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Effect of the momentum dependence of nuclear symmetry potential on π^-/π^+ ratio in heavy-ion collisions

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In the framework of the isospin-dependent Boltzmann-Uehling-Uhlenbeck transport model, effect of the momentum dependence of nuclear symmetry potential on π^-/π^+ ratio in the neutron-rich reaction ^{132}Sn+^{124}Sn at a beam energy of 400 MeV/nucleon is studied. We find that the momentum dependence of nuclear symmetry potential affects the compressed density of colliding nuclei, numbers of produced π^- and π^+, as well as the value of π^-/π^+ ratio. The momentum dependent nuclear symmetry potential increases the compressed density of colliding nuclei, numbers of produced resonances $\Delta(1232)$, $N^*(1440)$, π^- and π^+, as well as the value of π^-/π^+ ratio.

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Nowadays pion production in heavy-ion collisions has attracted much attention in the nuclear physics community [1–7]. The reason for this is that pion production is connected with the high-density behavior of nuclear symmetry energy [8]. The latter is crucial for understanding many interesting issues in both nuclear physics and astrophysics [9–15]. The high-density behavior of nuclear symmetry energy, however, has been regarded as the most uncertain property of dense neutron-rich nuclear matter [16, 17]. Many microscopic and/or phenomenological many-body theories using various interactions [18, 19] predict that the symmetry energy increases continuously at all densities. However, other models [9, 20–32] predict that the symmetry energy first increases to a maximum and then may start decreasing at certain suprasaturation densities. Thus, currently the theoretical predictions on the symmetry energy at suprasaturation densities are extremely diverse. Therefore, what is crucially needed for the first step is a qualitative observable to probe whether the symmetry energy at high densities is soft or stiff, this has been done originally by qualitatively comparing the n/p ratio of light and heavy preequilibrium emitting clusters [33]. Making further progress in determining the symmetry energy at suprasaturation densities needs some guidance from dialogues between experiments and transport models, which have been done extensively in the studies of nuclear symmetry energy at low densities [34–38].

To use π^-/π^+ to probe the high-density behavior of nuclear symmetry energy has evident advantage within both the Δ resonance model and the statistical model [39, 40]. Several hadronic transport models have quantitatively shown that π^-/π^+ ratio is indeed sensitive to the symmetry energy [5, 8, 41, 42], especially around pion production threshold. These transport models, however, usually use different momentum dependent interactions among nucleons. The importance of the momentum dependence of nuclear symmetry potential was seldom mentioned in other transport models except our transport model used in the present studies. In the framework of the isospin-dependent Boltzmann-Uehling- Uhlenbeck transport model, as an example, we studied the effect of the momentum dependence of nuclear symmetry potential on π^-/π^+ in the neutron-rich reaction of ^{132}Sn+^{124}Sn at a beam energy of 400 MeV/nucleon. It is found that the momentum dependence of nuclear symmetry potential affects the compressed density of colliding nuclei, numbers of produced π^- and π^+, as well as the value of π^-/π^+ ratio.

The isospin and momentum-dependent mean-field potential used in the present work is [43]

$$
\begin{aligned}
U(\rho,\delta,\mathbf{p},\tau) &= A_u(x)\frac{\rho_{\tau'}}{\rho_0} + A_l(x)\frac{\rho_\tau}{\rho_0} \\
&+B\left(\frac{\rho}{\rho_0}\right)^{\sigma}\left(1-x\delta^2\right) - 8x\tau\frac{B}{\sigma+1}\frac{\rho^{\sigma-1}}{\rho_0^{\sigma}}\delta\rho_{\tau'} \\
&+\sum_{t=\tau,\tau'}\frac{2C_{\tau,t}}{\rho_0}\int d^3\mathbf{p}'\frac{f_t(\mathbf{r},\mathbf{p}')}{1+\left(\mathbf{p}-\mathbf{p}'\right)^2/\Lambda^2}, \qquad (1)
\end{aligned}
$$

where ρ_n and ρ_p denote neutron ($\tau = 1/2$) and proton ($\tau = -1/2$) densities, respectively. $\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p)$ is the isospin asymmetry of nuclear medium. All parameters in the preceding equation can be found in refs.[44]. The variable x is introduced to mimic different forms of the symmetry energy predicted by various many-body theories without changing any property of symmetric nuclear matter and the value of symmetry energy at normal density ρ_0. Because the purpose of present studies is just to see how large the effect of momentum dependence of nuclear symmetry potential on charged pion ratio, we let the variable x be 1. In fact, behavior of nuclear symmetry energy at supra-densities is still in controversy. For example, some authors concluded from the FOPI data that the symmetry energy at supra-densities is very soft [1]. Others concluded, however, the opposite situation [45], which is supported by the work of the Catania group. With above choices the symmetry energy obtained from the preceding single-particle potential is consistent with the Hartree-Fock prediction using the original Gogny force [43] and is also favored by recent studies based on FOPI experimental data [1]. The main characteristic of the present single particle is the momentum dependence of nuclear symmetry potential, which has evident effect on energetic free n/p ratio in heavy-ion collisions [44]. But the momentum dependence of nuclear symmetry potential on π^-/π^+ ratio was seldom reported. In this note we study the momentum dependence of nuclear symmetry potential on π^-/π^+ ratio. We keep the isoscalar potential fixed while changing the symmetry potential from momentum dependent symmetry potential to momentum independent symmetry potential and keep the symmetry energy fixed [44]. The reaction channels related to pion production and absorption are

