The influence of the symmetry energy on the cone-azimuthal emission

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In the framework of the isospin-dependent Boltzmann-Uehling-Uhlenbeck transport model, effects of the symmetry energy on the evolutions of free n/p ratio and charged pion ratio in the semi-central collision of $^{197}$Au+$^{197}$Au at an incident beam energy of 400 MeV/nucleon are studied. At the beginning of the reaction (before 11 fm/c) they are both affected by the low-density behavior of the symmetry energy but soon after are affected by the high-density behavior of the symmetry energy after nuclei are compressed (after 11 fm/c) and the effects of the symmetry energy are generally smaller compared with the central collision case. Interestingly, their dependences on the symmetry energy are shown to arise with increase of cone-azimuthal angle of the emitted particles. In the direction perpendicular to the reaction plane, the $\pi^-/\pi^+$ ratio or free n/p ratio especially at high kinetic energies exhibits significant sensitivity to the symmetry energy.

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One of the main topics in the nuclear physics is to give a detailed description of the equation of state (EoS) of asymmetric nuclear matter. The EoS at density $\rho$ and isospin asymmetry $\delta$ ($\delta = (n - p)/(n + p)$) is usually expressed as

$$E(\rho, \delta) = E(\rho, 0) + E_{\text{sym}}(\rho)\delta^2 + O(\delta^4),$$

(1)

where $E_{\text{sym}}(\rho)$ is nuclear asymmetry energy. Around normal nuclear matter density, the symmetry energy has a value of about 30 MeV, e.g., from fitting the binding energies of atomic nuclei with the liquid-drop mass formula, but its behavior at supranormal densities is still poorly known. And yet it is very important for understanding the structure and evolution of many astrophysical objects such as neutron stars, supernova explosions, etc. In general, values of the symmetry energy at different densities can be obtained by many-body microscopic theories. However, predictions from various many-body approaches diverge widely, even with the same model but different parameters. New light has been thrown on this puzzle with the advent of model-independent studies of the high-density dependence of the symmetry energy has been carried out by Cozma, et al. [22], which constrain nuclear symmetry energy more scrupulously. To further constrain the EoS of asymmetric nuclear matter, it is worthwhile finding out more delicate observables to probe the high density behavior of the nuclear symmetry energy.

The anisotropic distribution of particle emissions in c.m. system has been studied for quite some time and it has been well known that in the direction perpendicular to the reaction plane the particles emitted carry more information of the squeezed-out dense nuclear matter [24, 25]. Here we revisit this question, as it may be an effective tool to probe the symmetry energy at high densities.

Studying isospin physics in the heavy-ion collision at intermediate energies, the isospin-dependent Boltzmann-Uehling-Uhlenbeck transport model (IBUU) has been a successful approach to describing the dynamical evolution of the systems in phase space. In this model, the mean-field potential (MDI) can be written as

$$U(\rho, \delta, \mathbf{p}, \tau) = A_\nu(x)\frac{\rho^\nu}{\rho_0} + A_I(x)\frac{\rho^I}{\rho_0} + B\left(\frac{\rho}{\rho_0}\right)^\sigma(1 - x\delta^2) - 8\pi T \frac{\rho^{\sigma-1}}{\sigma + 1} \frac{\rho^\sigma}{\rho_0}\delta\rho^\nu + \sum_{\ell = \tau, \tau'} \frac{2C_{\ell, \tau}}{\rho_0} \int d^3 p' \frac{f_\ell(r, p')}{1 + (p - p')^2/L^2},$$

(2)
where $\tau = 1/2$ ($-1/2$) for neutrons (protons) and the $f_t(r, p)$ is the phase space distribution function which is solved following a test particle evolution on a lattice. The $\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p)$ denotes the isospin asymmetry of nuclear medium. By varying the variable $x$ this potential can be used to get 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 $\rho_0$. In this work we choose the situations $x = 0$ (stiff) and $x = 1$ (soft) as comparison. The quantities $A_u(x), A_l(x)$ are $A_u(x) = -95.98 - \frac{2B}{\omega^2} x, A_l(x) = -120.57 + \frac{3B}{\omega^2} x$, here $B = 106.35$ MeV, $\Lambda = p^0_n$ is the nucleon Fermi momentum in symmetric nuclear matter, $C_{\tau, \tau'} = -103.4$ MeV and $C_{\tau, \pi} = -11.7$ MeV. The $C_{\tau, \tau'}$ and $C_{\tau, \pi}$ terms are the momentum-dependent interactions of a nucleon with unlike and like nucleons in the surrounding nuclear matter. The corresponding incompressibility of symmetric nuclear matter at saturation density is 211 MeV. Here the symmetry potential is momentum dependent. Its effects on the free $n/p$ ratio, the $\pi$ production and other observables were investigated. Another important ingredient in heavy-ion collisions is the nucleon-nucleon (NN) cross sections. Medium effects on the NN elastic cross sections have not been well determined so far. In our calculations, the reduction scale according to nucleon effective masses is adopted. This modification is isospin- and momentum-dependent and similar to the BHF with three-body force or DBHF approach calculations only if nucleonic momentum is not too large. The total and differential cross sections for all other particles are taken either from experimental data or obtained by using the detailed balance formula.

