ISOSPIN EFFECTS ON THE TRANSVERSE MOMENTUM SPECTRA OF PROTONS AND NEUTRONS*

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We present a theoretical study to see the effect of isospin degree of freedom and system size on the behavior of transverse momentum spectra, $dN/p_{\rm t}dp_{\rm t}$, of protons and neutrons. We find that most of the nucleons suffer soft collisions. In the Fermi energy region, transverse momentum spectra of both protons and neutrons show sensitivity towards the density dependence of symmetry energy.

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1. Introduction

The established and upcoming radioactive ion beam (RIB) facilities have provided unique opportunity to explore the role of isospin degree of freedom in various phenomena. In past decades, several experimental and theoretical efforts have been made to study the role of isospin degree of freedom on multifragmentation [1–5], collective and elliptic flow [6–8] and nuclear stopping [9, 10]. Recently, Puri and Kaur [4] studied the isospin effects on the peak mass production and found that maximal fragment production was insensitive to the isospin dependence of the cross section but sensitive to the symmetry energy. Also, Puri and coworkers [11] investigated the relative contribution of the symmetry energy as well as the isospin dependence of the nucleon–nucleon cross section towards collective flow. In another study, Jain *et al.* [12] checked the effect of isospin degree of freedom on $dN/p_{\rm t}dp_{\rm t}$ via isospin dependent cross section.

In another study, Li *et al.* [13] 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.* [14] suggested

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nucleon emissions and the nuclear radial flow as potential probes for symmetry energy at high densities. Their findings reveal that the isospin asymmetry of midrapidity nucleons and its transverse momentum dependence are very sensitive to the high-density behavior of the symmetry energy. The transverse flow of nucleons is also found to be sensitive to symmetry energy as well as to its density dependence in the Fermi energy region [7]. Kumar *et al.* [15] compared theoretical results of single and double neutron to proton ratios with the experimental data and favored the softness of the symmetry energy at sub-saturation densities. At supra-saturation densities, double neutron-to-proton ratio from free nucleons is found to be 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 symmetry energy as well as by its density dependence. The transverse momentum spectra of protons and neutrons would be a good observable to study the sensitivity of symmetry energy as well as its density dependence. In the present study, our aim is to see the sensitivity of transverse momentum spectra of neutrons and protons towards symmetry energy and its different density dependencies of symmetry energy on the same. The equation of state (EOS) of asymmetric nuclear matter is approximated as

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

where $\delta = (\frac{\rho_n-\rho_p}{\rho_n+\rho_p})$ is isospin asymmetry, and ρ_n and ρ_p are, respectively, neutron and proton densities. $E(\rho,0)$ is the energy of pure symmetric nuclear matter and $E_{\mathrm{sym}}(\rho)$ is the symmetry energy. The density dependence of symmetry energy is parametrized as

$$E(\rho) = E(\rho_o)\left(\frac{\rho}{\rho_o}\right)^{\gamma_i}\,, \tag{2}$$

where $E_{\mathrm{sym}}(\rho_o) = 32$ MeV is the symmetry energy at normal nuclear matter density. At sub-saturation densities γ_i is constrained to 0.5–1.1 [16], whereas at supra-saturation densities is still an open question. In the present study, we used the following forms of symmetry energy: $E_{\mathrm{sym}} \propto F_1(u)$, $E_{\mathrm{sym}} \propto F_2(u)$, and $E_{\mathrm{sym}} \propto F_3(u)$, where $u = \frac{\rho}{\rho_o}$, $F_1(u) \propto u^{0.5}$, $F_2(u) \propto u$, $F_3(u) \propto u^{1.5}$, and F_4 represents calculations without symmetry energy.

