Effects of nuclear symmetry energy and in-medium NN cross section in heavy-ion collisions at beam energies below the pion production threshold

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Based on the isospin-dependent Boltzmann–Uehling–Uhlenbeck (IBUU04) transport model, we explored effects of in-medium NN elastic scattering cross section and nuclear symmetry energy on the subthreshold pion production in the ^{132}Sn + ^{124}Sn reaction. We find that, with the decrease of the incident beam energy, the effects of the in-medium NN elastic scattering cross section on the π^-/π^+ ratio are larger than that of the symmetry energy, although the latter may be also larger. While keeping the effect of symmetry energy, the double ratio of π^-/π^+ from neutron-rich and neutron-poor reaction systems (with the same mass number of system) ^{132}Sn + ^{124}Sn and ^{128}Pm + ^{128}Pm almost fully cancels out the effects of the in-medium NN elastic scattering cross section.

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I. INTRODUCTION

Knowledge on the density dependence of the symmetry energy is crucial to understanding the structure of exotic nuclei, the dynamics of heavy-ion collisions, and many important issues in nuclear astrophysics such as neutron star cooling and supernova explosions [1–4]. While great progress has been made to constrain the symmetry energy at low densities [5–9], the high-density behavior of the symmetry energy diverges widely from interpreting FOPI data [10–15]. The π^-/π^+ ratio was found to be a sensitive probe to the high-density behavior of the symmetry energy by several transport models [16–20]. In fact, for pion production, at lower beam energies, effects of symmetry energy and the in-medium effect may both become larger [21,22]. It is thus necessary to do a comparative study of effects of the in-medium NN cross section and the effects of the symmetry energy on pion production in heavy-ion collisions at lower beam energies. And these experimental studies will become possible at facilities that offer fast radioactive beams, such as the National Superconducting Cyclotron Laboratory (NSCL) and the Facility for Rare Isotope Beams (FRIB) in the USA, the GSI Facility for Antiproton and Ion Research (FAIR) in Germany, or the Radioactive Isotope Beam Facility (RIBF) in Japan.

II. THE ISOSPIN-DEPENDENT BOLTZMANN–UEHLING–UHLENBECK MODEL

In this study, we adopt the semiclassical transport model called the isospin-dependent Boltzmann–Uehling–Uhlenbeck model (IBUU04), in which the isospin-dependent initial neutron and proton density distributions of the projectile and target are obtained by using the Skyrme–Hartree–Fock with Skyrme M^* (SM) force parameters [23]. An isospin- and momentum-dependent mean-field single nucleon potential is also used, i.e.,

$$\begin{aligned} U(\rho,\delta,\mathbf{p},\tau) = {} & A_u(x)\frac{\rho_{\tau'}}{\rho_0} + A_l(x)\frac{\rho_\tau}{\rho_0} \\ & + B\left(\frac{\rho}{\rho_0}\right)^\sigma (1-x\delta^2) - 8x\tau\frac{B}{\sigma+1}\frac{\rho^{\sigma-1}}{\rho_0^\sigma}\delta\rho_{\tau'} \\ & + \frac{2C_{\tau,\tau}}{\rho_0}\int d^3\mathbf{p}'\frac{f_\tau(\mathbf{r},\mathbf{p}')}{1+(\mathbf{p}-\mathbf{p}')^2/\Lambda^2} \\ & + \frac{2C_{\tau,\tau'}}{\rho_0}\int d^3\mathbf{p}'\frac{f_{\tau'}(\mathbf{r},\mathbf{p}')}{1+(\mathbf{p}-\mathbf{p}')^2/\Lambda^2}, \end{aligned} \quad (1)$$

where $\tau = 1/2$ $(-1/2)$ for neutrons (protons), $\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p)$ is the isospin asymmetry, and ρ_n and ρ_p denote neutron and proton densities, respectively. The parameters $A_u(x)$, $A_l(x)$, B, $C_{\tau,\tau}$, $C_{\tau,\tau'}\sigma$, and Λ are all given in Ref. [24]. $f_\tau(\mathbf{r},\mathbf{p})$ is the phase-space distribution function at coordinate $\mathbf{r}$ and momentum $\mathbf{p}$. Different x parameters can be used to mimic different forms of the symmetry energy. In this model, the reaction channels on pion production and absorption are

