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Double neutron/proton ratio of nucleon emissions in isotopic reaction systems as a robust probe of nuclear symmetry energy

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Abstract

The double neutron/proton ratio of nucleon emissions taken from two reaction systems using four isotopes of the same element, namely, the neutron/proton ratio in the neutron-rich system over that in the more symmetric system, has the advantage of reducing systematically the influence of the Coulomb force and the normally poor efficiencies of detecting low energy neutrons. The double ratio thus suffers less systematic errors. Within the IBUU04 transport model the double neutron/proton ratio is shown to have about the same sensitivity to the density dependence of nuclear symmetry energy as the single neutron/proton ratio in the neutron-rich system involved. The double neutron/proton ratio is therefore more useful for further constraining the symmetry energy of neutron-rich matter.

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1. Introduction

The density dependence of nuclear symmetry energy $E_{\mathrm{sym}}(\rho)$ is still poorly known but very important for both nuclear physics and astrophysics [1–6]. Heavy-ion reactions induced by neutron-rich nuclei provide a unique opportunity to constrain the symmetry energy in a broad density range. A number of potentially useful probes of the symmetry energy have been proposed in the literature mostly based on transport model simulations. Experimental data from several dedicated experiments just started emerging. Some comparisons between the available experimental data and transport model calculations have been carried out recently. These studies have allowed us to place important constraints on the density dependence of symmetry energy. For instance, by using the free-space experimental nucleon–nucleon (NN) cross sections within the transport model IBUU04 [7], a symmetry energy of $E_{\mathrm{sym}}(\rho) \approx 31.6(\rho/\rho_0)^{1.1}$ for densities less than $1.2\rho_0$ was extracted from the MSU data on isospin diffusion [8,9]. While using in-medium NN cross sections calculated within an effective-mass scaling approach [10], a symmetry energy of $E_{\mathrm{sym}}(\rho) \approx 31.6(\rho/\rho_0)^{0.69}$ was found most acceptable in comparison with both the MSU isospin diffusion data and the presently acceptable neutron-skin thickness in ^{208}Pb [10,11]. The currently existing isospin diffusion data alone cannot distinguish the above two forms of the symmetry energy within the experimental error bars [10]. Thus, complementary observables sensitive to the $E_{\mathrm{sym}}(\rho)$, more desirably, studies on correlations of several such observables, are still very much needed to further constrain the symmetry energy.

Because the symmetry potentials have opposite signs for neutrons and protons and the fact that the symmetry potentials are generally smaller compared to the isoscalar potential at the same density, most of the observables proposed so far use differences or ratios of isospin multiplets of baryons, mirror nuclei and mesons, such as, the neutron/proton ratio

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of nucleon emissions [12], neutron–proton differential flow [13], neutron–proton correlation function [14], $t/^3$He [15,16], π^-/π^+ [17–20], Σ^-/Σ^+ [21] and K^0/K^+ ratios [22], etc. Among these observables, the neutron/proton ratio of nucleon emissions has probably the highest sensitivity to the symmetry energy. This is because symmetry potentials act directly on nucleons and normally nucleon emissions are rather abundant in typical heavy-ion reactions. However, it is very challenging to measure some of these observables, especially those involving neutrons. The measurement of neutrons, especially the low energy ones, always suffers from low detection efficiencies even for the most advanced neutron detectors. Therefore, observables involving neutrons normally have large systematic errors. Moreover, for essentially all of these observables, the Coulomb force on charged particles plays an important role. It sometimes competes strongly with the symmetry potentials. One has to disentangle carefully effects of the symmetry potentials from those due to the Coulomb potentials. It is thus very desirable to find experimental observables which can reduce the influence of both the Coulomb force and the systematic errors associated with neutrons. The double neutron/proton ratio of nucleon emissions taken from two reaction systems using four isotopes of the same element, namely, the neutron/proton ratio in the neutron-rich system over that in the more symmetric system, was recently proposed by Lynch et al. [23] as a candidate of such an observable. They have actually measured the double neutron/proton ratio in central reactions of ^{124}Sn + ^{124}Sn and ^{112}Sn + ^{112}Sn at a beam energy of 50 MeV/nucleon at the National Superconducting Cyclotron Laboratory [23]. While the experimental data are currently being finalized, we report here transport model analyzes of the double neutron/proton rations. Besides the above two reactions we also study the double neutron/proton ratio in ^{132}Sn + ^{124}Sn and ^{112}Sn + ^{112}Sn reactions at 400 MeV/nucleon. It is shown that the double neutron/proton ratio has about the same sensitivity to the density dependence of symmetry energy as the corresponding single ratio in the respective neutron-rich system involved. Given the advantages of measuring the double neutron/proton ratios over the single ones, the study of double neutron/proton ratios will be more useful for further constraining the symmetry energy of neutron-rich matter.

