Effect of entrance-channel asymmetry on the isospin dependence of nucleon emission in heavy ion collisions*

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Abstract Using the isospin- and momentum-dependent hadronic transport model IBUU04, we have investigated the influence of the entrance-channel isospin asymmetry on the sensitivity of the pre-equilibrium neutron/proton ratio to symmetry energy in central heavy-ion collisions induced by high-energy radioactive beams. Our analysis and discussion are based on the dynamical simulations of the three isotopic reaction systems ^{132}Sn+^{124}Sn, ^{124}Sn+^{112}Sn and ^{112}Sn+^{112}Sn which are of the same total proton number but different isospin asymmetry. We find that the kinetic-energy distributions of the pre-equilibrium neutron/proton ratio are quite sensitive to the density-dependence of symmetry energy at incident beam energy $E/A = 400$ MeV, and the sensitivity increases as the isospin asymmetry of the reaction system increases.

Key words neutron to proton ratio, symmetry energy, isospin asymmetry of reaction system, hadronic transport model

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1 Introduction

Nowadays, one of the most important aims of heavy ion collisions (HIC) is to constrain the equation of state (EOS) of isospin asymmetric nuclear matter, especially the density dependence of nuclear symmetry energy. The high-density behavior of symmetry energy is expected to play an extremely important role in understanding many interesting phenomena and questions in astrophysics such as neutron-star structure and neutron-star cooling via neutrinos[1—3]. The density dependence of symmetry energy at low densities around and below normal nuclear matter density has been shown to be crucial for predicting the properties of radioactive nuclei far from stability line[4—7]. Up to now, the density dependence of symmetry energy especially the high-density behavior of symmetry energy is still poorly known. During the dynamical evolution of HIC at intermediate and high energies a transient state of dense and isospin asymmetric nuclear matter can be formed and therefore the experiment of HIC offers an unique opportunity in laboratory for exploring the EOS of asymmetric nuclear matter in a wide density range up to 2—3 times the normal nuclear matter density. Since the nuclear EOS can not be measured directly in the experiments, one has to compare the experimental observables and the theoretical simulations by using transport models. In order to extract reliable information on the density-dependence of symmetry energy from HIC induced by radioactive beams, the key point is to find the experimental probes which are sensitive to symmetry energy. Based on the isospin-dependent transport model calculations, some experimental observables have been proposed as promising probes to nuclear symmetry energy, such as the single and double neutron/proton (n/p) ratio of free nucleons[8—11], the single and double π^-/π^+ ratios[12], the neutron-proton differential flow[14—16], the proton differential elliptic flow[17], the isospin diffusion[18, 19], the

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neutron-proton correlation function[20] and the isobaric yield ratios of light clusters[13, 21]. Since the isovector part of nuclear mean field (i.e., isospin symmetry potential) is much smaller than the isoscalar part[22], its effect in HIC is of second-order as compared with the effect of the isoscalar part. Therefore it is extremely important to know the optimum conditions of entrance channel (including beam energy, impact parameter, isospin asymmetry of the reaction system) for getting the most pronounced effect of symmetry potential. In the previous paper[24], we explored the beam-energy dependence of the n/p ratio of free nucleons in HIC and found the n/p ratio in the ^{132}Sn+^{124}Sn collisions is most sensitive to symmetry potential at beam energies around $E_{\rm beam}/A = 400$ MeV. In the present work, we shall extend our previous investigation and examine the influence of the entrance-channel isospin-asymmetry (i.e., the isospin-asymmetry of the reaction system) on the pre-equilibrium nucleon emission. We shall study especially the effect of the entrance-channel isospin-asymmetry of the colliding system on the sensitivity of the pre-equilibrium n/p ratio to symmetry energy.

