Chapter 6

Summary, conclusions and future outlook

The statistical and dynamical aspects of the excited nuclei in the two dimensional space of excitation energy ($E_X$) and angular momentum ($J$) play a key role in understanding a wide range of nuclear phenomena. The heavy-ion collisions bring in high $E_X$ and $J$ values to the system and enable to study the excited nuclei of a variety of choices in a wide range of $E_X$ and $J$ by varying the $Z$ and $A$ of the projectile and target nuclei. In particular, the fusion reaction leads to compound nucleus formation where complete amalgamation of projectile and target takes place. In the first part of the present thesis, the statistical aspects in the decay of medium heavy compound nuclei ($Z \sim 50 - 70$), in particular the spin dependence of the nuclear level-density has been investigated. The second part of the thesis addresses the dynamical aspects involved in the nuclear fission decay. Summary, conclusions, and future outlook for the present thesis work are discussed in the following sections.

6.1 Summary and conclusions

With the motivation of investigating the spin dependence of the nuclear level-density parameter ‘$a$’, a series of experiments have been performed where we have measured the $\gamma$-ray-multiplicity-fold gated $\alpha$-particle energy spectra in heavy-ion fusion reactions
which populate residual nuclei in the shell-closure region of \( Z \sim 50 \) and mid-shell region of \( Z \sim 70 \) at an excitation energy range of 30 to 40 MeV. The target-projectile systems selected in the present work correspond to a range of entrance-channel mass-asymmetry, \( \alpha = (A_T - A_P) / (A_T + A_P) \) spanning both sides of the Businaro-Gallone critical mass-asymmetry (\( \alpha_{BG} \)). The results do not indicate any effect of \( \alpha_{BG} \) on the level-density parameter in the compound nuclear reactions.

Despite placing the charged particle detectors at the back angles with respect to the beam direction, the light mass impurities (carbon and oxygen) that are present in the targets contribute to the low energy tails in the energy spectra for mainly two of the light projectiles (\(^{11}\text{B} \) and \(^{12}\text{C} \)). The \( \alpha \) particles originating from the reactions with impurity elements appeared in the spectra at low energies, particularly for the low multiplicity folds. This low energy component was treated as a background and was removed in the shell-closure region of \( Z \sim 50 \) by following a least squares fit procedure. In the mid-shell region of \( Z \sim 70 \) and \( A \sim 180 \), the background dominated for low \( \gamma \)-ray folds (up to fold 3). Therefore, in the mass region of \( A \sim 180 \), analysis has been carried out only for fold 4 and above events, where the background contribution was seen to be negligible.

Fold to multiplicity conversion procedure was validated by measuring spontaneous fission \( \gamma \)-ray multiplicity of \(^{252}\text{Cf} \). The average \( \gamma \)-ray multiplicities of \(^{252}\text{Cf} \) for BGO energy thresholds of 100 keV and 150 keV were found to be \( \sim 7.8 \) and \( 9.3 \), respectively, which are consistent with the earlier reported values [144–147, 186, 187]. The first two moments of the multiplicity distributions in the reactions for the shell-closure region of \( Z \sim 50 \) were also determined. By comparing the moments of multiplicity distribution with those of initial compound nucleus spin distributions, the factor \( a_m \) used for conversion of \( \gamma \)-ray multiplicity to the compound nuclear angular momentum was determined to be around 1.5. Later on, the insensitivity of the slope of the high energy part of \( \alpha \) particle spectra with the factor \( a_m \) was confirmed. This ruled out any
possibility of uncertainty due to the factor $a_m$ in the the inverse level-density parameter $K = A/a$ determined from the slope of the high energy part of $\alpha$ particle spectra. In the analysis, each $\gamma$-ray multiplicity fold was converted to a corresponding average angular momentum in the residual nuclei following a procedure that utilizes the decay simulations and detector efficiency factors. The uncertainty of the assigned average angular momentum varied from $\pm 5$ to $\pm 3\hbar$ in going from low folds to high folds.