2. A summary of the IBUU04 transport model

Our study is carried out using the IBUU04 version of an isospin and momentum-dependent transport model for nuclear reactions induced by neutron-rich nuclei [7]. For completeness and consistency we outline here a few major features most relevant to the present study. More details of the model can be found in Refs. [7,10]. The single nucleon potential is one of the most important inputs to all transport models for nuclear reactions. In the IBUU04 transport model, we use a single nucleon potential derived within the Hartree–Fock approach using a modified Gogny effective interaction (MDI) [24], i.e.,

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

Here $\delta=(\rho_n-\rho_p)/\rho$ is the isospin asymmetry of the nuclear medium. In the above $\tau=1/2$ $(-1/2)$ for neutrons (protons) and $\tau\neq\tau'$; $\sigma=4/3$; $f_\tau(\vec{r},\vec{p})$ is the phase space distribution function at coordinate $\vec{r}$ and momentum $\vec{p}$. The parameters $A_u(x)$, $A_l(x)$, B, $C_{\tau,\tau}$, $C_{\tau,\tau'}$ and Λ were obtained by fitting the momentum-dependence of the $U(\rho,\delta,\vec{p},\tau,x)$ to that predicted by the Gogny–Hartree–Fock and/or the Brueckner–Hartree–Fock (BHF) calculations [25], the saturation properties of symmetric nuclear matter and the symmetry energy of about 30 MeV at normal nuclear matter density $\rho_0=0.16\ \text{fm}^{-3}$ [24]. The incompressibility K_0 of symmetric nuclear matter at ρ_0 is set to be 211 MeV consistent with the latest conclusion from studying giant resonances [26–28]. The parameters $A_u(x)$ and $A_l(x)$ depend on the x parameter according to

$$\begin{aligned}
A_u(x) &= -95.98 - x\frac{2B}{\sigma+1}, \\
A_l(x) &= -120.57 + x\frac{2B}{\sigma+1}.
\end{aligned} \tag{2}$$

The parameter x can be adjusted to mimic predictions on the density dependence of symmetry energy $E_{\text{sym}}(\rho)$ by microscopic and/or phenomenological many-body theories. Shown in Fig. 1 is the density dependence of the symmetry energy for $x=0$ and -1. The recent analyzes of the MSU isospin diffusion data have allowed us to constrain the x parameter to be between these two values for densities less than about $1.2\rho_0$ [10]. The corresponding symmetry energy can be parameterized as $E_{\text{sym}}(\rho)\approx 31.6(\rho/\rho_0)^{1.1}$ and $E_{\text{sym}}(\rho)\approx 31.6(\rho/\rho_0)^{0.69}$ for $x=-1$ and $x=0$, respectively. The main purpose of this work is to investigate whether the double neutron/proton ratio can

