# Systematic Study of Entrance Channel Effect using Langevin Dynamics in Heavy-ion Induced Reaction

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With the advancements in accelerator technologies, heavy-ion beams become available in the 1980s. Simultaneously, considerable progressions in theoretical approaches are made. Heavy-ion induced fusion reaction furnishes the opportunity for synthesizing heavy and superheavy elements in laboratories. The formation of super-heavy nuclei involves heavy projectiles and this process relies critically on the complicated features of the reaction mechanism. Generally, the process can be divided into two successive dynamical evolutions. First, a compact dinuclear configuration is formed through capture and then either it decays via quasifission or it equilibrates to a compound nucleus. Depending on the stages of the reaction process, the full dynamics of the reaction can be separated into entrance and exit channels. Hence, an accurate perception of the entrance channel dynamics is indispensable. In the frontier of reaction dynamics, time-dependent many-body quantum theories are regularly attempted[1]. Apart from quantum aspects, realistic reproduction of heavy-ion reactions require fluctuations in dynamical coordinates. But this characteristic is still missing within a quantum representation of nuclear reaction and, therefore, classical stochastic dynamics is generally applied to explore large-amplitude collective dynamics in nuclei.

The present thesis primarily concerns about the development of a Langevin dynamical model to study the nuclear capture process induced by heavy ions. In this model, classical stochastic Langevin equations in four dimensions are solved numerically to obtain partial and total capture cross sections and, in principle, it is pertinent for any value of projectile energy above the capture barrier[2]. Driving potential energy and the friction tensors are the most essential factors in this model and these are determined by employing the Migdal interaction[3] and the surface friction model[4], respectively. The present model does not incorporate any microscopic correlations like shell and pairing effects and, therefore, we expect better accuracy at relatively higher energy where microscopic effects are less prominent.

The model is applied to perform a systematic analysis of the capture process for target projectile combinations with a broad range of mass asymmetry[2]. Partial capture cross-sections corresponding to different values of $\ell$ are calculated for three different reaction channels with $^{16}$O, $^{48}$Ca, and $^{50}$Ti projectiles on the $^{208}$Pb target to disentangle the significances of collective angular momentum, target-projectile mass asymmetry, and dissipative forces. Irrespective of target-projectile mass asymmetry, the dynamics is found to be strongly affected by the collective angular momentum when it reaches beyond a critical value depending on the beam energy. Effects are more prominent for heavy projectiles like $^{48}$Ca and $^{50}$Ti as these systems populate higher angular momenta. Also, nuclear dissipation appears to be strongly correlated with angular momentum. In addition, we demonstrated that nuclear deformations remain unchanged during the capture dynamics and higher-order multipole deformations can be incorporated to enhance the precision of partial capture distributions. The possibility of neutron evaporation and the mass-transfer probability among the two components of DNS is estimated. Both the mech-

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anisms are found to be irrelevant during the capture process.

The present study may furnish better guidance in designing fusion experiments. The shape, particularly the tail part, of a spin distribution of capture events is firmly affected by dissipation. An event even with a very high angular momentum (larger than the critical value where the capture barrier vanishes) can form a dinuclear system through the dissipation of angular momentum. This distinct characteristic can only be appreciated from a dissipative dynamical model as we described in the thesis. This also establishes that the critical angular momentum, which can readily be obtained from a suitable analytical expression[4], has no physical significance in the case of a heavy projectile and the total spin distribution is rather important to predict the final outcome. Moreover, for heavy projectiles, dissipative effects considerably repress the total capture cross section and our model can predict this effect to acquire a *priori* knowledge of the capture cross section.

The efficiency of the neutron-multiplicity probe in extricating the information (mainly timescales) of entrance channel dynamics is investigated. Pre-scission neutron multiplicities are analyzed for two reactions $^{30}$Si+$^{178}$Hf and $^{48}$Ti+$^{160}$Gd having distinct values of entrance channel mass asymmetry but forming the same compound nucleus[5]. These two systems exhibit significant differences in the pre-scission neutron multiplicities. Also, both the reactions show an enhancement in the prescission multiplicity with respect to the multiplicities from the $^{16}$O+$^{194}$Pt reaction populating a nearby compound nucleus. A systematic theoretical analysis is performed to realize the role of different dynamical stages in producing the overall neutron multiplicity. Experimental multiplicities are compared with the theoretical predictions calculated from the Langevin dynamical model for fission. Dynamical simulations are also executed to estimate the capture cross-sections[2]. For the $^{16}$O induced reaction, the experimental multiplicities are reproduced without introducing any pre-equilibrium delay. On the other side, for the $^{30}$Si and $^{48}$Ti induced reactions, though no explicit dynamical calculation regarding the mass equilibration stage is performed, a substantial contribution of pre-equilibrium neutrons are needed to match the experimental data. The Contribution of the neutrons, emitted during the fusion process, is shown to be pivotal in determining the neutron multiplicities for symmetric systems that lie away from a compound nuclear configuration. Moreover, in the case of $^{48}$Ti+$^{160}$Gd reaction, rapid quasi-fission dynamics prevents neutron emission from the thermalized target-projectile composite. This study helps us to understand the relative importance of fusion and quasi-fission processes and their timescales depending on the entrance channel mass asymmetry.

This work also influences to determine the pre-equilibrium neutron emission within a dynamical model that explicitly simulates the mass-equilibration process. The capture model can be extended by incorporating the mass-asymmetry coordinate. This model, in combination with the capture dynamics, provides the opportunity to study the whole pre-equilibrium process *viz-a-viz* the observables like quasi-fission cross-section, compound-nuclear formation probability, and associated timescales.

## References

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