The aim in the present work was to compare the shape of the fold-gated as well as gross (summed over all $J$) experimental $\alpha$-particle spectra at well above the evaporation barrier energy with corresponding spectra from statistical model calculations using the code PACE2 and derive the inverse level density parameter $K$. By limiting the analysis of the energy spectra at well above the evaporation barrier, the uncertainties associated with the barrier transmission coefficients were avoided. Within the code PACE2, the phenomenological back-shifted Fermi-gas description of the nuclear level density was used. Ignatyuk's prescription for level-density parameter 'a' [41] was employed which takes into account the excitation energy dependent shell effects. The asymptotic value of the parameter 'a' was externally varied in the code through the input card. The normalization of the shape of the experimental spectra with that of the predicted one by statistical model calculation, was done by matching the area under the predicted spectra in the selected energy interval with that of the experimental spectra in the same energy interval. No attempts were made to fit the multiplicity of $\alpha$ particles.

In the shell closure region of $Z = 50$, the 'gross' $K$ value (summed over all $J$) was seen to be in the range 9.0 - 10.5 MeV, which is within liquid drop model estimate [137]. It was observed that the 'gross' $K$ value is the lowest for $Z_R = 50$, in contrast with what one would expect from known behavior of shell effects, by assuming persistence of shell effects even at this excitation energy. Maximum value of 'gross' $K$ was observed for $Z_R = 52$ and 53. We have no microscopic understanding of these observations but would like to point out that similar differences in level-density parameter in neighboring
nuclei have been observed earlier [193] at excitation energy around 60 to 90 MeV. The variation of $K$ as a function of angular momentum in the range of 5 to 30\,$h$ for the shell-closure region showed several interesting features not accounted by the shell and angular momentum corrected values of $K$ used in PACE2 calculations [137]. The overall trend in the shell-closure region did not suggest a constant value for $K$ over the full angular momentum range. Below about 15 \,$h$ of angular momentum, the $K$ values were similar to the corresponding ‘gross’ $K$ values for all the systems. For $Z_R = 49$, 50 and 51, a flat behavior for low angular momentum and then a downward trend for higher $J$ values was observed. Once the shell closure $Z_R = 50$ was crossed, for $Z_R = 52$ and 53 a dramatic change in the trend could be observed. In a repeat measurement we have re-confirmed the behavior for the $Z_R = 52$ system where there is a strong increase in $K$ with angular momentum. This trend continued for $Z_R = 53$ as well, but in a diminished manner. For $Z_R = 55$ and 48, the trend was also similar but with a much weaker increase of $K$ with angular momentum. In contrast to the shell closure region of $Z = 50$, in the mid-shell region of $Z \sim 70$ the average value of $K$ is 8.2 $\pm$ 1.1 MeV [138], and remains essentially constant around the average value in the angular momentum range of 15 to 30\,$h$ [138]. It is seen that the gross value of $K$ for the mid-shell region of $Z \sim 70$ and $A \sim 180$ is lower than that for the shell-closure region of $Z \sim 50$ and $A \sim 120$.

The present results are first of its kind for nuclei in the shell-closure region and in the mid-shell region, which point out certain effects not accounted for in the phenomenological prescriptions of NLD. These results would serve as important inputs for microscopic theories to understand the statistical properties of nuclei in different mass regions.

In case of heavy compound nuclear systems ($Z \gtrsim 80$ and $A \gtrsim 200$) populated in heavy-ion reactions, fission competes with particle emission and the dynamical effects become important along with the statistical ones. The dynamical effects during the
nuclear fission manifest in terms of the nuclear viscosity which lead to the energy dissipation from collective motion to the internal degrees of freedom. Despite substantial efforts, both experimentally and theoretically, the precise nature and magnitude of nuclear viscosity remains one of the major problems as yet unsolved in nuclear physics. The FFs kinetic energies, precession yields of neutrons, charged particles [96–98], GDR γ rays [99] from the compound system before fission have been used as probes to gain insight about the the precise nature and magnitude of nuclear viscosity.

