Sensitivity of transverse momentum spectra of nucleons towards symmetry energy

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Introduction

Nuclear reactions induced by the radioactive beams give unique opportunity to explore the role of isospin degree of freedom in various phenomena. In the era of isospin physics, density dependence of symmetry energy is one of the important aspects. Li *et al.* [1] found that the ratio of the number of pre-equilibrium neutrons to that of protons as a function of their kinetic energies is quite sensitive to the symmetry energy. Also Li *et al.* [2] suggested nucleon emissions and the nuclear radial flow as potential probes of symmetry energy at high densities. Gautam *et al.* [3] found that transverse flow of nucleons is sensitive to symmetry energy as well as to its density dependence in the Fermi energy region. In an another study, Kumar *et al.* [4] found that double neutron-to-proton ratio from free nucleons is highly sensitive to the symmetry energy and isospin asymmetry of the system. From the literature, it is concluded that the emission of nucleons is greatly affected by the density dependence of symmetry energy. In the present study, our aim is to see the effect of different density dependencies of symmetry energy on the transverse momentum spectra of neutrons and protons [5]. The various forms of symmetry energy used in present study are $E_{sym} \propto F_1(u)$, $E_{sym} \propto F_2(u)$, and $E_{sym} \propto F_3(u)$, where $u = \frac{\rho}{\rho_o}$, $F_1(u) \propto u^{0.5}$, $F_2(u) \propto u$, $F_3(u) \propto u^{1.5}$, and F_4 represents calculations without symmetry energy.

The Model

The present study is carried out within the framework of the isospin-dependent quantum molecular dynamics (IQMD) model [6]. In IQMD model, propagation of each nucleon is governed by the classical equations of motion:

$$\frac{d\vec{r_i}}{dt} = \frac{d\langle H\rangle}{d\vec{p_i}}, \qquad \frac{d\vec{p_i}}{dt} = -\frac{d\langle H\rangle}{d\vec{r_i}}, \qquad (1)$$

where H stands for the Hamiltonian which is given by:

$$H = \sum_i^A \frac{p_i^2}{2m} + \sum_i^A (V_i^{Sky} + V_i^{Yuk} + V_i^{Coul} + V_i^{sym}). \qquad (2)$$

The V_i^{Sky}, V_i^{Coul}, V_i^{Yuk} and V_i^{sym} are, respectively, the Skyrme, Yukawa, Coulomb, and symmetry potentials.

Results and Discussion

For the present study, we simulated the reaction of ^{60}Ca+^{60}Ca at incident energies of 100 and 400 MeV/nucleon for impact parameter in the range of $\hat{b}$ = 0.2 to 0.4. We used a

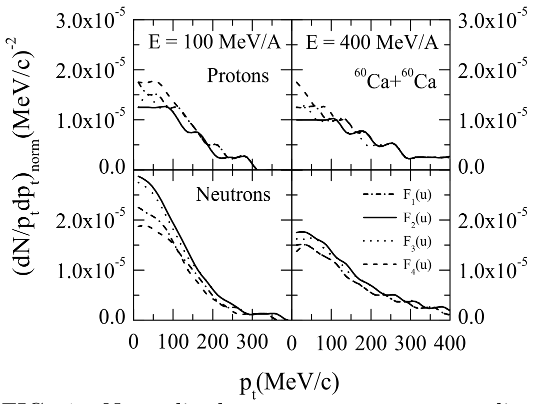

FIG. 1: Normalized transverse momentum distribution of protons (upper panel) and neutrons (lower panel) as a function of transverse momentum p_t calculated at 100 (left panel) and 400 MeV/nucleon (right panel) for different density dependencies of symmetry energy.

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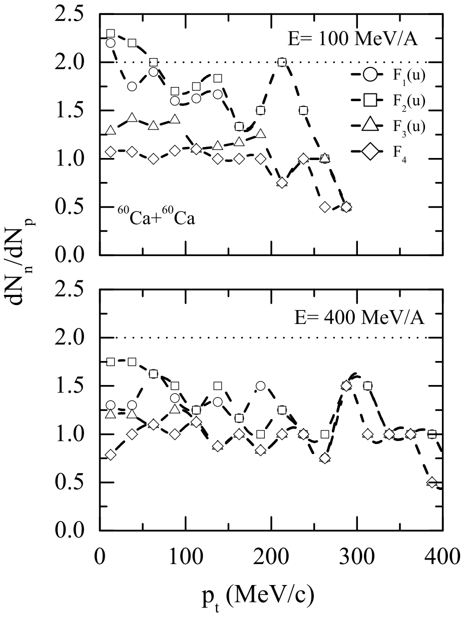

FIG. 2: The differential neutron/proton ratio, dN_n/dN_p, as a function of transverse momentum p_t for the reaction of ^{60}Ca+^{60}Ca. The open circles, squares, and triangles represent the symmetry energy proportional to $\rho^{0.5}$, ρ, and $\rho^{1.5}$, whereas diamonds represent calculations without symmetry energy. The lines are to guide the eye.

soft equation of state along with isospin- and energy-dependent nn cross section reduced by 20% i.e. $\sigma = 0.8\sigma_{nn}^{free}$. The reactions are followed till 200 fm/c and clusters are formed with the minimum spanning tree method using a clusterization radius of 4.0 fm.

In Fig. 1, we display normalized transverse momentum distribution of protons (upper panel) and neutrons (lower panel) as a function of transverse momentum p_t calculated at 100 (left panel) and 400 MeV/nucleon (right panel) for reaction of ^{60}Ca+^{60}Ca for different density dependencies of symmetry energy. Solid, dash dotted, and dotted lines represent the symmetry energy proportional to ρ, $\rho^{0.5}$, and $\rho^{1.5}$, whereas the dashed line represents calculations without symmetry energy. We find that in the low energy region (100 MeV/nucleon), the transverse momentum spectra of neutrons shows large sensitive to symmetry energy and to its density dependencies $F_1(u)$, $F_2(u)$, and $F_3(u)$ compared to protons. At energies above the Fermi energy, transverse momentum spectra of both protons and neutrons show insensitivity to the different forms of symmetry energies. This is because the repulsive n-n scattering dominates the mean field at high energies.

In Fig. 2, we display the differential neutron/proton ratio, dN_n/dN_p, as a function of transverse momentum p_t calculated at 100 (upper panel) and 400 MeV/nucleon (lower panel) for the reaction of ^{60}Ca+^{60}Ca. The various symbols are explained in the caption. The dotted line in the figure is the average $(n/p)_{sys}$ ratio of the reaction system. At 100 MeV/nucloen, in the low (high) p_t part the dN_n/dN_p is higher (lower) than the $((n/p)_{sys}$. Moreover, the low p_t part of the dN_n/dN_p ratio is more sensitive to the symmetry energy than the high p_t part. The sensitivity of dN_n/dN_p ratio toward density dependence of symmetry energy almost diminishes at higher energy (400 MeV/nucleon).

We find that in Fermi energy region, transverse momentum spectra of both protons and neutrons show sensitivity towards the density dependence of symmetry energy.

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