inclusive coincidence α-particle spectra shown in the Figs. 4.12 and 4.13 includes contributions from the compound system (precission), the accelerated fission fragments (postscission), and the near scission emission (NSE). The Procedure to disentangle the inclusive spectrum into precission, postscission and near-scission components, relies upon the energy and angular distributions of the α particles. The presciss-
sion and postscission particles are emitted isotropically in their respective rest frames, in the laboratory frames they are focused in the moving direction of the corresponding source; termed as the kinematic focusing. The near-scission emission of $\alpha$ particles takes place perpendicular to the scission axis. However, the kinematic focusing is more effective for lighter particles, but in case of $\alpha$ particles, the significant difference between the emission barriers for various emitting sources makes more effective the disentangling of the inclusive spectrum into prescission, postscission and near-scission components. For each system, multiplicity spectra are fitted simultaneously by the moving-source model including four different sources namely the compound nucleus, the two complementary fission fragments, and the NSE.

### 4.3.1 Prescission and postscission components

The $\alpha$-particles are assumed to be emitted isotropically in the rest frames of prescission and postscission sources. In the moving-source analysis, symmetric mass division is assumed for the fragments and mean values of fragment mass and charge have been used. The $\alpha$-particle energy spectra in the rest frames for prescission and postscission sources are calculated using the constant-temperature level-density formula with the expression [96, 203]:

$$n(\epsilon) = N \alpha_p \sigma(\epsilon) \exp \left( \frac{-\epsilon}{T} \right),$$  \hspace{1cm} (4.3)

where $\alpha_p$ and $\epsilon$ are the multiplicity and energy of the emitted $\alpha$-particles in the rest frame, $T$ is the temperature of the source, $\sigma(\epsilon)$ is the inverse reaction cross section and $N$ is a normalization constant, which was obtained using the condition:

$$\int_0^\infty n(\epsilon) d\epsilon = 1.$$  \hspace{1cm} (4.4)

The integration in the Eq. (4.4) was performed using the numerical recipe. The inverse reaction cross section $\sigma(\epsilon)$ is calculated using the Wong's expression [204]:

$$\sigma(\epsilon) = \frac{\hbar \omega R_0^2}{2\epsilon} \ln \left( 1 + \exp \left[ \frac{2\pi}{\hbar \omega} (\epsilon - V_B) \right] \right),$$  \hspace{1cm} (4.5)
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where $\hbar \omega$ is the curvature of fusion barrier for angular momentum $\ell = 0$. The values of $\hbar \omega$ for precission and postscission sources are determined from the fits to the fusion excitation functions for $^4\text{He} + ^{237}\text{Np}$ [205] and $^4\text{He} + ^{59}\text{Co}$ [206], respectively with the predictions of the one-dimensional barrier penetration model code CCUS [16]. Thus, $\hbar \omega_{\text{pre}}$ and $\hbar \omega_{\text{post}}$ values used in the moving-source model for precission and postscission sources are 4.8 and 4.0 MeV, respectively. The $V_B$ is the emission barrier height of the $\alpha$-particles and is calculated using the expression [134];

$$V_B = \frac{1.44Z_F(Z_S - Z_F)}{r_0 \left[ A_p^{1/3} + (A_S - A_p)^{1/3} \right] + \delta} \text{MeV}, \quad (4.6)$$

where $A_p$, $Z_F$ and $A_S$, $Z_S$ are the mass and charge of the $\alpha$-particle and emitting source, respectively. The value of $r_0$ is taken to be 1.45 fm [96]. $\delta$ is a factor which takes into account for the reduction in emission barrier due to deformation effects and it is taken to be 2.0 fm for compound nucleus [134] and 0.4 fm for fission fragment [98, 207]. Thus, the effective emission barrier heights ($V_B$) calculated for the compound nucleus and fission fragment are 20.2 and 13.4 MeV for $^{11}\text{B} + ^{232}\text{Th}$ system and 20.3 and 13.5 MeV for $^{12}\text{C} + ^{232}\text{Th}$ system, respectively. The temperatures $T_{\text{pre}}$ and $T_{\text{post}}$ are calculated using the relation $T = \sqrt{E^*/a}$, where $E^*$ is the intrinsic excitation energy of the source. The excitation energies for fission fragments are calculated using the relation:

