Transverse in-plane flow: a new probe of symmetry energy in Fermi energy region

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Introduction

After about three decades of extensive efforts in both nuclear experiments and theoretical calculations, the equation of state (EOS) of isospin symmetric matter is well understood through experiments of collective flow and subthreshold kaon production. Nowadays, the nuclear EOS of asymmetric nuclear matter has attracted a lot of attention. The EOS of asymmetric nuclear matter can be described approximately by

$$E(\rho,\delta) = E_0(\rho,\delta = 0) + E_{\mathrm{sym}}(\rho)\delta^2 \qquad (1)$$

where $\delta = \frac{\rho_n-\rho_p}{\rho_n+\rho_p}$ is isospin asymmetry, $E_0(\rho, \delta)$ is the energy of pure symmetric nuclear matter, and $E_{\mathrm{sym}}(\rho)$ is the symmetry energy, where $E_{\mathrm{sym}}(\rho_0) = 32$ MeV is the symmetry energy at normal nuclear matter density. The symmetry energy is $E(\rho,1)$ - $E_0(\rho,0)$, i.e., the difference of the energy per nucleon between pure neutron matter and symmetric nuclear matter. The symmetry energy is important not only to the nuclear physics community as it sheds light on the structure of radioactive nuclei, reaction dynamics induced by rare isotopes, but also to astrophysicists since it acts as a probe for understanding the evolution of massive stars and the supernova explosions. The existing and upcoming radioactive ion beam (RIB) facilities lead a way in understanding nuclear symmetry energy. Experimentally, symmetry energy is not a directly measurable quantity and has to be extracted from observables which are related to symmetry energy. Therefore, a crucial task is to find such observables which can shed light on symmetry energy. A large number of studies on the symmetry energy of nuclear matter have been done during the past decade [1]. In this paper, we aim to see the sensitivity of collective transverse in-plane flow to symmetry energy and also to see the effect of different density dependencies of symmetry energy on the same. The various forms of symmetry energy used in present study are: $E_{\mathrm{sym}} \propto F_1(u)$, $E_{\mathrm{sym}} \propto F_2(u)$, and $E_{\mathrm{sym}} \propto F_3(u)$, where $u = \frac{\rho}{\rho_0}$, $F_1(u) \propto u$, $F_2(u) \propto u^{0.4}$, $F_3(u) \propto u^2$, and F_4 represents calculations without symmetry energy. The study is carried out with IQMD model [2].

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Results and discussion

We simulate several thousands events for the neutron-rich system of ^{48}Ca+^{48}Ca at energies of 100, 400, and 800 MeV/nucleon at impact parameter of b/b_{max}=0.2-0.4.

In Fig. 1 we display the time evolution of $< p_x^{\mathrm{dir}} >$ for different symmetry energies used in this paper at 100 MeV/nucleon for particles lying in the different bins. To understand the sensitivity of transverse momentum to the symmetry energy as well as its density dependence in the Fermi energy region, we calculate the transverse flow of particles having $\frac{\rho}{\rho_0} < 1$ (bin 1) and particles having $\frac{\rho}{\rho_0} \geq 1$ (bin 2). Dotted, solid and dashed lines represent all particles, bin1 and bin2. Panels (a), (b), and (c) are for $E_{\mathrm{sym}} \propto \rho, \rho^{0.4}$, and ρ^2, respectively. Panel (d) is for calculations without symmetry energy. The total $< p_x^{\mathrm{dir}} >$ is negative during the initial stages and continues decreasing till 30 fm/c which indicates dominance of attractive interaction. In panels (a) and (b), it becomes positive whereas in panels (c) and (d) it remains negative during the course of the reaction. If we look at $< p_x^{\mathrm{dir}} >$ of particles lying in bin 1 for $F_1(u)$ [Fig. 1(a)] and $F_2(u)$ [Fig. 1(b)] in the time interval 0 to about 20-

25 fm/c, we see that it remains positive. It increases with time upto 15 fm/c and reaches a peak value. This is because in the spectator region (where high rapidity particles lie) the repulsive symmetry energy will accelerate the particles away from the overlap zone in the transverse direction. After 15 fm/c, $< p_x^{\rm dir} >$ (of particles in bin 1) begins to decrease. This is because these particles will now be attracted toward the central dense zone. From 10 to 20 fm/c particles in bin 2 continue increasing in the midrapidity region. In the case of $\mathrm{F}_1(u)$ and $\mathrm{F}_2(u)$, particles which enter the central dense zone (bin 2) have already a high positive value of $< p_x^{\rm dir} >$ (i.e., going away from the dense zone). So, the attractive mean field has to decelerate the particles first, make them stop, and then accelerate the particles back toward the overlap zone. At about 20-25 fm/c particles from bin 1 have zero $< p_x^{\rm dir} >$ [see shaded area in Fig. 1(a) and 1(b)]. Up to 30 fm/c, particles feel the attractive mean field potential after which the high density phase is over; i.e., in case of $\mathrm{F}_1(u)$ and $\mathrm{F}_2(u)$ between 0 and 30 fm/c, particles from bin 1 are accelerated toward the overlap zone only for a short time interval of about 5 fm/c, whereas for the case of $\mathrm{F}_3(u)$ [Fig. 1(c)] and F_4 [Fig. 1(d)] between 0-30 fm/c, particles from bin 1 are accelerated towards the overlap zone for a longer time interval of about 20 fm/c between 10-30 fm/c. Moreover, the $< p_x^{\rm dir} >$ of particles lying in the bin 1 [for $\mathrm{F}_3(u)$ and F_4] follows a similar trend. This is because for $\rho/\rho_0 < 1$ the strength of symmetry energy $\mathrm{F}_3(u)$ will be small and so there will be less effect of symmetry energy on the particles, which is evident from Fig. 1(c) where one sees that the $< p_x^{\rm dir} >$ remains about zero during the initial stages between zero to about 10 fm/c. The $< p_x^{\rm dir} >$ due to particles in bin 2 (dashed line) decreases in a very similar manner for all the four different symmetry energies between 0 and 10 fm/c. Between 10 and 25 fm/c, $< p_x^{\rm dir} >$ for $\mathrm{F}_3(u)$ and F_4 decreases more sharply as compared to in case of $\mathrm{F}_1(u)$ and $\mathrm{F}_2(u)$. This is because in this time interval particles from bin 1 enter into bin 2. As discussed earlier, $< p_x^{\rm dir} >$ of particles entering bin 2 from bin 1 in the case of $\mathrm{F}_1(u)$ and $\mathrm{F}_2(u)$ will be less negative due to stronger effect of symmetry energy as compared to the case of $\mathrm{F}_3(u)$ and F_4 [3].

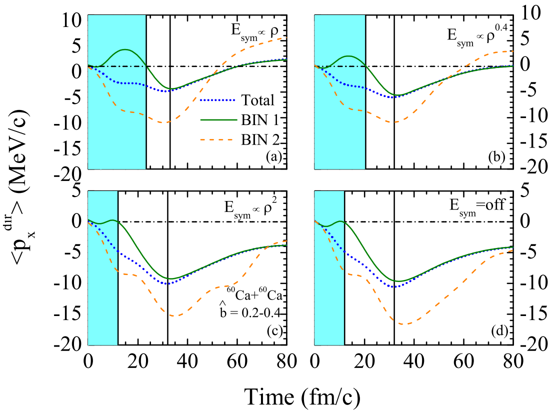

FIG. 1: The time evolution of $< p_x^{\rm dir} >$ for different forms of symmetry energy for different bins at $\mathrm{b/b_{max}}$=0.2-0.4.

Acknowledgments

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References

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