ABSTRACT

Heavy-ion physics is an area of research which seeks to study the properties of physical systems under the extreme conditions of density and temperature in experiments occurring in the terrestrial laboratories. The study of heavy-ion collisions at intermediate energies is of broad scientific interest that offers unique possibility to investigate various microscopic and macroscopic features of the complex nuclei at high densities and excitation energies. These investigations include the study of the compression of nuclear matter, production and properties of secondary particles as well as description of the collective effects like directed flow, elliptic flow, fragmentation, etc.

In early days, only light ions and particles could be accelerated by shooting them on the heavy targets, thus, the processes like fusion, fission were analyzed in most of the studies. With the advancements in the technology, it became possible to accelerate heavy nuclei with bombarding energies comparable to its rest mass energy. This led to the development of an innovative field of nuclear physics, known as intermediate energy heavy-ion physics. The study of heavy-ion physics helps to examine the production of compound nucleus formation and its breakage into free particles and fragments. This breaking of colliding nuclei into various fragments is known as "*multifragmentation*". Multifragmentation is also considered to be a potential candidate to study the liquid-gas coexistence of nuclear matter. In the past few decades, several experimental groups have carried out systematic studies of the fragment formation with 4π-detectors.

Also, the availability of high intensity radioactive ion beams at many facilities around the world has shifted the intention of the nuclear physics community towards the role of isospin degree of freedom in nuclear reactions. Such studies help to isolate the isospin-dependent part of the nuclear matter equation of state which is vital for the understanding of several astrophysical phenomena. It has been reported in the literature that studies have been carried out to investigate isospin effects in multifragmentation.

In the present work, an attempt has been made to study the fragmentation pattern and associated phenomena in the asymmetric reactions induced by the stable as well neutron-rich nuclei. The emphasis on asymmetric reactions rather than on symmetric reactions is motivated by the fact that dynamics of asymmetric reactions can be quite different than that of symmetric reactions. Whereas, the excitation energy is stored

in the form of compressional energy in the latter, the former has a significant share in terms of thermal energy. On the other hand, heavy-ion collisions induced by the neutron-rich nuclei have gained a lot of interest in connection with the nuclear symmetry energy that plays a crucial role in understanding the nuclear structures and reactions as well as astrophysical phenomena. The theme of the discussion of nuclear multifragmentation is related to the nuclear equation of state (EOS). The nuclear equation of state plays a major role in the physics of colliding nuclei at higher incident energies. It defines the compressibility of nuclear matter i.e., energy per nucleon (E/A) as a function of the density and temperature reached. The knowledge of EOS is not only of relevance for nuclear physics community, but is also important for the understanding of many astrophysical phenomena such as evolution of early universe, stability of neutron stars, dynamics of supernova explosions etc. Various studies have been reported in the literature that help to constrain the density dependence of nuclear symmetry energy up to certain extent in sub-saturation density region, whereas due to meager experimental data as well as unknown behavior of the three-body tensor forces at shorter distances, the behavior of density dependence of symmetry energy in supra-saturation density region is still unconstrained. Therefore, the study of the equation of state of asymmetric nuclear matter has gained recent interest and thus, lots of efforts are made in this direction by studying heavy-ion reactions induced by the neutron-rich beams. Various observables/non-observables have been proposed to study the isospin effects via symmetry energy and nucleon-nucleon scattering cross-section. These studies are restricted to symmetric reactions only. We know (as stated above) that the reaction dynamics of asymmetric collisions is different from that of symmetric reactions. So, it would be a matter of great interest to look for the isospin effects in asymmetric reactions; which follow quite different dynamics compared to symmetric reactions. Therefore, in the present study, we aim to shed light on the multifragmentation and associated phenomena using asymmetric reactions within the microscopic framework of Isospin-dependent Quantum Molecular Dynamics (IQMD) model as event generator. The whole work has been divided into seven chapters. A brief description of each chapter is presented below;

CHAPTER 1

Introduction

Chapter 1 contains a brief introduction of the work documented in the present thesis. It starts with the general introduction of heavy-ion physics, followed by the discussion on isospin physics and various radioactive ion beam facilities around the world. The details of the nuclear matter equation of state (both for symmetric and asymmetric nuclear matter) along with different phenomena affecting it is given in the later sections. It also presents a brief description of multifragmentation phenomenon; which is a key observable in the present study. Further, this chapter includes a brief review of various experimental and theoretical studies found in the literature to study multifragmentation and associated phenomena at intermediate energies. This chapter ended with the incorporation of the plan of the whole work.

CHAPTER 2

Methodology

In this chapter, the basic procedure of molecular dynamics approaches (used to generate phase space of nucleons) is discussed. This chapter starts with an introduction to the Intranuclear Cascade (INC) model; which takes into account nucleon-nucleon collisions and ignores the mean field as well as Pauli-blocking. After that, a brief survey is given of various transport models used in the literature to study the phase space of nucleons. Here, various modifications over the original QMD model have also been discussed. In particular, detailed discussion of the Isospin-dependent Quantum Molecular (IQMD) model that has been used extensively to conduct the present study is given. The IQMD model (based on the VUU code) is an extension of the QMD model (based on the BUU code). In this model, different charge states of nucleons, deltas and pions are treated explicitly. The isospin degree of freedom has been incorporated into the model via nucleon-nucleon cross-section, Coulomb potential as well as symmetry potential (in the same manner as in the IBUU model). This model follows three major steps (to generate an event) viz; *initialization*, *propagation* and *Scattering*. The details of the IQMD model along with various numerical tests to check the stability of nuclei generated in this framework are given in this chapter.