2. The model

The present study is carried out within the framework of isospin-dependent quantum molecular dynamics (IQMD) model [17] which treats different charge states of nucleons, Δs, and pions explicitly. In addition to the use of explicit charge states of all baryons and mesons, a symmetry potential between protons and neutrons corresponding to the Bethe–Weizsäcker mass formula has been included. Isospin effects come into the picture due to interplay between the Coulomb potential, isospin-dependent cross section, and symmetry potential. Two nucleons undergo a scattering if they are closer than a certain minimum distance. The cross section for neutron–neutron collisions is taken to be equal to the proton–proton cross section and cross section for neutron–proton is taken to be three times the neutron–neutron (proton–proton) cross section. This scattering is further subjected to the fulfillment of Pauli principle. In IQMD model, explicit Pauli blocking is included *i.e.*, Pauli blockings of the neutrons and of the protons are treated separately. Any scattering that violates the Pauli principle is neglected. Whenever an attempted collision is blocked, the scattering partners maintain the original momenta prior to scattering. The phase space generated is analyzed using the minimum spanning tree (MST) method [18].

3. Results and discussion

To see the role of neutron content on the transverse momentum distribution, we simulated the reactions of isospin symmetric as well asymmetric systems. In particular, we simulated reactions of ^{40}Ca+^{40}Ca, ^{52}Ca+ ^{52}Ca, ^{60}Ca+^{60}Ca, ^{110}Xe+^{110}Xe, ^{140}Xe+^{140}Xe, ^{162}Xe+^{162}Xe and ^{60}Zn+^{60}Zn at an incident energy of 100 MeV/nucleon. In Ref. [7], it has been shown that sensitivity of transverse flow of nucleons, observed in extremely neutron-rich systems (*e.g.* ^{60}Ca), remains preserved in reactions which are experimentally accessible (*e.g.* ^{48}Ca). In the present study, the impact parameter is in the range of $\hat{b} = 0.2$ to 0.4 (semi-central). Since in central and semi-central heavy-ion collisions, the density achieved is about twice the normal nuclear matter density [7]. Thus, transverse momentum spectra can be used to address the symmetry energy at densities about twice the normal nuclear matter density. Also, excitation energy is very high in central and semi-central collisions, that results in fast explosion of nuclei into free-nucleons and light fragments and a very few medium size fragments are formed. With increase in the impact parameter, the formation of light fragments diminishes and intermediate and heavy fragment formation dominates. Since we are going to study the transverse momentum distribution of free protons and neutrons, that is why the choice of semi-central collisions is made. Here, we used a soft EOS along with isospin- and energy-dependent cross section reduced by 20% *i.e.* $\sigma = 0.8\sigma_{nn}^{\mathrm{free}}$.

In Fig. 1, we display the normalized transverse momentum distribution of protons and neutrons for isotopes of Ca (left panels) and Xe (right panels). The figure reveals the following points:

1. As the transverse momentum increases, $dN/p_t dp_t$ decreases. This may be attributed due to the reason that with the increase in the transverse momentum, the number of particles in a particular bin decreases. This shows that most of the nucleons suffer soft collisions.
2. The value of $dN/p_t dp_t$ for neutrons increases with the increase in the isospin asymmetry.
3. In the case of neutron-rich systems, the value of $dN/p_t dp_t$ is higher for neutrons compared to protons, whereas for symmetric system of ^{40}Ca+^{40}Ca, it is the same for neutrons and protons.
4. The system size has a negligible effect on the transverse momentum distribution of protons and neutrons.