$$E_f^* = E_{\text{CN}} + Q_f - TKE - E_{\text{part}}^\text{pre}, \quad (4.7)$$

where, $E_{\text{CN}}$ is the excitation energy of the compound nuclei and its value for $^{11}\text{B} + ^{232}\text{Th}$ and $^{12}\text{C} + ^{232}\text{Th}$ systems are 45.5 and 42.8 MeV respectively. In Eq. (4.7), the $Q_f$ and $TKE$ are the $Q$-value for the fission process and average total kinetic energy of the fission fragments. The values of $Q_f$ are calculated from experimental masses assuming symmetric fission. The $TKE$ values are calculated using the Viola’s systematics [105]. In Eq. (4.7), $E_{\text{part}}^\text{pre}$ is the CN excitation energy loss due to precission particle emission; it is a sum of kinetic energy and binding energy of the precission particle (dominantly neutron) emission. The average kinetic energy of the neutron was assumed to be 2.5
MeV. The precission neutron multiplicity $\nu$, was estimated from the systematics. The level-density parameter $a$ is taken as \( A/11 \) for compound nucleus and \( A/7 \) for fission fragments \cite{96}. $T_{\text{pre}}$ is scaled down by a factor of \( 11/12 \) to account for multi-step evaporation \cite{96, 208, 209}. Thus, $T_{\text{pre}}$ and $T_{\text{post}}$ values are calculated to be 1.2 and 1.25 MeV for \(^{11}\text{B} + ^{232}\text{Th}\) system and 1.18 and 1.25 MeV for \(^{12}\text{C} + ^{232}\text{Th}\) system, respectively.

### 4.3.2 Near-scission component

Near scission emission takes place dominantly perpendicular to the scission axis \cite{77} and peaks at an energy in-between the compound nucleus emission and fragment emission peaks. The energy and angular distributions for NSE are assumed to be Gaussian in the rest frame as given by the expression \cite{96};

\[
n(\epsilon, \theta) = N_{\text{nse}} \alpha_{\text{nse}} \exp \left[ \frac{-(\epsilon - \epsilon_p)^2}{2\sigma_e^2} \right] \exp \left[ \frac{-(90^\circ - \theta)^2}{2\sigma_\theta^2} \right],
\]

where $\epsilon$, $\alpha_{\text{nse}}$, $\epsilon_p$, $\theta$, $\sigma_e$, and $\sigma_\theta$ are the $\alpha$-particle multiplicity of near scission emission, peak (or mean) energy, relative angle of $\alpha$-particles with respect to the scission axis, standard deviations of the energy, and the angular distributions, respectively, in the rest frame. The $N_{\text{nse}}$ is the normalization constant.

The $\alpha$-particle spectra calculated in rest frames of four sources are converted to laboratory frames using the appropriate Jacobians and finally summed up to fit the measured spectra. In the moving-source fit, the parameters $T_{\text{pre}}$, $T_{\text{post}}$, $V^\text{pre}_B$, and $V^\text{post}_B$ are not varied whereas the precission and postscission multiplicities ($\alpha_{\text{pre}}$ and $\alpha_{\text{post}}$) and parameters related to NSE, are kept as free parameters. The mean fragment velocities are determined using Viola’s systematics \cite{105} for the total kinetic energy released in fission process.
Figure 4.15: The α-particle multiplicity spectra in $^{11}$B + $^{232}$Th reaction along with fits of moving-source model for different combination of laboratory angles of CsI(Tl) detectors with respect to beam direction, $\theta_\alpha$ and detected fission fragments, $\theta_{\alpha/\text{fd}}$. The dotted, long-dashed, and short-dashed, are contributions from compound nucleus, detected fission fragment, and complementary fission fragment, respectively. The solid curve indicates the total contribution from three sources.