Employing above probes the effect of nuclear viscosity inside and outside the saddle has been understood to a good extent. However, at the time of scission, the actual snapping up of the neck joining the two nascent fission fragments is still not clearly understood. Moreover, the probes mentioned above are not suitable in a wide energy regime from spontaneous fission to the heavy-ion fission. A suitable probe sensitive to scission point needs to be employed to address the above questions. Ternary fission (or near scission emission) presents a good choice for studying the nuclear viscosity in the wide energy regime. Using the NSE as a probe, the scission point characteristics such as the kinetic energy of the FFs, neck radius, FF separation, etc. can be determined. The kinetic energy at scission point carries important information about the transition from saddle to scission and energy dissipation during this transition. Thus, the NSE can provide the information about the nuclear viscosity not only during the scission process but also during the descent from saddle to scission.

With these motivations, measurements were carried out for α-particle energy spectra in coincidence with fission fragments for the systems of $^{11}$B (62 MeV) + $^{232}$Th ($Z^2/A = 37.14$) and $^{12}$C (69 MeV) + $^{232}$Th ($Z^2/A = 37.77$) in a wide range of relative angles with respect to FF emission direction. These measurements have been described in the second part of the present thesis. The measured energy spectra were fitted with moving source model calculations to extract the α-particle multiplicities corresponding to different emission stages of the fusion-fission process. The results in $^{11}$B + $^{232}$Th reaction
have been analyzed along with data from literature over a wide range of excitation energy \(E_{CN}\) and fissility \(x\) of the compound system to develop the systematic features of prefission and near-scission emission as a function of \(\alpha\)-particle emission Q-value and \(Z^2/A\) of the compound system.

The fraction of near-scission multiplicity \(\alpha_{nsc}\) is observed to be nearly same at around 10% of the total precession multiplicity \(\alpha_{pre} + \alpha_{nsc}\) for various systems over a wide range of \(Z^2/A\) and excitation energy suggesting that the near scission emission of \(\alpha\)-particles is a statistical process in heavy-ion induced fission reactions [139]. It is seen that precession \(\alpha\)-particle multiplicity \(\alpha_{pre}\) normalized to \(E_{CN}^{2/3}\) shows a systematic linearly increasing trend with \(\alpha\)-particle emission Q-value [139, 141]. The above observations indicate that the \(\alpha\)-particle emission from the neck is a statistical decay process at higher excitation energies, in contrast to low energy and spontaneous fission where the neck-emission is a dynamical or fast process. Therefore, it can be inferred that nuclear collective motion during scission exhibits a change over from super-fluid to viscous nature with increasing excitation energy. Existence of superfluidity within the nuclear medium has been a longstanding puzzle.

In case of \(^{12}\text{C}\) (69 MeV) + \(^{232}\text{Th}\) reaction, the near-scission multiplicity is observed to be anomalously enhanced in comparison to the heavy-ion systematics, indicating the presence of another source of \(\alpha\)-particle emission in the \(^{12}\text{C} + ^{232}\text{Th}\) reaction in addition to pre-, post-, and near-scission emission stages [140]. In the two-dimensional particle identification plot, a high energy component corresponding to the summed energy of two \(\alpha\) particles is observed. The observation of these 2\(\alpha\)-events suggests that due to the \(\alpha\)-cluster structure of \(^{12}\text{C}\), there is a significant component of \(^{8}\text{Be}\) breakup followed by \(\alpha\)-transfer induced fission events. Since the \(\alpha\)-transfer grazing angle for \(^{12}\text{C}\) (69 MeV) + \(^{232}\text{Th}\) system is at \(\sim 120^\circ\) [5], the intensity of these 2\(\alpha\)-events dominates at the backward angles with respect to the beam direction. The analysis of \(^{8}\text{Be}\) breakup explains very well the 2\(\alpha\)-particle multiplicity spectra at different laboratory angles.
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For the first time, a new component corresponding to transfer-breakup process has been considered in the moving source model to disentangle the different contributions to the inclusive $\alpha$-particle multiplicity. Reanalysis of the $\alpha$-particle multiplicity spectra including five sources in the moving source model: the compound nucleus, both the fission fragments, the NSE, and $^8$Be breakup was carried out. The results obtained for pre- and near-scission multiplicities follow the recently developed heavy-ion systematics very well. The present results clearly indicate an extra source of $\alpha$-particle emission in heavy-ion fusion-fission reactions due to $\alpha$-clustering in projectile nuclei [140].