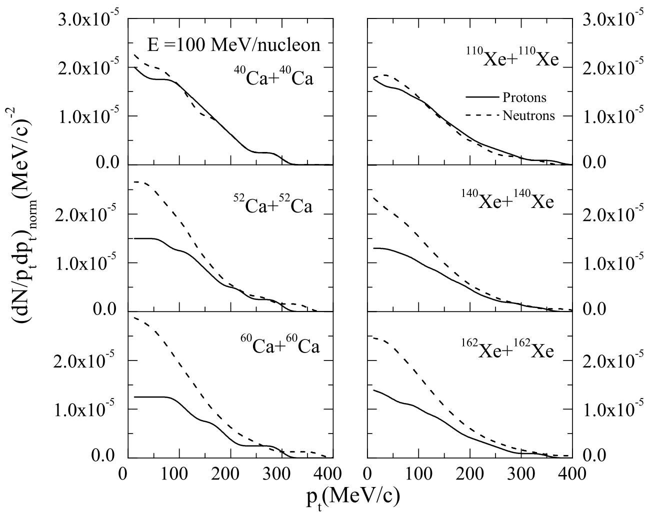

Fig. 1. Normalized final transverse momentum distribution of protons (solid lines) and neutrons (dashed lines) for the reactions of ^{40}Ca+^{40}Ca, ^{52}Ca+^{52}Ca, and ^{60}Ca+^{60}Ca (left panels) and ^{110}Xe+^{110}Xe, ^{140}Xe+^{140}Xe, and ^{162}Xe+^{162}Xe (right panels).

In the above figure, we have compared the transverse momentum distribution of protons and neutrons for different isotopes of Ca and Xe, *i.e.* both mass and isospin asymmetry have increased along the isotopic series. To see the effect of isospin degree of freedom on $dN/p_t dp_t$, we simulate the reactions of ^{60}Ca+^{60}Ca and ^{60}Zn+^{60}Zn (which are having the same mass but differ in isospin asymmetry). In Fig. 2, we display the normalized final transverse momentum distribution of protons and neutrons for the reactions of ^{60}Ca+^{60}Ca and ^{60}Zn+^{60}Zn. We find that the value of $(dN/p_t dp_t)_{norm}$ for protons is higher for neutron-poor system (^{60}Zn+^{60}Zn) than that of neutron-rich system (^{60}Ca+^{60}Ca) and reverse is the case for neutrons.

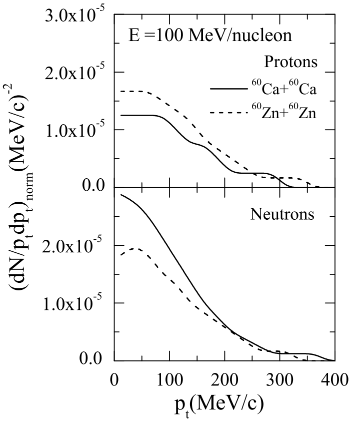

Fig. 2. Normalized final transverse momentum distribution of protons (upper panel) and neutrons (lower panel) for the reaction of ^{60}Ca+^{60}Ca (solid lines) and ^{60}Zn+^{60}Zn (dashed lines).

In Fig. 3, we display normalized transverse momentum distribution of protons (upper panel) and neutrons (lower panel) as a function of transverse momentum p_{t} for the reaction of ^{60}Ca+^{60}Ca. The 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 Fermi energy region, the transverse momentum spectra of neutrons show large sensitivity to the symmetry energy and to its density dependencies compared to protons.

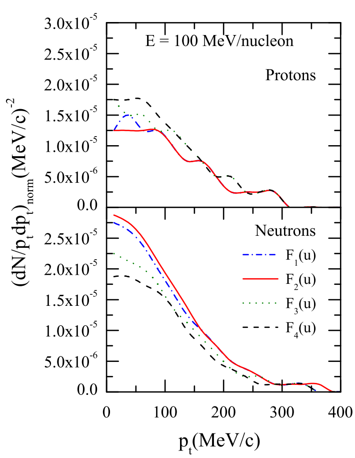

Fig. 3. (Color online) Normalized transverse momentum distribution of protons (upper panel) and neutrons (lower panel) as a function of transverse momentum p_{t} for different density dependencies of symmetry energy. Various lines are explained in the text.

4. Summary

We studied the effect of isospin degree of freedom and system size on the behavior of the transverse momentum distribution of nucleons. We find that $dN/p_{\rm t}dp_{\rm t}$ decreases with increase in the transverse momentum and the value of $dN/p_{\rm t}dp_{\rm t}$ of neutrons is higher for neutron-rich systems. We noticed that in the Fermi energy region, the transverse momentum spectra of both protons and neutrons show sensitivity towards density dependence of the symmetry energy.

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