2 Theoretical model

Our work is based on the isospin- and momentum-dependent transport model IBUU04[25]. The most important inputs for all transport models are NN cross sections and single nucleon potential. In the present calculation, we adopt the in-medium NN cross sections determined by using an effective-mass scaling model consistent with the adopted single particle potential[12]. The single nucleon potential includes generally an isoscalar part and an isovector part. In the IBUU04 transport model, the single nucleon potential of Ref. [26] derived within the Hartree-Fock approach using a modified Gogny effective interaction (MDI) has been adopted. The isovector part of single nucleon potential can be described by the isospin symmetry potential defined as: $U_{\rm sym}=(U_{\rm n}-U_{\rm p})/2\beta$, where $U_{\rm n}$ and $U_{\rm p}$ are the neutron and proton potentials, respectively; $\beta\equiv(\rho_{\rm n}-\rho_{\rm p})/(\rho_{\rm n}+\rho_{\rm p})$ is the isospin-asymmetry parameter. In order to mimic different theoretical predictions by various microscopic and/or phenomenological many-body approaches on isospin symmetry potential corresponding to different density dependence of symmetry energy $E_{\rm sym}(\rho)$, a parameter x is introduced in the MDI potential. In the present work, we choose two values of x parameter, i.e., $x=0$ and $x=-1$. The symmetry potentials with these two values of x parameter correspond to two different density dependence of symmetry energy as shown in Fig. 1. It can be seen from the figure that the density dependence of symmetry energy obtained by adopting $x=-1$ is stiffer than the one by $x=0$. It is worth mentioning that the difference between the two density-dependence of symmetry energy here is smaller than that in our previous work[24] in which the two values of $x=1$ and $x=-1$ were adopted. We refer the reader to Refs. [25, 26] for more details about the IBUU04 model and the MDI potential.

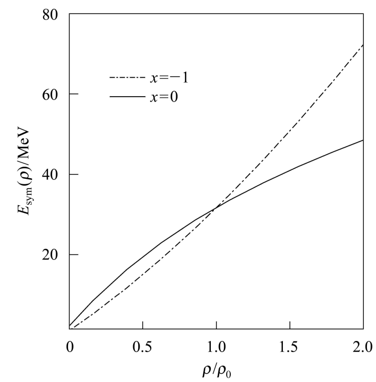

Fig. 1. Density dependence of nuclear symmetry energy with two different values of parameter x, i.e., $x=0$ and $x=-1$.

3 Results and discussions

In this work we have studied the reactions of the three isotopic systems ^{132}Sn+^{124}Sn, ^{124}Sn+^{112}Sn and ^{112}Sn+^{112}Sn at a beam energy of $E_{\rm beam}/A=400$ MeV and an impact parameter of 1 fm. Among the three systems, the ^{132}Sn+^{124}Sn system is most asymmetric in neutrons and protons with an isospin asymmetry of $\beta=(N-Z)/(N+Z)\approx 2.2$, while the system ^{112}Sn+^{112}Sn is the most symmetric one with $\beta\approx 0.11$. At the incident energy of $E_{\rm beam}/A = 400$ MeV, the maximum average baryon density reached in the reaction region is about $2\rho_0$[28]. Free nucleons are defined as those with the local baryon densities less than $\rho_0/8$. Shown in Fig. 2 is the time evolution of free n/p ratios in the two reactions of ^{132}Sn+^{124}Sn and ^{124}Sn+^{112}Sn. The solid (dashed) and dashed-dot (dotted) lines are the results for the ^{132}Sn+^{124}Sn (^{124}Sn+^{112}Sn) system obtained by adopting the two different symmetry potentials with $x=0$ and $x=-1$, respectively. First, we notice that the free n/p ratios increase rapidly with time during the early stage of the collisions, reach their maximum values at about 7 fm/c, then start to decrease, and finally saturate at the freeze-out time of about 30 fm/c[28, 29]. Here, the freeze-out time is defined and determined at the time the colliding system reaches isospin equilibrium, i.e., after which the n/p ratio of free nucleons becomes almost unchanged with time. The above-obtained result can be explained as follows. During the early stage of the collisions, free nucleons are mainly emitted from the overlap region of the surfaces of the two colliding nuclei where the isospin asymmetry is much higher than that of the colliding system and thus the effect of symmetry potential is expected to be extremely strong. With the evolution of time, a compressed reaction region of the two colliding nuclei is formed and the nucleon emission from the reaction region becomes dominant. Since the asymmetry in the reaction region is about the same as that of the colliding system and much smaller than that in the surface region of the colliding nuclei, the free n/p ratios start to decrease as soon as the emitted nucleons from the reaction region become dominant. Second, from Fig. 2 we find that the free n/p ratio is rather sensitive to the density dependence of symmetry energy. The stiff symmetry energy ($x=-1$) leads to a higher n/p ratio than the soft one ($x=0$) since its repulsion (attraction) on neutrons (protons) is stronger as compared with the soft one. Third, the free n/p rations in the collisions of the ^{132}Sn+^{124}Sn system turn out to be larger than the corresponding n/p ratios in the ^{112}Sn+^{112}Sn system. This is because the isospin asymmetry of the ^{132}Sn+^{124}Sn system is much higher than that of the ^{112}Sn+^{112}Sn system and thus the effect of the isovector part of the single nucleon potential is more pronounced.