$$\begin{aligned} &NN \longrightarrow NN, \\ &NR \longrightarrow NR, \\ &NN \longleftrightarrow NR, \\ &R \longleftrightarrow N\pi, \end{aligned} \tag{2}$$

where R denotes Δ or N^* resonances. In the present work, we use the isospin-dependent in-medium reduced NN elastic scattering cross section from the scaling model according to nucleon effective mass [46–49]. For in-medium NN inelastic scattering cross section, we use the forms in free space since it is quite controversial.

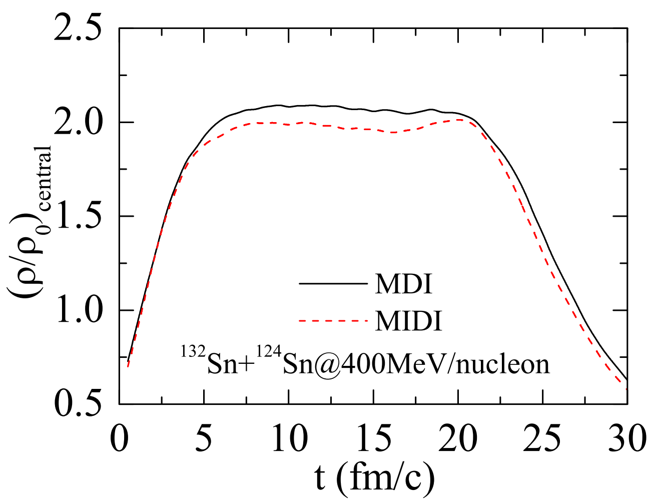

FIG. 1: (Color online) Evolution of the central baryon density for the central reaction ^{132}Sn+^{124}Sn at a beam energy of 400 MeV/nucleon with and without momentum dependence of nuclear symmetry potential, signed with MDI and MIDI, respectively.

Fig. 1 shows the effect of the momentum dependence of nuclear symmetry potential on the central baryon density of colliding nuclei. It is seen that the maximum baryon density is about 2 times normal nuclear matter density. Moreover, the compression is sensitive to the momentum dependence of nuclear symmetry potential. The momentum independence of nuclear symmetry potential makes the nuclear matter less compressed whereas the momentum dependence of nuclear symmetry potential causes a larger compression.

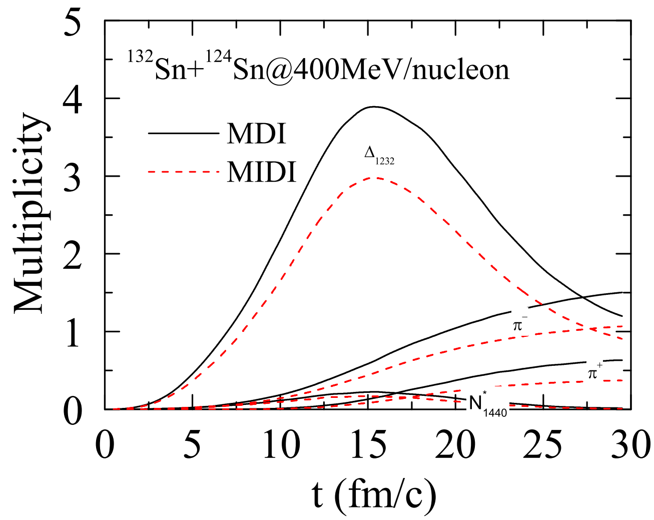

FIG. 2: (Color online) Evolution of π^-, π^+ and $\Delta(1232)$, $N^*(1440)$ multiplicities in the central reaction ^{132}Sn+^{124}Sn at a beam energy of 400 MeV/nucleon with and without momentum dependence of nuclear symmetry potential, respectively.