CHAPTER 3

Multifragmentation in nearly symmetric and asymmetric reactions: A detailed study and comparison with experimental measurements

This chapter explores various aspects of multifragmentation phenomenon in asymmetric reactions at intermediate energies. It was pointed out earlier by various other research groups that Quantum Molecular Dynamics (QMD) model (with and without Pauli-potential) failed to reproduce the measured multiplicities in asymmetric reactions. We investigate the problem and try to solve the issue by using the IQMD model. The choice of this model to probe the problem is based on the fact that it has additional repulsion due to symmetry potential, isospin-dependent of the nucleon-nucleon cross-section as well as initial large Fermi-momentum. In addition, IQMD model has improved Pauli-blocking mechanism compared to the QMD model. Very interestingly, we observe that IQMD model with these refined ingredients is able to reproduce the measured multiplicities in asymmetric reactions and thus, refutes the apprehension raised earlier regarding the failure of the molecular dynamics approaches to explain the dynamics for such reactions. Further, the reason behind different outcomes (for the multiplicity of intermediate mass fragments) for the asymmetric reaction of $^{84}_{36}$Kr + $^{197}_{79}$Au with two different approaches (i.e., QMD and IQMD models) is also probed in this chapter, Interestingly, for the first time, this study has predicted that refined ingredients in the IQMD model such as symmetry potential and initial large Fermi-momentum are responsible for different outcomes of a reaction when compared with QMD model. With the inclusion of these refined ingredients (as in the IQMD model), one can handle the dynamics of asymmetric reactions in the Fermi-energy region. This chapter also represents a comparison of bulk of calculated results using IQMD model with the available measurements and it has been found that IQMD model nicely reproduce the measurements for asymmetric reactions around Fermi-energies, whereas, deviations can be seen at lower as well as higher incident energies.

The results presented in this chapter are published in the journal of Nuclear Physics A [Nucl. Phys. A, Vol. 945, 95 (2016)].

CHAPTER 4

A microscopic analysis of isospin effects on the onset of multifragmentation in light and heavy charged systems via Coulomb forces

Chapter 4 of this thesis pertains to the study of isospin effects via Coulomb forces and the nuclear equation of state and its momentum dependence on the onset of multifragmentation i.e., critical energy point. The onset of multifragmentation is one of the hot topics in nuclear physics research and is also associated with the phenomenon of liquid-gas phase transition in nuclear matter. Here, in this chapter, the results of calculations (using the IQMD model) for the onset of multifragmentation in light and heavily charged reactions of $^{40}_{18}$Ar + $^{45}_{21}$Sc and $^{84}_{36}$Kr + $^{197}_{79}$Au, respectively are presented with reference to Coulomb forces. This study concludes that the Coulomb forces influence the onset of multifragmentation and result in the shift of critical energy point towards lower and higher incident energies with and without their presence, respectively. Further, in this chapter, it has been displayed that for 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. This shows the dependence of the onset of multifragmentation i.e., critical energy point on the reaction asymmetry as well as on the Coulomb forces. One of the striking points of this study is the consistency of critical energy point obtained for the reaction of $^{40}_{18}$Ar + $^{45}_{21}$Sc using IQMD model with the one obtained using Percolation model for the same reaction.

The results presented in this chapter are published in European Journal of Physics A [Eur. Phys. J. A, Vol. 52, 42, (2016)].

CHAPTER 5

Asymmetric reactions as a probe for density dependence of symmetry energy in intermediate energy heavy-ion collisions: A detailed investigation

This chapter concerns with the effect of isospin dependence of nucleon-nucleon cross-section as well as density dependence of nuclear symmetry energy on fragments yield and their transverse momentum spectra (p_T spectra) for nearly symmetric and highly asym-

metric reactions such as p + $^{197}_{79}$Au. This study reports, for the first time, that highly asymmetric reactions remove the dual dependence (on the binary nucleon-nucleon cross-section and density dependence of the symmetry energy). It has been observed that for the highly asymmetric reactions of p + $^{197}_{79}$Au, one can see significant difference in the results using soft and stiff forms of density dependence of symmetry energy; which on the other hand, remains mute towards isospin dependence of nucleon-nucleon cross-section. This study will be helpful in constraining the density dependence form of symmetry energy.

The results presented in this chapter are submitted for the publication in Physical Review C [PRC, Under Review, (2016)].

CHAPTER 6

Study of the role of some of model ingredients in asymmetric reactions induced by neutron-rich nuclei

This chapter presents the effect of isospin degree of freedom via various model ingredients such as symmetry energy and nucleon-nucleon cross-section in the asymmetric reactions induced by neutron rich targets. It has been stated in this chapter that symmetry energy alters the dynamics of asymmetric heavy-ion collisions having neutron-rich targets at lower incident energies and its effect is said to be more pronounced for highly neutron-rich targets. On the other hand, isospin independent nucleon-nucleon cross-section shows marginal effect at higher beam energies for such reactions. Moreover, in this chapter, calculated results using IQMD model for baryon density and rapidity distribution of protons using soft and stiff forms of density dependence of symmetry energy are also displayed and it has been observed that IQMD model calculations are consistent with the ones obtained using other transport models (such as IBUU), though, quantitative variations in the findings occur. These results support the efficacy of the IQMD model to perform the present study.

The results presented in this chapter are published in the journal of American Institute of Physics [AIP, Conf. Proc. Vol. 1675, pp. 030099 (2015)].

CHAPTER 7

Summary of the thesis and outlook

Finally, the whole work of this thesis is summarized in Chapter 7. It includes important findings obtained in perspectives of nuclear physics from the calculations done for the multifragmentation and associated phenomena in asymmetric reactions. This chapter also contains an outlook of the present thesis.