The nuclear symmetry energy effect on flow: role of initialization

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Introduction

The knowledge of nuclear matter EOS is of great importance not only to nuclear physics community but also to astrophysicists as it sheds light on the formation of stars, explosion mechanism of supernova and composition of neutron stars etc. [1]. The extensive efforts on both theoretical and experimental front have led to determining of the EOS of symmetric nuclear matter. The knowledge about the nuclear matter EOS of isospin asymmetric nuclear matter is hot topic in present nuclear physics research, in particular the density dependence of the symmetry energy. The density dependence of the symmetry energy at sub-saturation density region has been constrained through various experimental measurements via nuclear reactions and structural aspects. On the other hand, the behavior of symmetry energy at supra saturation density region is largely unconstrained. In this direction, various observables have been proposed. Recently, collective transverse in-plane flow and its disappearance at energy of vanishing flow (N/Z dependence of energy of vanishing flow) have been proposed as sensitive to symmetry energy and its density dependence at supra saturation density region [2].

Since the discovery of atomic nucleus, determining the size and shape of a nucleus is one of the most important subjects of interest. The conventional $A^{1/3}$ power law has not been followed by nuclei lie far from the stability line. This observation was found due to discovery of halo nuclei. The density distribution of neutrons and protons will be different in such neutron-rich nuclei and neutrons will have expanded density distribution, termed as neutron skin. A lot of studies have been done in recent past demonstrating that neutron skin thickness is related to symmetry energy and its density dependence [4]. A recent study has also demonstrated the effect of different initialization on reaction dynamics [3]. In the present work, we aim to see the effect of initialization (through radii of initialized nuclei taking into account different radii for protons and neutrons). The present study is carried using isospin-dependent quantum molecular dynamics model [5].

The model

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, Yukawa potential and Coulomb interactions. A symmetry potential between protons and neutrons corresponding to the Bethe-Weizsacker mass formula has also been included. The hadrons propagate using Hamilton equations of motion:

$$\frac{d\vec{r_i}}{dt} = \frac{d\langle H\rangle}{d\vec{p_i}}; \quad \frac{d\vec{p_i}}{dt} = -\frac{d\langle H\rangle}{d\vec{r_i}} \tag{1}$$

with

$$\begin{aligned}\langle H\rangle &= \langle T\rangle + \langle V\rangle \\ &= \sum_i \frac{p_i^2}{2m_i} + \sum_i \sum_{j>i} \int f_i(\vec{r}, \vec{p}, t) \\ &\quad V^{ij}(\vec{r}\,', \vec{r}) f_j(\vec{r}\,', \vec{p}\,', t) d\vec{r}\, d\vec{r}\,' d\vec{p}\, d\vec{p}\,'\end{aligned} \tag{2}$$

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The baryon potential V^{ij}, in the above relation, reads as

$$\begin{aligned} V^{ij}(\vec{r}\,' - \vec{r}) &= V^{ij}_{Sky} + V^{ij}_{Yuk} + V^{ij}_{Coul} + V^{ij}_{sym} \\ &= [t_1\delta(\vec{r}\,' - \vec{r}) + t_2\delta(\vec{r}\,' - \vec{r})\rho^{\gamma-1} \\ &\quad (\frac{\vec{r}\,' + \vec{r}}{2})] + t_3\frac{\exp(|(\vec{r}\,' - \vec{r})|/\mu)}{(|(\vec{r}\,' - \vec{r})|/\mu)} \\ &\quad + \frac{Z_i Z_j e^2}{|(\vec{r}\,' - \vec{r})|} \\ &\quad + t_4\frac{1}{\varrho_0}T_{3i}T_{3j}\delta(\vec{r_i}\,' - \vec{r_j}). \end{aligned} \quad (3)$$

Here Z_i and Z_j denote the charges of *ith* and *jth* baryon, and T_{3i} and T_{3j} are their respective T_3 components (i.e., 1/2 for protons and −1/2 for neutrons).

Results and discussion

We simulate the reactions of ^{60}Ca + ^{60}Ca using soft equation of state at incident energy of 100 MeV/nucleon. We use standard isospin- and energy-dependent nucleon-nucleon (nn) cross section $\sigma = 0.8\ \sigma_{NN}{}^{free}$. The reactions are followed till 100 fm/c for ^{60}Ca when transverse flow saturates. The various forms of the symmetry energy used for present study are $E_{sym} \propto \rho$, $\rho^{0.4}$ and ρ^2. The radius parametrisations used are Ngô-Ngô [6], Denisov [7] and Royer [8].

In Fig. 1, we display the transverse in-plane flow $< p_x^{dir} >$ as a function of impact parameter for ^{60}Ca + ^{60}Ca reactions. Circles, squares and triangles represent the calculations for $E_{sym} \propto \rho$, $\rho^{0.4}$ and ρ^2, respectively. From figure, we see that flow decreases with softer symmetry energy ($\propto \rho^{0.4}$), and becomes much lesser for superstiff ($\propto \rho^2$) symmetry energy. This is because of the fact that acceleration time of low density particles (having density $< \rho/\rho_0$) towards the central dense zone decide the final value of flow. The strength of the symmetry energy $\propto \rho^2$ for low density particles is less and thus it reduces the flow. From figure we also see that effect of density dependence of the symmetry energy on flow is larger for the case when nuclei are initialized using radius parametrization suggested by Denisov, whereas it is least for Royer initialization. This suggests that initialization

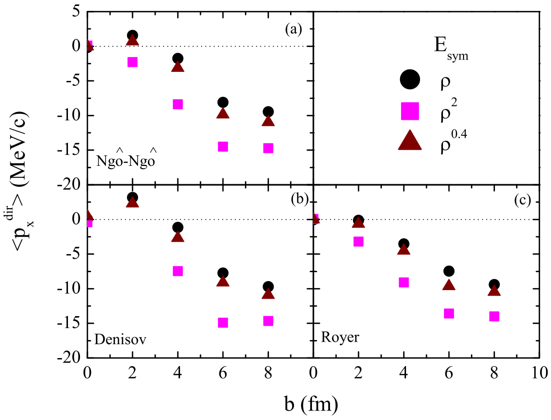

FIG. 1: The impact parameter dependence of directed transverse in-plane flow $< p_x^{dir} >$ for ^{60}Ca + ^{60}Ca for different forms of symmetry energy. Various symbols are explained in text.

effects has significant role in reaction dynamics.

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