To see more clearly effect of the momentum dependence of nuclear symmetry potential on pion production, we show in Fig. 2 the multiplicities of π^+, π^- and $\Delta(1232)$, N^* as a function of time. We can first see that, owing to small compression with momentum independent symmetry potential shown in Fig. 1, the momentum independence of nuclear symmetry potential decreases the productions of resonances, especially $\Delta(1232)$. More $\Delta(1232)$ resonances are produced than N^*. This is because $N^*(1440)$ is related to more energetic collisions. Second, we see that numbers of produced charged pions are also reduced with the momentum independent symmetry potential, especially for π^-. In the studies, the usage of momentum dependence of nuclear symmetry potential increases charged pions about 30%. We also made simulations of changing nuclear incompressibility ($\delta K \sim 20$) and find that the isoscalar part of the Equation of State has little effects on charged pion yields. But the momentum dependence of the isoscalar part of the Equation of State also has evident affection on pion yields [50]. All these results indicate the importance of the momentum dependence of nuclear potential on the studies of pion production.

Shown in Fig. 3 is effect of the momentum dependence of nuclear symmetry potential on the $(\pi^-/\pi^+)_{like}$ ratio as a function of time in the central reaction ^{132}Sn+^{124}Sn at a beam energy of 400 MeV/nucleon. In the dynamics of pion resonance productions and decays the $(\pi^-/\pi^+)_{like}$

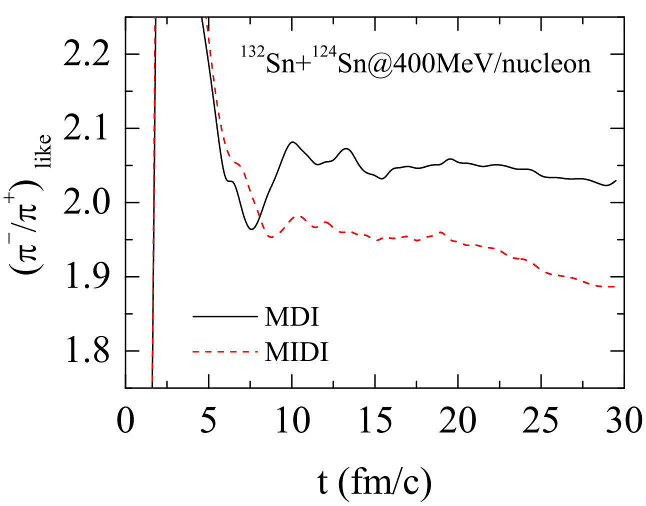

FIG. 3: (Color online) Evolution of the π^-/π^+ ratio in the reaction ^{132}Sn+^{124}Sn at a beam energy of 400 MeV/nucleon with and without momentum dependence of nuclear symmetry potential.

ratio reads

$$(\pi^-/\pi^+)_{like} \equiv \frac{\pi^- + \Delta^- + \frac{1}{3}\Delta^0 + \frac{2}{3}N^{*0}}{\pi^+ + \Delta^{++} + \frac{1}{3}\Delta^+ + \frac{2}{3}N^{*+}}. \qquad (3)$$

This ratio naturally becomes π^-/π^+ ratio at the freeze-out stage. From Fig. 3 we can first see that sensitivity of $(\pi^-/\pi^+)_{like}$ ratio to the effect of the momentum dependence of nuclear symmetry energy is clearly shown after $t = 10fm/c$. With the momentum dependent symmetry potential (MDI), π^-/π^+ ratio is higher than that with the momentum independent symmetry potential (MIDI), the effect of the momentum dependence of nuclear symmetry potential in this study is about 7.4%. The π^-/π^+ ratio with the momentum dependent symmetry potential is higher than that with the momentum independent symmetry potential is consistent with the free n/p ratio's momentum dependence of nuclear symmetry potential [44]. With the momentum dependent symmetry potential, free n/p ratio is lower than that with the momentum independent symmetry potential. The n/p ratio of dense matter thus has a opposite situation, i.e., with the momentum dependent symmetry potential, *dense* matter's n/p ratio is higher than that with the momentum independent symmetry potential. According to both the Δ resonance model and the statistical model [39, 40], with the momentum dependent symmetry potential, π^-/π^+ ratio is higher than that with the momentum independent symmetry potential.

Therefore, if the published PRL paper [1] of Xiao et al. uses a momentum independent symmetry potential, according to the experimental data, the resulting symmetry energy will be more soft. The whole physical result of that PRL paper [1] still does not change, just more soft. To study the momentum dependence of nuclear symmetry potential, high p_t or kinetic energy's neutron to proton ratio or light over heavy cluster's n/p ratio may be useful [33, 44].

In conclusion, based on the isospin-dependent Boltzmann-Uehling-Uhlenbeck transport model, effect of the momentum dependence of nuclear symmetry potential on π^-/π^+ ratio in the neutron-rich reaction ^{132}Sn+^{124}Sn at a beam energy of 400 MeV/nucleon is studied. It is found that momentum dependent nuclear symmetry potential increases the compressed density of colliding nuclei, numbers of produced resonances $\Delta(1232)$, $N^*(1440)$, π^- and π^+, as well as the value of π^-/π^+ ratio. It is therefore necessary to consider the momentum dependence of nuclear symmetry potential while studying the effect of nuclear symmetry energy by using heavy-ion collisions.

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