Chapter 7

Summary of the thesis and outlook

7.1 Summary

In this thesis, I have presented the details of the multifragmentation process as well as other associated phenomena observed in heavy-ion collisions at intermediate energies. In particular, the effect of isospin degree of freedom on the fragmentation pattern in nearly symmetric and asymmetric reactions induced by the stable as well as by the neutron-rich nuclei has been studied. Here, I have simulated different reactions at various incident energies within the framework of Isospin-dependent Quantum Molecular Dynamics (IQMD) model. After, the successful generation of the phase space of nucleons, various clusterization algorithms have been used to identify fragments and to extract information regarding the multiframentation phenomenon.

In **Chapter 1**, I have first presented an introduction to heavy-ion physics and then discussed the multifragmentation phenomenon in detail. Here, I have also emphasized on the importance of studying the isospin asymmetric nuclear matter as the isospin asymmetry in the system leads to the evolution of symmetry energy. A brief review of various experimental and theoretical studies found in the literature (to study multifragmentation and associated phenomena) at intermediate energy heavy-ion collisions has also been presented .

In **Chapter 2**, I have presented the brief survey of various theoretical models used in the literature to study the phase space of nucleons. I have also reviewed various realizations of the QMD model as well as its time to time modifications/improvements over original version. In particular, the IQMD model has been discussed in detail because this model has been used extensively for the present study. Further, in the same chapter,

I have also put forward various secondary algorithms such as MST and MSTP in detail.

Next, in **Chapter 3**, I have explored various aspects of multifragmentation in asymmetric heavy-ion collisions at intermediate energies. A couple of decades ago, it was pointed out that Quantum Molecular Dynamics (QMD) approach (with and without Pauli-potential) did fail to explain the measured multiplicities in asymmetric reactions. I revisited the problem and tried to solve the issue with the help of the Isospin-dependent Quantum Molecular Dynamics (IQMD) model. This is because of the fact that IQMD model has additional repulsion due to symmetry potential, isospin-dependent of the nucleon-nucleon cross-section as well as large initial Fermi-momentum of nucleons. In addition, IQMD model has also improved Pauli-blocking mechanism compared to the original QMD model. Very interestingly, it has been found that IQMD model with these refined ingredients is able to reproduce the measurements of asymmetric reactions and refutes the apprehension raised earlier that molecular dynamics approaches failed to give appropriate results (when compared with measurements) in the asymmetric heavy-ion collisions. Further, I have also investigated the reason behind the different outcomes of a reaction (for the multiplicity of intermediate mass fragments in asymmetric reaction of $^{84}_{36}$Kr + $^{197}_{79}$Au) with two different approaches (i.e., QMD and IQMD models). Interestingly, this study, for the first time, could explain that ingredients like symmetry potential and initial large Fermi-momentum of nucleons are responsible for the better reproduction of measured results for asymmetric reactions using IQMD model and these ingredients lead to different results compared to QMD model. With the inclusion of these ingredients (as in the IQMD model), one can handle the dynamics of various asymmetric reactions in the Fermi-energy region. I have also compared bulk of my calculated results with the available measurements for asymmetric reactions and the detailed analysis revealed that IQMD model calculations nicely reproduce the measurements for such reactions around Fermi-energies, whereas, deviations can be seen at lower as well as higher incident energies.

One of the hot topics of nuclear physics research is the study of onset of multifragmentation i.e., critical energy point of the liquid-gas phase transition. In **Chapter 4**, I have presented the results of study carried out for the isospin effects via Coulomb forces and the nuclear equation of state and its momentum dependence on this phenomenon (i.e., the onset of multifargmentation) in light and heavily charged reactions of $^{40}_{18}$Ar + $^{45}_{21}$Sc and $^{84}_{36}$Kr + $^{197}_{79}$Au, respectively. Here, it has been concluded that Coulomb forces influence the onset of multifragmentation and result in the shift of the critical energy point towards

lower and higher incident energies with and without their presence, respectively. It has been further noted that for the highly charged system of $^{84}_{36}$Kr + $^{197}_{79}$Au, the critical energy point is sharp when compared with light charged system of $^{40}_{18}$Ar + $^{45}_{21}$Sc; which lead to the dependence of onset of multifragmentation (i.e., critical energy point) on the reaction asymmetry as well as on the strength of the Coulomb forces.

In **Chapter 5**, I have studied the effect of isospin dependence of nucleon-nucleon cross-section as well as density dependence of nuclear symmetry energy on the fragments yields and their transverse momentum spectra (p_T spectra) for nearly symmetric as well as highly asymmetric reactions such as p + $^{197}_{79}$Au. Here, it has been reported, for the first time, that highly asymmetric reactions remove the dual dependence (on the binary NN cross-section and density dependence of symmetry energy). For the highly asymmetric reactions of p + $^{197}_{79}$Au, one can see a significant difference in the results using soft and stiff forms of density dependence of symmetry energy; which, on the other hand, remain mute towards isospin dependence of the NN cross-section. Obviously, this study has added one more observable in the literature to pin down the density dependence of symmetry energy; which is a crucial issue in the present era.

Motivated with the study presented in Chapter 5, in **Chapter 6**, I have studied the effect of isospin degree of freedom via various model ingredients such as symmetry energy and nucleon-nucleon cross-section in the asymmetric heavy-ion collisions involving neutron-rich targets. From these investigations, it has been revealed that symmetry energy alters the dynamics of such asymmetric heavy-ion collisions at lower incident energies and its effect is more pronounced for very neutron-rich targets. On the other side, isospin independent NN cross-section shows marginal effect at higher beam energies for such reactions. Further, I have also compared my calculated results (using IQMD model) for baryon density and rapidity distribution of protons using different (i.e., soft and stiff) density dependent forms of symmetry energy and found that the results obtained using the IQMD model are consistent with the ones obtained using other transport models, though, quantitative variation in the findings can occur. This further supports the efficacy of the IQMD model to perform the present study.

7.2 Outlook

Though, I have studied the role of isospin degree of freedom on the reaction dynamics via multifragmentation process and associated phenomena, there are still many challenges yet to be solved. The different forms of density dependence of symmetry energy ($\gamma' =$ 0.5 - 2) affect the fragmentation in asymmetric reactions, but the exact parametrization for the density dependence of symmetry energy is still an open question for the nuclear physics community. Although, a large number of observables have been reported in the literature that shed light on the density dependence of symmetry energy, but results have been found to be model dependent and sometimes contradictory to each other. Therefore, one has to look for new observables that can help to constrain the density dependence of symmetry energy, especially, in supra-saturation density region. Also, in Chapter 4, I have discussed the onset of multifragmentation (liquid-gas phase transition) for light and heavily charged systems in the light of Coulomb forces. It would be interesting to extend this study (i.e., onset of multifragmentation) for super-heavy nuclei; which will shed light on, how the critical energy point alters in the reactions involving super-heavy nuclei. In addition, one is also interested to study the onset of multifragmentation i.e., critical energy point for the asymmetric reactions induced by the neutron-rich nuclei.