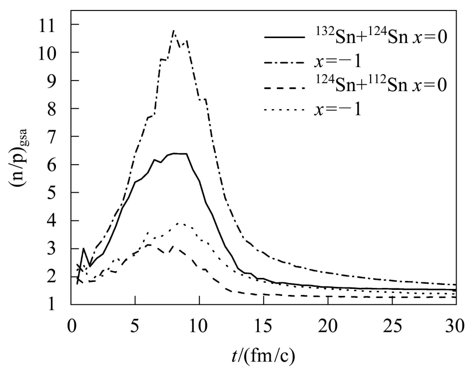

Fig. 2. Time evolution of free neutron to proton ratio with two symmetry energy at incident energy 400 MeV/nucleon.

We report in Fig. 3 the pre-equilibrium n/p ratio $\mathrm{d}N_\mathrm{n}/\mathrm{d}N_\mathrm{p}$ as a function of kinetic energy E_kin for the three isotopic systems. By the notation of pre-equilibrium nucleons we mean the free nucleons emitted before the reaction system reaches freeze-out. It is seen that the n/p ratios decrease as the kinetic energy increases, mainly due to the effect of the Coulomb force which pushes the emitted protons away from low energy to high energy. By comparing the filled squares and the corresponding empty squares, it is clear that the pre-equilibrium n/p ratio is rather sensitive to symmetry potential, especially for the ^{132}Sn+^{124}Sn system which is most asymmetric, and thus can be used as a promising probe for constraining the density-dependence of symmetry energy. The n/p ratio predicted by adopting the stiff symmetry potential ($x=-1$) turns out to be larger than that by the soft symmetry potential ($x=0$), since the effect of a stiffer symmetry potential is more repulsive on neutrons and less repulsive on protons than that of a softer one. It is also noticed that the pre-equilibrium n/p ratio at lower kinetic energies is more sensitive to symmetry energy than that at higher kinetic energies, mainly due to the momentum dependence of the symmetry potential which has been shown to be essentially a decreasing function of momentum at densities of $\rho \leqslant 2\rho_0$[22, 23, 26, 27].