The CsI(Tl)-Si(PIN) detectors, used for charged particle measurements in the second part of the thesis work, were characterized on various aspects [142]. Pulse height response of the detectors was investigated for fission fragments (FFs) produced in spontaneous fission of $^{252}$Cf. The scintillation light yield is observed to increase linearly as a function of energy for both the light and heavy FFs. At a given energy the light yield for heavier fragments is observed to be more than that of lighter ones. This indicates that the scintillation light yield for fission fragments follow the similar dependence on $dE/dx$ as of light charged particles and heavy-ions. The time resolution of the CsI(Tl)-Si(PIN) has been determined to be $134 \pm 3$ ns using $\gamma-\gamma$ coincidence method.

6.2 Future outlook

In the first part of the thesis, we obtained quite interesting results on spin dependence of the inverse level-density parameter $K$ in the shell-closure region of $Z \sim 50$ and mid-shell region of $Z \sim 70$ in the excitation energy range of 30 to 40 MeV. In order to understand the anomalous results of the shell-closure region of $Z \sim 50$, further refined measurements and at the same time microscopic calculations are worth to attempt.

In the present work, the parameter $K$ is determined for the residual nuclei after $\alpha$-particle emission. As pointed out earlier, $\alpha$-particle emission leaves residual
nuclei with $Z_R = Z_{CN} - 2$. Although, a major fraction of the $\alpha$ particles is emitted as a first chance emission, still some uncertainty remains in the mass of the residual nucleus. If coincidence measurements of $\alpha$-particles and $\gamma$ rays are performed with the tagging of the evaporation residues (ERs) of well defined mass and charge, issues related to the background and mass of the residual nucleus for which the parameter $K$ is determined, will be better resolved.

- In the present study, the parameter $K$ is determined by selecting one exit channel of the compound nuclear decay, the $\alpha$-particle emission. It is worth to investigate spin dependence of the parameter $K$ through other exit channels such as the proton and neutron emission.

- In the present study different final nuclei are produced using quite different reactions (in particular with different mass asymmetries). Though, the analysis of the reactions based on Businaro-Gallone critical mass-asymmetry reveals that all these reactions undergo normal compound nuclear formation without a di-nuclear complex formation. The BG analysis only serves as a guideline and is not a substitute to rule out the possible entrance channel effects. It would be helpful for the understanding if one and the same compound nucleus had been produced using different reactions (with different mass asymmetries), or if all compound nuclei had been produced by reactions with similar projectiles (and similar mass asymmetry), or best of all above to disentangle two effects, namely possible entrance-channel (reaction) effects on the $\alpha$-particle spectra and structure (level-density) effects.

- Due to limited efficiency of $\gamma$-ray detection and the uncertainty of angular momentum carried by individual $\gamma$-ray, it was not possible to convert $\gamma$-ray fold to spin value on event-by-event basis. Each $\gamma$-ray fold corresponds to a window of the angular momentum populated in the residual nuclei. It would be helpful to carry out these measurements with a larger $\gamma$-array with higher detection
efficiency to reduce the width of the assigned spin values to different $\gamma$-ray folds.