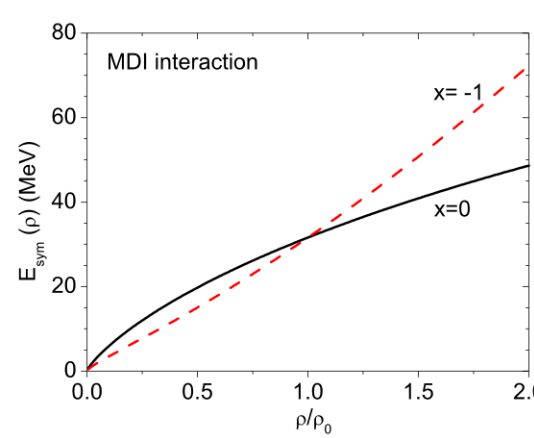

Fig. 1. (Color online.) Symmetry energy as a function of density for the MDI interaction with $x=0$ and -1.

help further narrow down the uncertainty of the symmetry energy.

The last two terms in Eq. (1) contain the momentum-dependence of the single-particle potential. The momentum dependence of the symmetry potential stems from the different interaction strength parameters $C_{\tau,\tau'}$ and $C_{\tau,\tau}$ for a nucleon of isospin τ interacting, respectively, with unlike and like nucleons in the background fields. More specifically, we use $C_{\rm unlike} = -103.4$ MeV and $C_{\rm like} = -11.7$ MeV. With these parameters, the isoscalar potential estimated from $(U_{\rm neutron} + U_{\rm proton})/2$ agrees reasonably well with predictions from the variational many-body theory [29], the BHF approach [25,30,31] including three-body forces and the Dirac–Brueckner–Hartree–Fock (DBHF) calculations [32] in broad ranges of density and momentum. For the MDI potential we used here, the neutron–proton effective mass splitting due to the momentum dependence of the symmetry potential is positive [7]. This is consistent with predictions of both the BHF and DBHF models [25,30–33].

The IBUU04 model can use either the free-space experimental NN cross sections [34] or the in-medium NN cross sections calculated using an effective-mass scaling model consistent with the single particle potential used [10]. In the present work the in-medium NN cross sections are used.

3. Results and discussions

We present and discuss here the double neutron/proton ratios of free nucleons in central and mid-central reactions using three Sn isotopes at a beam energy of 50 MeV/nucleon and 400 MeV/nucleon, respectively. Free nucleons are identified as those having local baryon densities less than $\rho_0/8$. For a comparison and as an example, we first study the single neutron/proton ratio of free nucleons for ^{124}Sn + ^{124}Sn and ^{112}Sn + ^{112}Sn reactions at a beam energy of 50 MeV/nucleon and an impact parameter of 2 fm, respectively. Shown in Fig. 2 are the time evolutions of the single neutron/proton ratios versus the nucleon kinetic energy in the c.m.s frame of the respective reaction. It is seen that the neutron/proton ratio becomes stable after about 100 fm/c. As one expects, the neutron/proton ratio in the neutron-richer system is more sensitive to the symmetry energy, especially for fast nucleons. With the softer symmetry energy of $x = 0$, the symmetry energy and the magnitude of the symmetry potential are higher at sub-saturation densities compared to the case with $x = -1$. At supra-saturation densities, however, it is just the opposite as shown in Fig. 1. In the above two reactions the maximum density reached is about $1.2\rho_0$ [9]. One thus expects to see a higher neutron/proton ratio of free nucleons with the softer symmetry energy of $x = 0$ due to the stronger repulsive (attractive) symmetry potential for neutrons (protons). For the more symmetric system ^{112}Sn + ^{112}Sn, effects of the symmetry energy are negligible because of the small isospin asymmetry in the system. The rise of the neutron/proton ratio at low energies in both systems is due to the Coulomb force which pushes protons away from the center of mass of the reaction. These features are all consistent with those found in an earlier study using a momentum-independent transport