$$\begin{aligned} & NN \to NN, \quad NR \to NR, \\ & NN \leftrightarrow NR, \quad R \leftrightarrow N\pi, \end{aligned} \quad (2)$$

where R represents Δ or N^* resonances. The experimental free-space nucleon-nucleon (NN) scattering cross section and the in-medium NN cross section can be used optionally. For the latter, we use the isospin-dependent in-medium NN elastic cross section, which is from the scaling model according to nucleon effective masses [25–28]:

$$R_{\text{medium}}(\rho,\delta,\vec{p}) = \sigma^{\text{medium}}_{NN_{\text{elastic}}}/\sigma^{\text{free}}_{NN_{\text{elastic}}} = (\mu^*_{NN}/\mu_{NN})^2, \quad (3)$$

where μ_{NN} and μ^*_{NN} are the reduced masses of the colliding nucleon pair in free space and in the medium, respectively.

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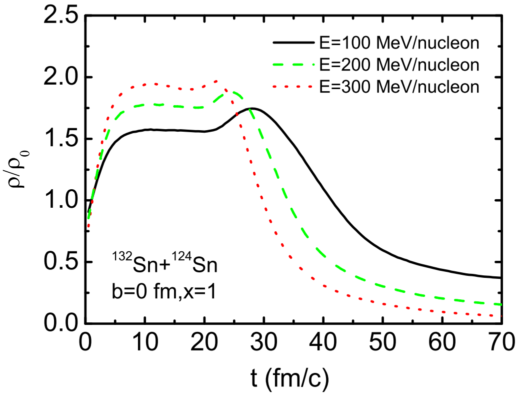

FIG. 1. (Color online) Maximal baryon densities reached in central reaction $^{132}\mathrm{Sn} + ^{124}\mathrm{Sn}$ at $E_{\mathrm{beam}} = 100$, 200, and 300 MeV/nucleon.

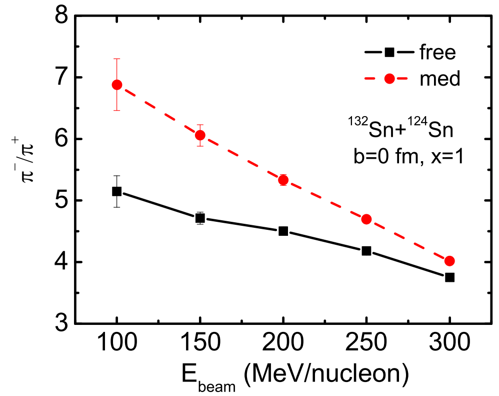

FIG. 2. (Color online) Effects of in-medium NN elastic scattering cross section on the π^-/π^+ ratio in central collision $^{132}\mathrm{Sn} + ^{124}\mathrm{Sn}$ at $E_{\mathrm{beam}} = 100$, 150, 200, 250, and 300 MeV/nucleon, respectively.

And the effective mass of the nucleon in isospin-asymmetric nuclear matter is given by

$$m_\tau^* = \left\{1 + \frac{m_\tau}{p}\frac{dU_\tau}{dp}\right\}^{-1} m_\tau. \quad (4)$$

From the definition and Eq. (1), it is seen that the effective mass depends not only on the density and asymmetry of nuclear matter, but also on the momentum of the nucleon [29]. For the inelastic cross section we use the experimental data from free space NN collisions since the in-medium inelastic NN cross section is still very controversial. The total and differential cross sections for all other particles are taken either from experimental data or obtained by using the detailed balance formula. The isospin dependent phase-space distribution functions of the particles involved are solved by using the test-particle method numerically. The isospin dependence of Pauli blocking for fermions is also considered.