- If we closely examine the trends of the parameter $K$ with the spin in those cases of
  the shell-closure region of $Z \sim 50$ where strong variations are observed, it seems
  that $K$ increases with spin up to a certain spin value and then drops down. It
  would be interesting to investigate the parameter $K$ in higher spin domains in
  the reactions for which the dropping region of the $K$ was not feasible due to small
  value of the maximum angular momentum of the residual nuclei.

- From theoretical point of view, present study serves to provide important
  inputs for microscopic theories to understand the statistical properties of nuclei in
  different mass regions. It would be interesting to carry out calculations to repro-
  duce the parameter $K$ determined around the shell-closure and in the mid-shell
  regions. Recently, for the shell-closure region of $Z = 50$ of the present work,
  microscopic calculations were carried out [197] which show that the parameter $K$
  increases with angular momentum in all cases. These calculations are not fully
  consistent with the present measurements and detailed microscopic calculations
  will be useful to understand the dependence of $K$ on angular momentum.

In the second part of the thesis, we have developed for the first time the systematics
for pre- and near-scission emission $\alpha$-particle multiplicities in heavy-ion fission. In
case of $^{12}\text{C}$ (69 MeV) + $^{232}\text{Th}$ reaction, the near-scission multiplicity was observed
 to be anomalously enhanced in comparison to the heavy-ion systematics, which has
been understood by incorporating $^8\text{Be}$ breakup followed by $\alpha$-transfer induced fission
events. Present study invites further measurements as well as theoretical calculations
as discussed below;

- In case of near-scission systematics, since the available data are limited, it is de-
  sirable to measure the near-scission multiplicity for many other systems covering
  a wide range of fissility and excitation energy ($E_x$).
In the low excitation energy region, though the $E_X$ dependence is fairly weak, but at the same time it is also seen that the ternary yield in thermal or 1-MeV neutron induced fission (corresponding $E_{CN} = 6 - 8$ MeV) is less than in spontaneous fission of the same fissioning nucleus [122-124]. This behavior suggests that there might be a minimum in the $\alpha$-particle yield if measured at various energies in the interval of 1 to 20 MeV. This expectation is consistent with our conclusions that with increasing $E_X$ ternary $\alpha$-particle emission is governed by the statistical process, as opposed to the spontaneous fission case in which $\alpha$-particle emission takes place by dynamical process. This change over from dynamical emission to statistical process needs to be investigated in a systematic manner. Therefore, it is desirable to carry out measurement for the ternary yields in the energy interval of 1 to 20 MeV.

The peak energy for NSE $\alpha$ particles ($\epsilon_\alpha$) in low energy fission is constant within 15 to 16 MeV whereas in heavy-ion induced fission it is scattered from 12.5 to 19.5 MeV for different systems [96, 97, 129-132]. For low energy fission, inverse trajectory calculations [114-117] have been carried out to reproduce the observed peak energies, where in the initial conditions of three charges (positions and momenta) were considered without paying any attention to the neck rupture process. The available data on peak energy in heavy-ion fission systems are quite scattered and seems to fall into two groups. It would be interesting to carry out inverse trajectory calculations incorporating the neck rupture process in heavy-ion fission to reproduce the peak energies.

For $^{12}$C (69 MeV) + $^{232}$Th system, the $\alpha$-transfer grazing angle is at $\sim120^\circ$ with respect to the beam direction which is close to perpendicular to the scission axis in the present experimental geometry, therefore, NSE $\alpha$ particles had a strong overlap with the ones produced from $^8$Be breakup, enhancing the near scission multiplicity. It is worth to carry out these measurements at various beam
energies. With increasing beam energies of \(^{12}\text{C}\), the corresponding \(\alpha\)-transfer grazing angle will shift at forward angles with respect to the beam direction. Moreover, it would be of further interest to carry out the measurements using \(^{13}\text{C}\) projectile where \(\alpha\)-transfer will result in \(^{9}\text{Be}\) having high threshold for breakup.