In the following, to see the correlation between the anisotropic distribution of the azimuthal angle of the particle emission and effects of the symmetry energy in heavy-ion collisions more specifically, we use 40,000 semi-central $^{197}$Au+$^{197}$Au reaction events for each case to study the influence of the symmetry energy on the azimuthal emission.

Fig. 1(a) shows the effect of the symmetry energy on the evolution of free $n/p$ ratio. At first stage, values of $n/p$ ratio with the soft symmetry energies ($x= 1$) are higher than that with the stiff symmetry energies ($x= 0$). This is because at the beginning of the reaction, compressed nuclear matter densities are lower than normal nuclear density, the $n/p$ ratio at this stage just reflects the low-density behavior of the symmetry energy. After that, nuclear matter’s density reaches above normal density and more free nucleons emit. Finally, the free $n/p$ ratio reflects high-density behavior of the symmetry energy, thus the values of free $n/p$ ratio with the stiff symmetry energy ($x= 0$) are larger than that with the soft symmetry energy ($x= 1$). Nevertheless the discrepancy with the two symmetry energies is quite smaller.

Another common probe is the emission of pion. In this study pions are created by the decay of the resonances $\Delta(1232)$ and $N^*(1440)$ produced in dense matter since the cross section of direct pion production is very small at the considered energies. The reaction channels related to pion production and absorption are given as follows:

\[
\begin{align*}
NN & \rightarrow NN, \\
NR & \rightarrow NR, \\
NN & \leftrightarrow NR, \\
R & \leftrightarrow N\pi,
\end{align*}
\]

here $R$ denotes $\Delta$ or $N^*$ resonances and the energy and momentum dependent decay width is used in the present work. Furthermore, the $(\pi^-/\pi^+)$$_{like}$ ratio is adopted and based on the dynamics of pion resonance productions and decays, it read as $(\pi^-/\pi^+)$$_{like} = \frac{\pi^- \Delta \rightarrow \Delta \pi^-}{\Delta \pi^+ \rightarrow \pi^+ \Delta \pi^+}$. Fig. 1(b) shows the charged pion ratio as a function of time with different symmetry energies. It is interesting to see that at time $t \sim 11$ fm/c, there is a cross similar to free $n/p$ ratio as shown in Fig. 1(a), but for the charged pion ratio the values are larger for the stiff symmetry energy.
Anisotropic distribution of the azimuthal angle of the particle emission in heavy-ion collisions has been observed in a number of experiments. The analysis of the angle distributions can help us to extract the information of the hot and dense nuclear matter. The azimuth dependence of the effect of the symmetry energy on the ratio $n/p$ and $\pi^-/\pi^+$ is plotted in Fig. 2(a) and Fig. 2(b) where $\phi$ is the cone-azimuthal angle of the emitted particle with respect to the reaction plane and defined as $\phi = \arcsin(p_y/\sqrt{p_x^2 + p_y^2 + p_z^2})$. From Fig. 2 we can clearly see that with increasing $\phi$ the ratios both exhibit more sensitivity to the symmetry energy.

Plotted in Fig. 3 is the kinetic energy dependence of the ratios of $n/p$ and $\pi^-/\pi^+$ in the direction perpendicular to the reaction plane. Compared with that shown in Fig. 1, effects of the symmetry energy on the two observables are indeed enlarged evidently and increase with particle's kinetic energy, e.g., in high kinetic region for charged pion ratio shown in Fig. 3(b) effect of symmetry energy can be as high as more than 20%, whereas its effect on the total charged pion ratio shown in Fig. 1 is about 5%.

This enlargement of the effect of the symmetry energy is reasonable and consistent with the findings in Ref. [23]. It is well known that the squeeze-out of nuclear matter occurs in non-central heavy-ion collisions. Particles emitted in the direction perpendicular to the reaction plane carry direct information about the high density phase and thus reflect the high density behavior of nuclear symmetry energy. Moreover, the energetic particles are mostly produced in the high density region. As a result the free $n/p$ or $\pi^-/\pi^+$ ratios at high kinetic energies in the direction perpendicular to the reaction plane
exhibit significant sensitivity to the symmetry energy. In conclusion, based on the isospin-dependent Boltzmann-Uehling-Uhlenbeck transport model, the semi-central collision of $^{197}$Au+$^{197}$Au at an incident beam energy of 400 MeV/nucleon are studied. It is found that the sensitivities to the symmetry energy of the charged pion ratio, as well as the free neutron/proton ratio, arise with increase of cone-azimuthal angle of the emitted particles. And in the direction perpendicular to the reaction plane, the $\pi^{-}/\pi^{+}$ ratio or free n/p ratio especially at high kinetic energies exhibits significant sensitivity to the symmetry energy.

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