III. RESULTS AND DISCUSSIONS

As shown in Fig. 1, the maximal baryon densities reached in $^{132}\mathrm{Sn} + ^{124}\mathrm{Sn}$ collisions are about 1.5 $\sim$ 2 times the saturation density at $E_{\mathrm{beam}} = 100$, 200, and 300 MeV/nucleon. We can also see that the maximal baryon density increased with incident beam energy. However, the existing time of supradensity matter becomes shorter with increasing beam energy.

Figure 2 shows the effects of the in-medium NN elastic scattering cross section on the π^-/π^+ ratio in central collisions $^{132}\mathrm{Sn} + ^{124}\mathrm{Sn}$ at $E_{\mathrm{beam}} = 100$, 150, 200, 250, and 300 MeV/nucleon, respectively. From Fig. 2 we can see that the value of the π^-/π^+ ratio decreases with increasing beam energy, which is consistent with Ref. [21]. This is partially because the production of pions is from repeated nucleon-nucleon collisions at higher beam energies, i.e., a neutron converts a proton by producing π^- and subsequent collisions of that proton can convert again to a neutron by producing π^+. More interestingly, one can see that the effects of the in-medium NN elastic cross section on the value of the π^-/π^+ ratio become larger and larger with decreasing beam energy. At the lower beam energy of 100 MeV/nucleon, the effects of in-medium NN elastic cross section on the π^-/π^+ ratio can reach about 40%. When one changes the NN elastic cross section, total NN collision number would also changes accordingly. As there is a certain probability of inelastic processes in total NN collisions, NN inelastic collisions are thus affected by the NN elastic cross section. At high beam energy, NN inelastic processes may be more than elastic processes. So the elastic NN cross section should have small effects on pion production. But at low beam energy, pion production is via many NN scatterings, so a large number of NN elastic scatterings increases the whole NN scatterings, since there is a certain probability of inelastic processes in an NN collision, pion production should be affected by NN elastic scatterings.

To see more clearly how the in-medium NN cross section affects the π^-/π^+ ratio and the effect of the symmetry energy on pion production, we plot the evolution of pion meson production with different NN cross sections and symmetry energies. Shown in Figs. 3 and 4 are time evolutions of π^- and π^+ mesons with different symmetry energies ($x = 0$, $x = 1$) and different NN elastic scattering cross sections (in-medium, free) in the central collision $^{132}\mathrm{Sn} + ^{124}\mathrm{Sn}$ at beam energies of 100 and 200 MeV/nucleon, respectively. In both Figs. 3 and 4, we can see that the effects of the in-medium NN elastic scattering cross section on π^+ production is larger than that on π^- production. However, the effects of symmetry energy on the π^+ production is smaller than that of π^- production. The reason in-medium effects on π^+ production are larger than that on π^- production is that the reduction factor R_{medium} of pp (proton-proton) pair is smaller than that of nn (neutron-neutron) pair [29] as well as pp (nn) collision mainly produce π^+ (π^-). And due to Coulomb actions among protons, π^+ production is also less sensitive to the symmetry energy. In Figs. 3 and 4, we can also see that, for π^- production, the effects of the in-medium NN cross section are smaller than that of the symmetry energy whereas for π^+ production, the effects of the in-medium NN cross section are obviously larger than that of the symmetry energy. And with increasing beam energy, the effects of the in-medium NN cross section become smaller.

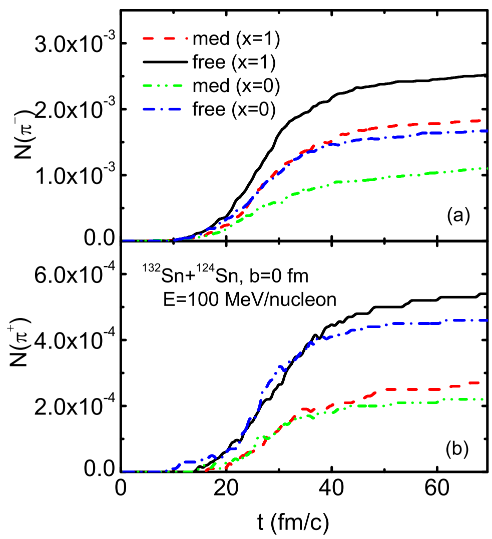

FIG. 3. (Color online) Time evolution of π^- and π^+ mesons with different symmetry energies ($x = 0, x = 1$) and different NN elastic scattering cross sections (in-medium, free) in the central collision ^{132}Sn + ^{124}Sn at the beam energy of 100 MeV/nucleon.