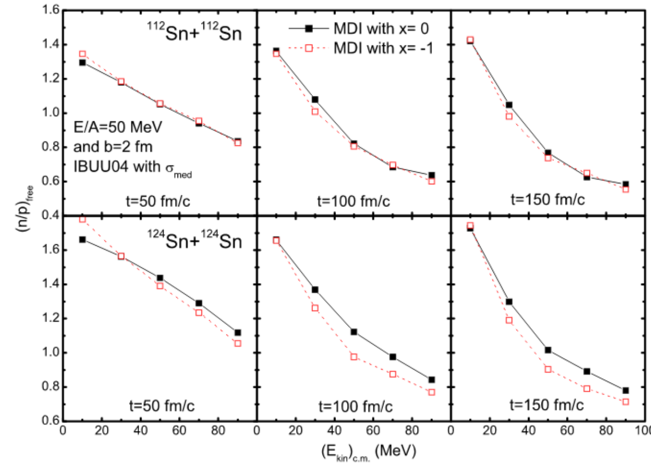

Fig. 2. (Color online.) Time evolution of the neutron/proton ratio of free nucleons as a function of kinetic energy for the reaction of ^{124}Sn + ^{124}Sn (lower windows) and ^{112}Sn + ^{112}Sn (upper windows) at 50 MeV/nucleon and an impact parameter of 2 fm, respectively. The calculations are done with the MDI interaction of $x = 0$ (filled square) and $x = -1$ (open square).

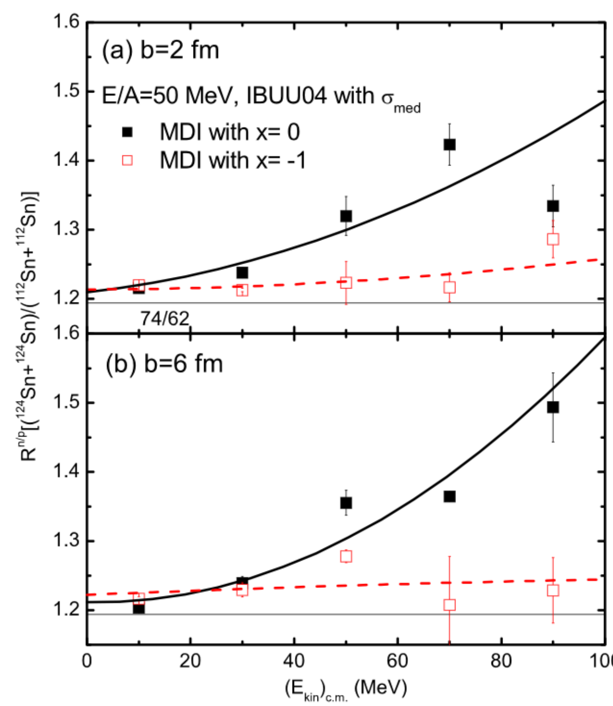

Fig. 3. (Color online.) The double neutron/proton ratio of free nucleons taken from the reactions of ^{124}Sn + ^{124}Sn and ^{112}Sn + ^{112}Sn at 50 MeV/nucleon and an impact parameter of 2 fm (upper window) and 6 fm (lower window), respectively.

model [12]. Unlike the results in Ref. [12], however, the observed symmetry energy effect is only about 10% to 15% even for the most energetic nucleons in the ^{124}Sn + ^{124}Sn reaction. This is understandable since the symmetry energy used here has already been severely constrained by the recent isospin diffusion data. In Ref. [12], however, a much wider uncertainty range between approximately $30(\rho/\rho_0)^{0.5}$ and $30(\rho/\rho_0)^2$ was used for the symmetry energy.

