Study of asymmetric and neutron-rich heavy-ion collisions using isospin-dependent quantum molecular dynamics model

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Introduction

In heavy-ion collisions at intermediate energies, nuclear multifragmentation is one of the most interesting phenomenon. It provides the possibility to probe various microscopic and macroscopic features of complex nuclei at high densities and excitation energies. The various experiments performed to study multifragmentation process can be broadly classified into symmetric and asymmetric collisions. This classification is based on the fact that symmetric collisions lead to higher compression whereas, asymmetric collisions lack compressional effects and hence, a large share of excitation energy is available in the form of thermal energy.

The present thesis incorporates the detailed theoretical study of the multifragmentation and its associated phenomenon for the dynamics of nearly symmetric and asymmetric reactions. This study is carried out with in the microscopic framework of Isospin-dependent Quantum Molecular Dynamics (IQMD) model [1, 2]. In this model, different charge states of nucleons, deltas and pions are treated explicitly, as inherited from the Vlasov-Uehling-Uhelenbeck (VUU) model. Also, in IQMD model, the isospin degree of freedom is incorporated through symmetry potential, nucleon-nucleon cross-section and Coulomb interactions. After the successful generation of phase space by the IQMD model, the Minimum Spanning Tree (MST) method is used to clusterize the phase space.

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Results and discussions

As a first part of the thesis, we 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. We revisited the problem and tried to solve the issue with the help of the 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, we 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 [2]. Further, we 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 [3]. With the inclusion of these ingredients (as in the IQMD model), one can handle the dy-

namics of various asymmetric reactions in the Fermi-energy region [2]. We also compared bulk of our 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 [2].

Next, we performed calculations to study the onset of multifragmentation i.e., critical energy point of the liquid-gas phase transition as it is one of the hot topics of nuclear physics research. We 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. We 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 [4]. We 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 [4].

We also 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. We 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) [5]. 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 [5]. 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.

Lastly, we 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, we 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 [6]. On the other side, isospin independent NN cross-section shows marginal effect at higher beam energies for such reactions [6]. Further, we also compared our 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.

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