Chapter 7

Summary, discussions and future outlook

7.1 Summary and discussions

In the present thesis, different aspects of statistical and dynamical models of heavy-ion induced nuclear fission are investigated in detail with the objective to understand the nature of nuclear dissipation and its importance in the fission dynamics. A general overview of the theoretical models and their applications in the study of fission processes is presented in Chapter 1. Specifically, we have elaborated on the two different chronological scenarios corresponding to the developments which happened before and after the advent of dissipative dynamics in the study of fission. We next discussed, in Chapter 2, the Langevin dynamical model for fission and the collective properties of an excited nucleus required for the dynamical calculations. The one-dimensional Langevin dynamical calculations are applied as benchmark in the subsequent chapters.

In Chapter 3, a statistical model calculation for the decay of a compound nucleus is presented where the compound nuclear spin dependence of the Kramers’ modified fission width is included [108]. Specifically, the spin dependences of the frequencies of the harmonic oscillator potentials osculating the rotating liquid-drop model potential at equilibrium and saddle regions are considered. First, the method of obtaining these frequencies is explained with the
view that the approximated potential resembles closely the corresponding liquid drop model potential over a wide range of nuclear deformation. Subsequently, statistical model calculations are performed for the $^{16}\text{O}+^{208}\text{Pb}$ system. Results show that the energy dependence of the dissipation strength extracted from fitting experimental data is substantially reduced when the spin dependence of the frequencies is properly taken into account.

In Chapter 4, it is shown that Kramers’ fission width, originally derived for a system with constant inertia, can be extended to systems with a deformation-dependent collective inertia, which is the case for nuclear fission. The predictions of Kramers’ width for systems with slowly varying inertia are found to be in very good agreement with the stationary fission widths obtained by solving the corresponding Langevin equations [27]. In general, the inertia associated with a collective coordinate depends on the choice of the collective coordinate and the underlying microscopic motion. We therefore extend the work on shape-dependent inertia and obtain an expression for stationary fission width for systems with steep shape-dependent nuclear collective inertia [109]. The domain of validity of this modified expression is examined by comparing its predictions with widths obtained from the corresponding Langevin equations.

In Chapter 5, we have examined the validity of extending Kramers’ expression for fission width to systems with shape-dependent dissipations [110]. For a system with a shape-dependent dissipation, Kramers’ width obtained with the presaddle dissipation strength is found to be different from the stationary width obtained from the corresponding Langevin equations. It is demonstrated that the probability of a hot compound nucleus undergoing fission depends on both the presaddle and the postsaddle dynamics of collective nuclear motion. The predictions for precission neutron multiplicity and evaporation residue cross section from statistical model calculations are also found to be different from those obtained from Langevin dynamical calculations when a shape-dependent dissipation is considered. For systems with shape-dependent dissipations, we conclude that the strength of presaddle dissipation determined by fitting experimental data in statistical model calculations does not represent the true strength of presaddle dissipation.
In Chapter 6, the fragment mass distribution from fission of hot nuclei is studied in the framework of two-dimensional Langevin equations. The mass asymmetry coordinate distribution is obtained from the dynamical calculation both at the saddle and the scission regions in order to investigate the role of saddle-to-scission dynamics in fission fragment mass distribution [103]. First, the collective properties are calculated in two dimensions. Subsequently, Langevin dynamical trajectories are obtained on the two-dimensional potential contours of different nuclei having a broad range of saddle-to-scission distances. Role of different dynamical forces in the fission fragment mass distribution during the saddle-to-scission transition are then examined quantitatively. Before that, a systematic study of the two-dimensional fission width is also presented in this chapter. At the end, statistical model predictions of mass asymmetry distributions at saddle and scission are compared with the dynamical model results. We point out that the observed near cancellation of the effects due to conservative and random forces during the descent of a CN from saddle to scission in determining the fission fragment mass distribution is specific to the collective fission coordinates and the nature of dissipation used in the present work. Questions may naturally arise regarding the consequences of including more collective degrees of freedom or changing the nature of dissipation on the saddle-to-scission dynamics and the resulting fission fragment mass distribution. It was shown earlier [181] that inclusion of the neck degree of freedom substantially increases the most probable fission path from saddle to scission. Consequently, one may expect that a fission trajectory will be subjected to random forces for a longer period, giving rise to a larger mass dispersion. The saddle-to-scission dynamics also changes when one considers a non-Markovian dissipation (and random force) instead of the Markovian dissipation used in the present work. By considering non-Markovian stochastic dynamics of fission, it has been shown [83] that the mean descent time from saddle to scission increases with the relaxation time of the collective coordinates. Thus the introduction of non-Markovian features in stochastic fission dynamics is also expected to increase the fission fragment mass variance. Evidently, more calculations are needed to explore the role of saddle-to-scission descent under different stochastic dynamical models in giving rise to the fission fragment mass distribution.
7.2 Future outlook