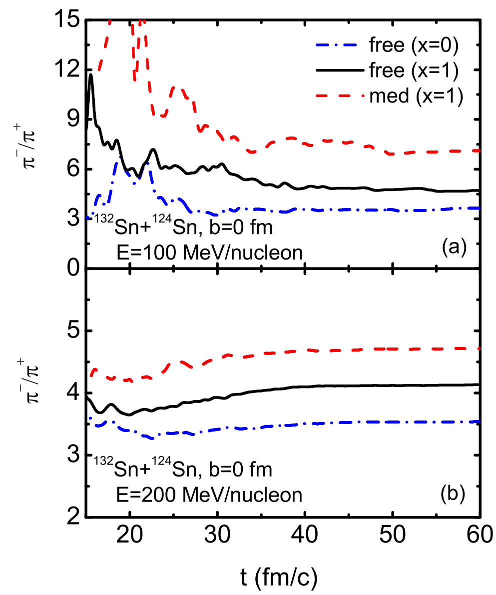

FIG. 5. (Color online) Effects of in-medium NN cross section and symmetry energy on π^-/π^+ ratio in central collision ^{132}Sn + ^{124}Sn at beam energies of 100 and 200 MeV/nucleon, respectively.

To see more clearly the effects of the in-medium NN elastic scattering cross section and symmetry energy on the π^-/π^+ ratio, in Fig. 5 we show the time evolution of the π^-/π^+ ratio with different symmetry energies and the NN elastic scattering cross sections at beam energies of 100 and 200 MeV/nucleon, respectively. We can clearly see that the effects of the in-medium NN cross section on the π^-/π^+ ratio are about two times larger than that of the symmetry energy at an incident beam energy of 100 MeV/nucleon. However, at an incident beam energy of 200 MeV/nucleon, the effects of the in-medium NN cross section on the π^-/π^+ ratio are almost equal to that of the symmetry energy.

In order to reduce the effects of in-medium and retain effects of the symmetry energy on the π^-/π^+ ratio, we calculate double ratio of π^-/π^+ by using two reaction systems of the same neutron-rich and neutron-poor isotopes [16]. Shown in Fig. 6 is the time evolution of the double π^-/π^+ ratio from ^{132}Sn + ^{124}Sn and ^{100}Sn + ^{100}Sn. It is seen that effects of the in-medium NN cross section on the double π^-/π^+ ratio is about 30%, but the effects of the symmetry energy is about 42%. However, from the top panel of Fig. 5, we see that effects of the in-medium NN cross section on the π^-/π^+ ratio is about 50%, but the effects of the symmetry energy is about 25%. Thus the double ratio of π^-/π^+ from two reaction systems of the same neutron-rich and neutron-poor isotopes can indeed reduce uncertainties from in-medium properties of hadrons and keep the effects of the symmetry energy. While from Fig. 6, we can see that, even when use the double ratio of observables, the effects of the in-medium

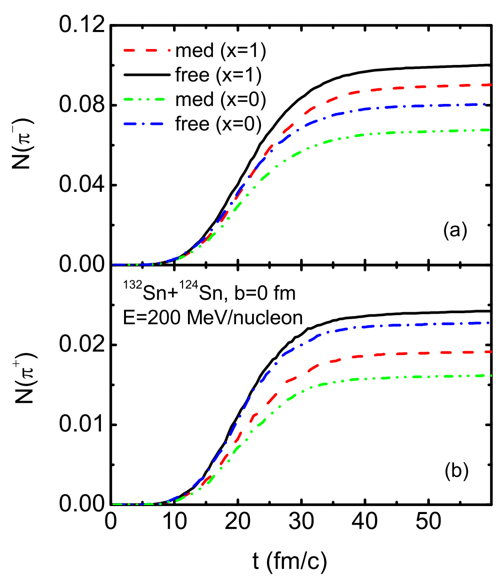

FIG. 4. (Color online) Same as Fig. 3 but at the beam energy of 200 MeV/nucleon.

