Observable to explore high density behaviour of symmetry energy

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Introduction

The nuclear matter equation of state (EOS) of asymmetric nuclear matter has attracted a lot of attention recently [1]. 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, $\mathrm{E}_0(\rho, \delta)$ is the energy of pure symmetric nuclear matter, and $\mathrm{E}_{\mathrm{sym}}(\rho)$ is the symmetry energy. 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. Although E_{sym} at saturation density is known to be around 30 MeV its value at higher densities is poorly known. 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. In this paper, we aim to see the sensitivity of collective transverse in-plane flow to symmetry energy at low as well as high densities 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: $\mathrm{E}_{\mathrm{sym}} \propto (u)$, $\mathrm{E}_{\mathrm{sym}} \propto (u)^{0.4}$, and $\mathrm{E}_{\mathrm{sym}} \propto (u)^2$, where $u = \frac{\rho}{\rho_0}$. The different density dependencies of symmetry energy are shown in Fig. 1. The present study is carried out using IQMD model which is described briefly in the next section.

The model

In IQMD [2] model the hadrons propagate using Hamilton equations of motion:

$$\frac{d\vec{r_i}}{dt} = \frac{d\langle H\rangle}{d\vec{p_i}}; \quad \frac{d\vec{p_i}}{dt} = -\frac{d\langle H\rangle}{d\vec{r_i}} \; \textit{where} \qquad (2)$$

$$\begin{aligned}\langle H\rangle &= \langle T\rangle + \langle V\rangle \\ &= \sum_i \frac{p_i^2}{2m_i} + \sum_i \sum_{j>i} \int f_i(\vec{r}, \vec{p}, t) V^{ij}(\vec{r}\,', \vec{r}) \\ &\quad \times f_j(\vec{r}\,', \vec{p}\,', t) d\vec{r}\, d\vec{r}\,'\, d\vec{p}\, d\vec{p}\,'. \qquad (3)\end{aligned}$$

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

$$\begin{aligned}V^{ij}(\vec{r}\,' - \vec{r}) &= V^{ij}_{Skyrme} + V^{ij}_{Yukawa} + V^{ij}_{Coul} \\ &\quad + V^{ij}_{mdi} + V^{ij}_{sym}. \qquad (4)\end{aligned}$$

Where the potential terms in eq. 4 represent, respectively, Skyrme, Yukawa, Coulomb, momentum dependent interaction, and symmetry potential.

Results and Discussion

There are several methods used in the literature to define the nuclear transverse in-plane flow. In most of the studies, one uses (p_x/A) plots where one plots (p_x/A) as a function of $Y_{\mathrm{c.m.}}/Y_{\mathrm{beam}}$. Using a linear fit to the slope, one can define the so-called reduced flow (F). Alternatively, one can also use a more integrated quantity "directed transverse in-plane flow $\langle p_x^{\mathrm{dir}}\rangle$" which is defined as [3]:

$$\langle p_x^{\mathrm{dir}}\rangle = \frac{1}{A}\sum_i \mathrm{sign}\{Y(i)\}\; p_x(i), \qquad (5)$$

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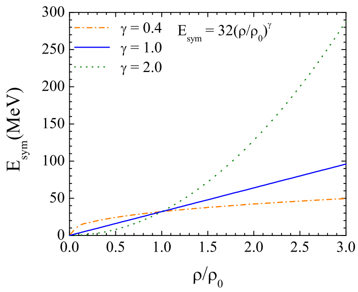

FIG. 1: Different forms of symmetry energy.

where $Y(i)$ and $p_x(i)$ are the rapidity distribution and transverse momentum of the *ith* particle. In this definition, all rapidity bins are taken into account. It therefore presents an easier way of measuring the in-plane flow than complicated functions such as (p_x/A) plots.

In Fig. 2 we display $< \frac{p_x}{A} >$ as a function of $\mathrm{Y_{c.m.}}/Y_{\mathrm{beam}}$ at final time (left panels) and the time evolution of $< p_x^{\mathrm{dir}} >$ (right panels) calculated at 100 (top panel), 400 (middle) and 800 MeV/nucleon (bottom) for different density dependencies of symmetry energy. Solid, dash dotted, and dotted lines represent the symmetry energy proportional to ρ, $\rho^{0.4}$ and ρ^2, whereas dashed line represents calculations without symmetry energy. Comparing the left and right panels in Fig. 2, we find that both the methods show similar behavior to symmetry energy. For example, at incident energy of 100 MeV/nucleon for $\mathrm{E_{sym}} \propto \rho^{0.4}$, $< p_x^{\mathrm{dir}} >$ $= 0$. Similarly, the slope of $< \frac{p_x}{A} >$ at midrapidity is zero. We also find that the transverse momentum is sensitive to symmetry energy and to its density dependences $\mathrm{F_1}(u)$, $\mathrm{F_2}(u)$ and $\mathrm{F_3}(u)$ in the low energy region (100 MeV/nucleon) only. At energies above Fermi energy, both the methods show insensitivity to the different symmetry energies. This could be because (i) the repulsive nn scattering dominates the mean field at high energies. (ii) As explained in ref [3] that the effect of E_{sym} on nucleons during the initial stages of the reaction (0-30 fm/c) decide the fate of final state $< p_x^{\mathrm{dir}} >$. At low energies duration of high dense phase will prevail for a longer duration

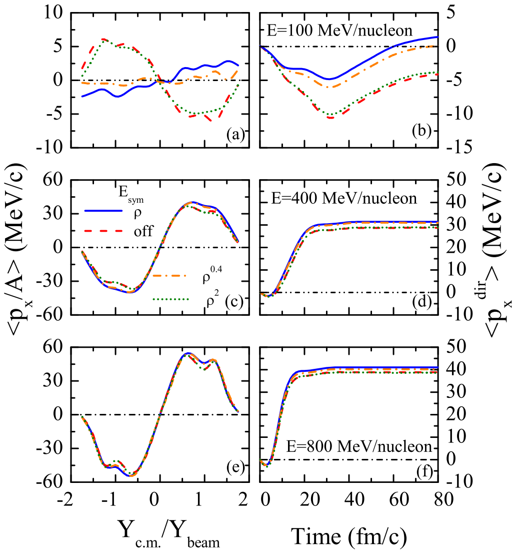

FIG. 2: Left panel: $< \frac{p_x}{A} >$ as a function of $\mathrm{Y_{c.m.}}/Y_{\mathrm{beam}}$ and $< p_x^{\mathrm{dir}} >$ at different incident energies. Panels and lines are explained in the text.

alllowing the E_{sym} to affect the flow. Whereas at high energies, although maximum density reached will be larger but the duration of high density phase will be very small not providing E_{sym} with sufficient time to make an impact on flow.

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