Our studies on the statistical and dynamical models of fission open up the following directions of research which can be attempted in future. In the present thesis, the conservative force for the fission dynamics is extracted from the finite range liquid drop model potential. To be more realistic, proper thermodynamic potential can be used for the dynamical evolution instead of the internal energy which is usually calculated from a liquid drop model. Dynamical model calculations are preformed [117] now a days using the free energy as the thermodynamic potential. A statistical model calculation is also developed [105] following the same consideration. However, for these type of calculations, one need to know the shape dependence of the level density parameter very accurately. Also, the choice of a particular thermodynamic potential in case of fission dynamics is not unique [185]. Nevertheless, if free energy is considered instead of liquid drop model potential then the nuclear potential profile becomes flatter along the fission degree of freedom and hence fission happens to be a faster process. As a result, larger dissipation strength will be required to reproduce the experimental data. However, the main findings of the present thesis are expected to remain unchanged with this modification.

Theoretically it is observed [186] that the dynamical fission width increases with the increase in the number of collective degrees of freedom. It therefore gives us the opportunity to study the effects due to the dimensionality of the dynamical modeling on various fission observables. Three dimensional Langevin dynamical calculations have already been performed [99, 101, 117]. Recently, a five-dimensional dynamical model is also developed [79] for strongly damped shape evolution. To this end, our Langevin dynamical model can be extended to perform more realistic calculations by including larger number of collective coordinates. In this way, we can also study the relative importance of different collective coordinates in different fission observables.

One of the major thrusts in the study of heavy-ion induced fusion-fission reactions is the proper estimation of nuclear dissipation. It was found [108] that different values of dissipation strength are required to reproduce the experimental results on the evaporation residue cross section and prescission neutron multiplicity. Consequently, shape dependent dissipation strength was invoked [78] to obtain both of these observables simultaneously. These studies established the importance of shape dependence in nuclear dissipation. However, the shape dependences,
obtained in the above investigations, were completely phenomenological in nature. In a sub-
sequent study, chaos weighted wall friction was introduced [97], where the shape-dependent
dissipation of similar nature was observed. All these preceding studies motivate the micro-
scopic quantum mechanical calculation of nuclear dissipation [67] and its application in the
fission dynamics.

Another aspect, which is very essential from the perspective of studies related to the super
heavy elements and the exotic nuclei, is the incorporation of shell effects in the nuclear potential.
A complete microscopic calculation of nuclear potential gives the shell correction in the liquid
drop potential, which in effect predicts the existence of super heavy elements. On the other
hand, fission is a dominant decay channel for the super heavy elements. For the exotic nuclei,
the information regarding the nuclear potential, as well as the inter-nucleonic interactions, are
not known very accurately and hence the microscopic models are needed to be tested. Along
these lines, nuclear potentials are estimated recently by using microscopic density functional
theory [185]. To proceed further, one has to implement theoretical models for the nuclear
decay by including microscopic potentials. However, this remains to be tested quantitatively
in dynamical calculations.