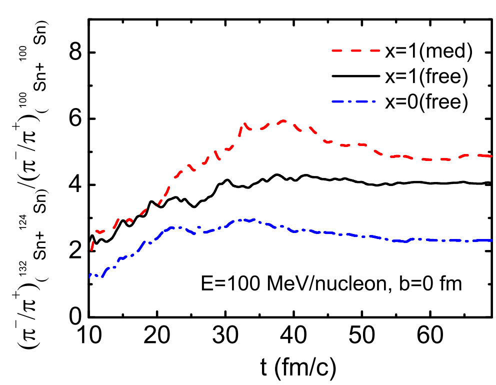

FIG. 6. (Color online) Effects of medium and symmetry energy on the double π^-/π^+ ratio from ^{132}Sn + ^{124}Sn and ^{100}Sn + ^{100}Sn at the beam energy of 100 MeV/nucleon.

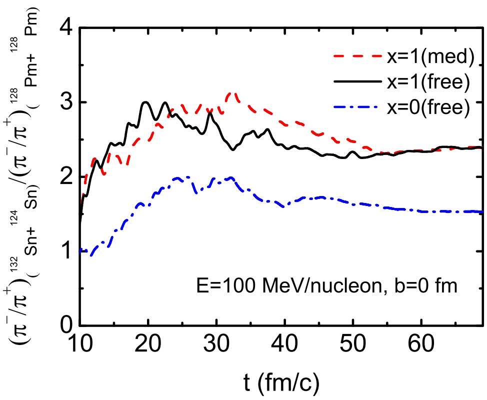

FIG. 7. (Color online) Effects of medium and symmetry energy on the double π^-/π^+ ratio from ^{132}Sn + ^{124}Sn and ^{128}Pm + ^{128}Pm at the beam energy of 100 MeV/nucleon.

NN cross section are still very obvious. Besides theoretical efforts [27] and advanced methods such as photon emission in heavy-ion collisions [30], we also simulated the double ratio of π^-/π^+ from two reaction systems (with the same mass number of system but different isotopes) ^{132}Sn + ^{124}Sn and ^{128}Pm + ^{128}Pm. Interestingly, from Fig. 7 one sees that effects of the symmetry energy are kept but the effects of the in-medium NN elastic scattering cross section are almost fully canceled out. This is because the latter-two neutron-rich and neutron-poor reaction systems have the same baryon number, evolutions, and distributions of baryon density in the two reactions are almost the same.

IV. CONCLUSIONS

In summary, we studied the effects of in-medium NN cross section and the effects of symmetry energy on the π^-/π^+ ratio at lower incident beam energies. We find that, at lower incident beam energy, for the π^-/π^+ ratio, the effects of the in-medium NN cross section are larger than that of the symmetry energy. The double ratio of π^-/π^+ from reaction systems of the same neutron-rich and neutron-poor isotopes cannot fully cancel out the effects of the in-medium NN cross section. However, the double ratio of π^-/π^+ from reaction systems of different neutron-rich and neutron-poor isotopes but with the same mass number of reaction system almost fully cancels out the effects of the in-medium NN cross section.

