Study of fragmentation and associated phenomena in neutron-rich heavy-ion collisions

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Introduction

Heavy-ion collisions induced by neutron-rich nuclei have gained a lot of interest in connection to nuclear symmetry energy which plays a crucial role in understanding nuclear structures and reactions as well as astrophysical phenomena. Nuclear multifragmentation is one of the most interesting phenomenon in heavy-ion collisions which helps to study properties of nuclear matter at sub-saturation densities and high excitation energies. Multifragmentation is considered to be a potential candidate to study the liquid-gas coexistence of nuclear matter. The light fragments such as free-nucleons, light charged particles (treated as gas) and intermediate mass fragments (treated as liquid droplets) constitute the coexistence region. The light fragments can be helpful to extract the information about early hot and dense phase whereas the rise and fall of intermediate mass fragments with incident energy can shed light on the liquid-gas phase transition.

In present work, we made a systematic study to check the role of neutron-richness of the reacting partners on the fragmentation pattern and other associated phenomena. Here, we have simulated the different reactions for different values of incident energies using isospin-dependent quantum molecular dynamics (IQMD) model [1] as event generator. In IQMD model, different charge states of nucleons, delta and pions are treated explicitly, as inherited from the Vlasov-Uehling-Uhlenbeck (VUU) model. The isospin degree of freedom is incorporated through symmetry potential, nucleon-nucleon cross sections, and Coulomb interactions. The phase-space, generated via IQMD model, is, then, clusterized using minimum spanning tree method.

Results and discussion

In the first part of the thesis, we have studied the maximal production of intermediate mass fragments (IMFs) for stable as well as neutron-rich colliding pairs. We compared our calculations for the reactions of ^{40}Ar+^{45}Sc, ^{58}Ni+^{58}Ni, ^{86}Kr+^{93}Nb, and ^{84}Kr+^{197}Au with available experimental data [2]. The good agreement of our calculations with experimental data motivated us to study the isospin effects on the peak multiplicity of IMFs ($\langle \mathrm{N_{IMF}} \rangle^{max}$) and peak center-of-mass energy ($E_{c.m.}^{max}$, energy at which maximal production of IMFs occurs). We found that $E_{c.m.}^{max}$ did not show any systematic behavior along isotopic series due to intermixing of mass and isospin effects. However, for isobaric pairs, $E_{c.m.}^{max}$ is lower for neutron-rich systems compared to neutron-poor systems. The Coulomb potential, symmetry energy and isospin-dependence of nucleon-nucleon cross section give rise to isospin effects. Our study revealed the dominance of symmetry energy over Coulomb potential and nucleon-nucleon cross section in isospin effects on $E_{c.m.}^{max}$ for isobaric pairs [2]. $\langle \mathrm{N_{IMF}} \rangle^{max}$ increases with the system mass but insensitive to isospin degree of freedom. This behavior is preserved over the whole range of impact parameter. We also studied thermalization achieved during heavy-ion collisions of neutron-rich colliding pairs at $E_{c.m.}^{max}$. We found that density shows a weak system size dependence whereas a significant system size dependence is observed for temperature. We found that nuclear dynamics at $E_{c.m.}^{max}$ is not much affected by isospin degree of freedom.

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In next part of thesis, we studied light cluster and entropy production in heavy-ion collisions. Entropy is proposed to preserve the memory of the early hot and dense phase of the nuclear matter and it can be estimated via yields of light clusters [3]. We studied light cluster and entropy production in heavy-ion collisions. For this analysis, we simulated central reactions of ^{40}Ca+^{40}Ca and ^{93}Nb+^{93}Nb at different incident energies and compared our results with Plastic Ball experimental data. We, further, extended this study to see the effect of neutron content of reacting partners on the production of d_{like} and p_{like} clusters and entropy. We simulated the reactions of ^{52}Ge+^{52}Ge (at 400 and 1050 MeV/nucleon), ^{52}Fe+^{52}Fe (at 400 and 1050 MeV/nucleon), $^{40-60}$Ca+$^{40-60}$Ca (at 400 and 1050 MeV/nucleon) and $^{83-123}$Nb+$^{83-123}$Nb (at 400 and 650 MeV/nucleon) over the whole range of impact parameter. Our study revealed that entropy decreases with increase in N/Z ratio for both isotopic as well as isobaric colliding pairs [4]. Various factors governing the isospin effects did not affect d_{like}/p_{like} ratio and hence entropy production. To pin down the decrease of entropy with neutron-richness of the composite system, we checked the relative contribution of the yields of p_{like} and d_{like} clusters towards entropy production. We found that the decrease in entropy with neutron content can be attributed due to the altered production of d_{like} and p_{like} clusters with neutron content.

Various entrance channels and model ingredients play crucial role in deciding the fate of the reaction and fragment structure. Since entropy is estimated via yields of light clusters, thus, next, we studied the role of model ingredients on composite particle yield ratios and entropy production. We found that composite particle yield ratios and entropy are not affected by nucleon-nucleon cross section and momentum-dependent interactions. However, in case of lighter systems, some sensitivity is observed towards equation of state. Our study revealed that the different choices of interaction range plays a significant role in light cluster and entropy production [5]. An extended wave packet has larger interaction range and it will connect large number of nucleons in a fragment that will generate more heavier fragments. Hence, the yield of the light fragments will eventually decrease with the width of the Gaussian. The effect is more prominent at higher incident energies for lighter systems. Since the size of fragments produced in the reaction of ^{20}Ne+^{20}Ne is close to d_{like} clusters, they will break into free-nucleons with further increase in the incident energy. This not only decreases the number of d_{like} clusters, but will also increase p_{like} clusters that leads to net fall in the ratio of the d_{like}/p_{like} clusters and hence rise in the entropy production. However, in the case of heavier nuclei, intermediate fragments break into free-nucleons and d_{like} clusters, therefore, keeping their ratio nearly unaffected.

At last, we studied the initial-final stage correlations in the formation of fragments and also checked the contribution of participant and spectator matter towards various kind of fragments. We found higher contribution of spectator matter towards heavier fragments compared to lighter fragments. We also found that heavier IMFs preserve the time correlations. The nucleons emerging as lighter IMFs however, are well separated in phase space at the start of the reaction and form the cluster at later times.

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