4.4 Results and discussion

For $^{11}$B + $^{232}$Th system, the fitted spectra for the individual source and after summing are shown in Fig. 4.12. The values of the parameters corresponding to the best fit are found to be $\alpha_{\text{pre}} = (5.2 \pm 0.1) \times 10^{-3}$, $\alpha_{\text{post}} = (0.17 \pm 0.02) \times 10^{-3}$, $\alpha_{\text{nse}} = (0.5 \pm 0.05) \times 10^{-3}$, $\epsilon_p = 19.3 \pm 0.3$ MeV, $\sigma_x = 3.4 \pm 0.2$ MeV, and $\sigma_\theta = 11.5^\circ \pm 1.6^\circ$ having a minimum $\chi^2/(\text{degree of freedom})$ value of 5.07. Fits, for $^{11}$B + $^{232}$Th system are also obtained by excluding the NSE component in the moving-source model, the fitted spectra for the individual source and after summing are shown in Fig. 4.15 for typically 6 of 24 combinations of $\theta_\alpha$ and $\theta_{\alpha/\text{fd}}$. The best-fitted values are $\alpha_{\text{pre}} = (5.8 \pm 0.1) \times 10^{-3}$ and $\alpha_{\text{post}} = (0.16 \pm 0.02) \times 10^{-3}$, corresponding to minimum $\chi^2/(\text{degree of freedom})$ value of 6.1. Here the errors quoted in the extracted parameters include only statistical uncertainties. It is seen that fitting quality of the spectra improves
Table 4.2: α-particle multiplicities corresponding to different emission stages for both the systems. The temperatures, emission barriers, and parameters related to near-scission emission are also given.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$^{11}$B + $^{232}$Th</th>
<th>$^{12}$C + $^{232}$Th.</th>
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</thead>
<tbody>
<tr>
<td>$E_{CN}$ (MeV)</td>
<td>45.5</td>
<td>42.8</td>
</tr>
<tr>
<td>$T_{pre}$ (MeV)</td>
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<td>1.18</td>
</tr>
<tr>
<td>$T_{post}$ (MeV)</td>
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<td>1.25</td>
</tr>
<tr>
<td>$V_{pre}^B$ (MeV)</td>
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<td>20.3</td>
</tr>
<tr>
<td>$V_{post}^B$ (MeV)</td>
<td>13.4</td>
<td>13.5</td>
</tr>
<tr>
<td>$\alpha_{pre}$</td>
<td>$(5.2 \pm 0.1) \times 10^{-3}$</td>
<td>$(5.4 \pm 0.2) \times 10^{-3}$</td>
</tr>
<tr>
<td>$\alpha_{post}$</td>
<td>$(0.17 \pm 0.02) \times 10^{-3}$</td>
<td>$(0.13 \pm 0.04) \times 10^{-3}$</td>
</tr>
<tr>
<td>$\alpha_{nse}$</td>
<td>$(0.5 \pm 0.05) \times 10^{-3}$</td>
<td>$(3.1 \pm 0.2) \times 10^{-3}$</td>
</tr>
<tr>
<td>$\epsilon_p$ (MeV)</td>
<td>19.3 ± 0.3</td>
<td>19.25 ± 0.10</td>
</tr>
<tr>
<td>$\sigma_\epsilon$ (MeV)</td>
<td>3.4 ± 0.2</td>
<td>1.66 ± 0.10</td>
</tr>
<tr>
<td>$\sigma_\theta$</td>
<td>$11.5^\circ \pm 1.6^\circ$</td>
<td>$17.9^\circ \pm 1.1^\circ$</td>
</tr>
</tbody>
</table>

particularly for $\theta_{\alpha_{ld}} \sim 90^\circ$ if the NSE component is included in the moving-source model. It should be noted here that in contrast to the works by Wilczynska et al. [132] for $^{40}$Ar + $^{232}$Th and Lindl et al. for $^{37}$Cl + $^{124}$Sn and $^{28}$Si + $^{144}$Pr systems [129], in the $^{11}$B + $^{232}$Th reaction the small value of $\alpha_{nse}$ and closeness of peak energies of precission and near-scission emission do not make the spectral shapes of $\theta_{\alpha_{ld}} \sim 90^\circ$ differ very much from those which are away from $\theta_{\alpha_{ld}} = 90^\circ$.

For $^{12}$C + $^{232}$Th system, the fitted spectra for the individual source and after summing are shown in Fig. 4.13 for 9 out 12 combinations of $\theta_{\alpha}$ and $\theta_{\alpha_{ld}}$. The best fitted values of the parameters are found to be $\alpha_{pre} = (5.4 \pm 0.2) \times 10^{-3}$, $\alpha_{post} = (0.13 \pm 0.04) \times 10^{-3}$, $\alpha_{nse} = (3.1 \pm 0.2) \times 10^{-3}$, $\epsilon_p = 19.25 \pm 0.10$ MeV, $\sigma_\epsilon = 1.66 \pm 0.10$ MeV, and $\sigma_\theta = 17.9^\circ \pm 1.1^\circ$ corresponding to a minimum $\chi^2$/degree of freedom value of 3.71. The results obtained from four-source analysis for $^{11}$B + $^{232}$Th and $^{12}$C + $^{232}$Th systems are shown in the Table 4.2. The $\alpha_{pre}$ and $\alpha_{post}$ values for both the systems are similar, whereas the NSE multiplicity for $^{12}$C + $^{232}$Th system is significantly larger than
\(11^B + ^{232}\text{Th}\) system having similar fissility, excitation energy, and angular momentum. Extracted standard deviations for energy and angular distributions of the near-scission emission (\(\sigma_\varepsilon\) and \(\sigma_\theta\)) are also observed to be significantly different for both the systems. These observations indicate that due to \(\alpha\)-cluster structure of \(^{12}\text{C}\) there is an admixture of some other source of \(\alpha\)-particle emission to the NSE component in the \(^{12}\text{C} + ^{232}\text{Th}\) reaction apart from earlier mentioned four conventional sources involved in the fusion-fission process.

In the next chapter, an attempt made to reproduce the precission multiplicities using the statistical model codes, will be discussed. Further, the precission and near-scission data from \(11^B + ^{232}\text{Th}\) system has been analyzed along with the literature data to develop certain global features of the precission and near-scission emission characteristics. The anomalous results obtained above for \(^{12}\text{C} + ^{232}\text{Th}\) reaction are then compared with systematics which provide more strong clue to understand these puzzling results.