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[1] B. A. Li, L. W. Chen, and C. M. Ko, Phys. Rep. **464**, 113 (2008).
[2] V. Baran, M. Colonna, V. Greco, M. Di Toro, Phys. Rep. **410**, 335 (2005).
[3] J. M. Lattimer and M. Prakash, Science **304**, 536 (2004).
[4] A. W. Steiner, M. Prakash, J. M. Lattimer *et al.*, Phys. Rep. **411**, 325 (2005).
[5] M. B. Tsang, Yingxun Zhang, P. Danielewicz, M. Famiano, Zhuxia Li, W. G. Lynch, and A. W. Steiner, Phys. Rev. Lett. **102**, 122701 (2009).
[6] M. B. Tsang, Z. Chajecki, D. Coupland, P. Danielewicz, F. Famiano, R. Hodges, M. Kilburn, F. Lu, W. G. Lynch, J. Winkelbauer, M. Youngs, and YingXun Zhang, Prog. Part. Nucl. Phys. **66**, 400 (2011).
[7] M. B. Tsang, J. R. Stone, F. Camera, P. Danielewicz, S. Gandolfi, K. Hebeler, C. J. Horowitz, Jenny Lee, W. G. Lynch, Z. Kohley, R. Lemmon, P. Moller, T. Murakami, S. Riordan, X. Roca-Maza, F. Sammarruca, A. W. Steiner, I. Vidaña, and S. J. Yennello, Phys. Rev. C **86**, 015803 (2012).
[8] Y. X. Zhang, Z. Li, K. Zhao, H. Liu, and M. B. Tsang, Nuclear Science and Techniques **24**, 050503 (2013).
[9] K. S. Jeong and S. H. Lee, Nuclear Science and Techniques **24**, 050506 (2013).
[10] W. M. Guo, G. C. Yong, Y. J. Wang, Q. Li, H. F. Zhang, and W. Zuo, arXiv:1404.7217.
[11] Z. G. Xiao, B. A. Li, L. W. Chen, G. C. Yong, and M. Zhang, Phys. Rev. Lett. **102**, 062502 (2009).
[12] Z. Q. Feng and G. M. Jin, Phys. Lett. B **683**, 140 (2010).
[13] P. Russotto, P. Z. Wu, M. Zoric, M. Chartier, Y. Leifels, R. C. Lemmon, Q. Li, J. Ł. ukasik, A. Pagano, P. Pawłowski, and W. Trautmann, Phys. Lett. B **697**, 471 (2011).
[14] W. J. Xie and F. S. Zhang, Nuclear Science and Techniques **24**, 050502 (2013).
[15] M. D. Cozma, Y. Leifels, W. Trautmann, Q. Li, and P. Russotto, Phys. Rev. C **88**, 044912 (2013).
[16] G. C. Yong, B. A. Li, L. W. Chen, and W. Zuo, Phys. Rev. C **73**, 034603 (2006).
[17] B.-A. Li, Phys. Rev. Lett. **88**, 192701 (2002).
[18] T. Gaitanos, M. Di Toro, S. Typel *et al.*, Nucl. Phys. A **732**, 24 (2004).
[19] Q. F. Li, Z. X. Li, S. Soff, M. Bleicher, and H. Stöcker, Phys. Rev. C **72**, 034613 (2005).
[20] Y. Gao, G. C. Yong, Y. J. Wang, Q. F. Li, and W. Zuo, Phys. Rev. C **88**, 057601 (2013).
[21] F. Zhang, Y. Liu, G. C. Yong, and W. Zuo, Chin. Phys. Lett. **29**, 052502 (2012).
[22] J. Xu, L. W. Chen, C. M. Ko, B. A. Li, and Y. G. Ma, Phys. Rev. C **87**, 067601 (2013).
[23] J. Friedrich and P. G. Reinhard, Phys. Rev. C **33**, 335 (1986).
[24] C. B. Das, S. Das Gupta, C. Gale, and B. A. Li, Phys. Rev. C **67**, 034611 (2003); B. A. Li *et al.*, Nucl. Phys. A **735**, 563 (2004).
[25] J. W. Negele and K. Yazaki, Phys. Rev. Lett. **47**, 71 (1981).
[26] V. R. Pandharipande and S. C. Pieper, Phys. Rev. C **45**, 791 (1992).
[27] F. Sammarruca, Eur. Phys. J. A **50**, 22 (2014).
[28] B. A. Li and L. W. Chen, Phys. Rev. C **72**, 064611 (2005).
[29] G. C. Yong, Eur. Phys. J. A **46**, 399 (2010).
[30] G. C. Yong, W. Zuo, and X. C. Zhang, Phys. Lett. B **705**, 240 (2011).