Effect of density dependence of symmetry energy on heavy-ion collisions at intermediate energies

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Introduction

The theoretical investigations are proven very useful to enrich our knowledge about the symmetry energy term (as well as its density dependence) of the nuclear equation of state [1]. In the present scenario, it seems essential, to determine the exact form of density dependence of symmetry energy, which can provide a more clear picture of the heavy-ion reactions. The density dependence of symmetry energy can be parametrized as; $E_{sym}(\rho) = E_{sym}(\rho_0)\left(\frac{\rho}{\rho_0}\right)^{\gamma}$, where parameter gamma (γ) determines the stiffness (or strength) of the symmetry energy. In the present work, we explored the role of density dependence of symmetry energy on multifragmentation, fragment flow (elliptical flow) and nuclear stopping.

In addition to that, the density and temperature reached in heavy-ion collisions is also studied, when subjected to different parametrizations of density dependence of symmetry energy. Also, we provide the justification for the correlation between nuclear stopping and temperature reached in heavy-ion reactions.

The whole analysis is performed within the framework of isospin dependent quantum molecular dynamics (IQMD) model [2]. The IQMD model treats different charge states of nucleons, deltas, and pions explicitly, as inherited from the Vlasov-Uehling Uhlenbeck (VUU) model. The isospin degree of freedom enters into the calculations via symmetry potential, cross sections and Coulomb interaction. The nucleons of the target and projectile interact by two- and three- body Skyrme forces. A symmetry potential between protons and neutrons corresponding to the Bethe-Weizsacker mass formula has also been included.

Results and discussion

As a first part of the problem, we investigated the yield of light charged particles at and around the transition energy. The study was conducted to see that whether the fragment structure at the transition energy of elliptical flow differs from the multifragmentation pattern obtained below or above the transition energy. A detailed study over a wide range of incident energies show no typical structure at the transition energies [3].

The next part deals with the influence of density dependent symmetry energy and momentum dependent interactions on the multiplicity of fragments for the system ^{197}Au + ^{197}Au. We observed that the symmetry energy affect the fragment production within 2.7 % for FN's and 4.6 % for LCP's on an average [4]. The mild variation in multiplicity of fragments is due to the fact that the density at which fragmentation takes place is not high enough to see the role of various forms of symmetry energy. The momentum dependent interactions has a considerable impact on the fragment production, especially at the peripheral collisions. The momentum dependent interactions enhance the production of light and medium mass fragments due to its repulsive nature. With the inclusion of momentum dependent interactions, the density dependent symmetry energy concludes larger variation, i.e. 7.5 % for FN's and 10.3 % for LCP's on an average. In the presence of momentum dependent interactions and density dependent symmetry energy, results are more

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compatible with the experimental findings.

Further, we elaborate our study by exploring the role of symmetry energy via. elliptical flow in heavy-ion collisions. The elliptical flow (or squeeze-out flow) is produced at non-central collisions resulting in an orthogonal asymmetry in the configuration space and re-scattering. We checked the sensitivity of elliptical flow towards various forms of density dependent symmetry energy (i.e. $\gamma = 0.66$, 1.33 & 2) for the reaction of $^{197}Au + {}^{197}Au$. We found that the elliptical flow is highly sensitive towards various forms of density dependent symmetry energy [5]. The transition energy tends to give different behaviour for the light particles compared to heavy fragments. Larger squeeze-out is observed for the elliptical flow (at mid-rapidity) with the inclusion of density dependence of symmetry energy (for $\gamma = 0.66$).

In addition to that, our findings concluded that the elliptical flow is significantly influenced by the momentum dependent interactions and isospin dependent cross section [6]. The mid-rapidity region observes a larger squeeze-out for the protons compared to the neutrons due to the interplay of symmetry energy. The $[v_2(neutrons) - v_2(protons)]$ can provide an estimate for the strength of symmetry energy at sub-supra saturation densities.

Motivated by these results, we carry out an analysis for the density and temperature reached in heavy-ion collisions for the reactions of Ca + Ca, Ni + Ni and Sn + Sn with different isostopic composition (i.e. N/Z = 1, 1.5 & 2). Our findings with stiffness parameter $\gamma = 0.66$, 1.33 & 2, indicate that the density and temperature increases for the larger values of gamma [7]. However, the nuclear stopping shows a very mild sensitivity towards different forms of density dependent symmetry energy. The nuclear stopping decreases for the stiff density dependence of symmetry energy [8]. The global nuclear stopping is found to be associated to the temperature of the nuclear matter. Therefore, the nuclear stopping can give us a good estimation of the temperature of the nuclear matter in heavy-ion collisions [7]. The investigation of the role of protons and neutrons in nuclear stopping clearly shows the larger contribution of protons in global stopping, which increases with the isospin asymmetry of the nuclear matter [9]. The size of rapidity bin is found to affect the nuclear stopping drastically along the whole colliding geometry, which is due to the larger number of nucleons (associated to nuclear stopping) belongs to the mid-rapidity region (or participant zone).

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