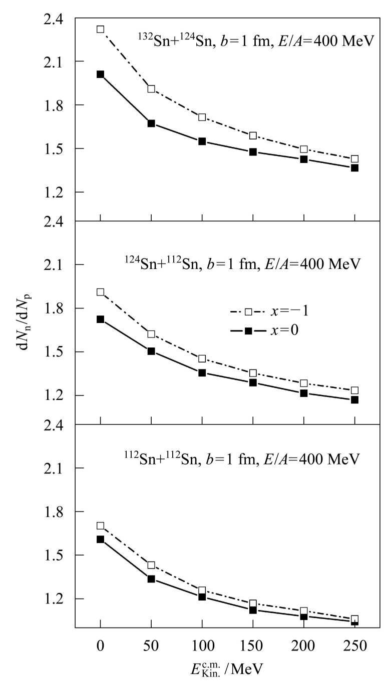

Fig. 3. Pre-equilibrium neutron/proton ratio as a function of kinetic energy in the reactions of the Sn + Sn isotopic systems at $E_\mathrm{beam}/A=$ 400 MeV and $b=1$ fm. The filled and empty squares are obtained by adopting the two different symmetry potentials with $x=0$ and $x=-1$, respectively.

By comparing the three panels of Fig. 3, one can see that as the reaction system becomes more asymmetric in neutrons and protons, the predicted n/p ratio increases and becomes more sensitive to symmetry potential. This can be readily understood according to the isospin dependence of the isovector part of nuclear mean field. In Refs. [22, 27] within the microscopic BHF framework, it is found that the symmetry potential in asymmetric nuclear medium is almost independent on the isospin asymmetry, implying that the isovector part of nuclear mean field increases linearly as a function of isospin asymmetry, i.e., $U_\mathrm{n}(\rho)-U_\mathrm{p}(\rho)=2\beta U_\mathrm{sym}(\rho)$. Accordingly, the effect of the isovector part of nuclear mean field is expected to be more pronounced for a reaction system with higher isospin asymmetry.

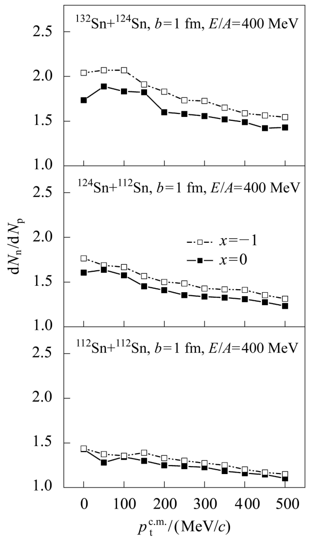

Fig. 4. Transverse-momentum distribution of pre-equilibrium neutron/proton ratio with the two symmetry energies in the reactions of the three Sn+Sn isotopic systems at $E_{\rm beam}/A=$ 400 MeV and an impact parameter of 1 fm.

We report in Fig. 4 the transverse-momentum distribution of the pre-equilibrium n/p ratio $dN_n/dN_p(p_t^{c.m.})$ for the three reaction systems predicted in the two cases of $x=0$ and $x=-1$. It is seen that the dependence of the transverse-momentum distribution of dN_n/dN_p on the entrance-channel asymmetry is similar to that of the kinetic-energy distribution of dN_n/dN_p. The $dN_n/dN_p(p_t^{c.m.})$ which turns out to be larger and more sensitive to symmetry potential for the reaction system with a higher isospin-asymmetry. Therefore, we can conclude that it is more efficient by using more asymmetric reaction system for constraining the density-dependence of symmetry energy by the pre-equilibrium n/p ratio.

4 Summary

In summary, within the framework of the isospin- and momentum-dependent transport model (IBUU04) and adopting two different symmetry potentials, we have investigated the kinetic energy and transverse momentum distributions of the pre-equilibrium n/p ratio in three isotopic Sn+Sn reaction systems at a beam energy of 400 MeV/nucleon and an impact parameter $b=1$ fm. It is found that both the kinetic energy and the transverse momentum distributions of the pre-equilibrium n/p ratio are quite sensitive to the density dependence of symmetry energy. The sensitivity of the n/p ratio to the density dependence of symmetry energy is shown to increase with the isospin asymmetry in the reaction system and it is especially pronounced for the ^{132}Sn+^{124}Sn system which is most asymmetric in neutrons and protons among the three isotopic reaction systems considered here. Our result indicates that it is more promising by using more asymmetric colliding systems to probe the density-dependence of symmetry energy by the pre-equilibrium n/p ratio in HIC.

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