We now turn to the double neutron/proton ratio of free nucleons. Shown in Fig. 3 are the double neutron/proton ratios calculated for the $^{124}Sn + ^{124}Sn$ and $^{112}Sn + ^{112}Sn$ reactions at a beam energy of 50 MeV/nucleon and an impact parameter of 2 fm (upper window) and 6 fm (lower window), respectively. As a reference, a straight line at 74/62 corresponding to the double neutron/proton ratio of the entrance channel is also drawn. Below the pion production threshold, statistically, one would expect the double neutron/proton ratio of nucleon emissions to be a constant close to this value neglecting effects due to both the Coulomb and symmetry potentials. Indeed, the observed double neutron/proton ratios especially at low kinetic energies with $x = -1$ at both impact parameters are almost constants just slightly above the straight line at 74/62. The fact that the double neutron/proton ratio is slightly higher than 74/62 even with $x = -1$ (which corresponds to a weaker symmetry potential at sub-saturation densities compared to the case with $x = 0$) is due to the appreciable repulsive/attractive symmetry potential on neutrons/protons in the $^{124}Sn + ^{124}Sn$ reaction. For the double ratios in the two reactions involving isotopes of the same element one expects that the Coulomb effects are largely cancelled out. More energetic nucleons have gone through denser regions of the reactions, effects of the symmetry potentials on them are thus higher especially in the case with $x = 0$. Therefore, the double neutron/proton ratios increase when the x parameter is changed from $x = -1$ to $x = 0$, especially for energetic nucleons.

At both impact parameters, effects of the symmetry energy are about 10–15% changing from $x = -1$ to $x = 0$ for the energetic nucleons which are mostly from pre-equilibrium emissions. The observed sensitivity to the symmetry energy is about the same as the single neutron/proton ratio shown in Fig. 2. It should also be mentioned that since the neutron/proton ratio at kinetic energies less than about 50 MeV is rather insensitive to the symmetry energy in the reactions at a beam energy of 50 MeV/nucleon, neutron detectors with a threshold energy of 50 MeV is sufficient for the study discussed here. However, as we shall discuss in the following, with reactions at beam energies above the pion production threshold even the low energy neutrons are useful.

Moving to beam energies above the pion production threshold, the reference line at 74/62 is no longer useful. In fact, the π^-/π^+ ratio itself is a promising probe of the symmetry energy at high densities [17–20]. Although the symmetry energy at supra-saturation densities is currently not constrained by any experimental data, for this study, we keep using the two parameters $x = 0$ and $x = -1$ to be consistent with the symmetry energy used for sub-saturation densities. Shown in Fig. 4 are the double neutron/proton ratios from the reactions of $^{132}Sn + ^{124}Sn$ and $^{112}Sn + ^{112}Sn$ at a beam energy of 400 MeV/nucleon and an impact parameter of 1 fm (left window) and 5 fm (right window), respectively. At both impact parameters, effects of the symmetry energy are about 5–10% changing from the case with $x = 0$ to $x = -1$. One notices here that the low energy nucleons are having the largest sensitivity to the variation of the symmetry energy for such high energy heavy-ion collisions. In fact, the neutron/proton ratio of midrapidity nucleons which have gone through the high density phase of the reaction are known to be most sensitive to the symmetry energy [35]. Compared to the results at the beam energy of 50 MeV/nucleon, it is interesting to see a clear turnover in the dependence of the double neutron/proton ratio on the x parameter, namely the double ratio is lower at 50 MeV/nucleon but higher at 400 MeV/nucleon with $x = -1$ than that with $x = 0$. The maximum density reached at the beam energy of 50 and 400 MeV/nucleon is about $1.2\rho_0$ and $2\rho_0$ [35], respectively. The turnover clearly indicates that the double neutron/proton ratio reflects closely the density dependence of the symmetry energy as shown in Fig. 1. This observation also indicates that systematic studies of the double neutron/proton ratio over a broad beam energy range will be important for mapping out the density dependence of the symmetry energy. It is useful to mention that the double π^-/π^+ ratio in the reactions at 400 MeV/nucleon has also been examined. There is some indication that the double π^-/π^+ ratio for intermediate energy pions is more sensitive to the symmetry energy than the single π^-/π^+ ratio in the $^{132}Sn + ^{124}Sn$ reaction. However, unlike the double neutron/proton ratio in the same ensemble of events, the double π^-/π^+ ratio has much larger statistical errors mostly because of the poor statistics of the single π^-/π^+ ratio in the $^{112}Sn + ^{112}Sn$ reaction. Studies on the double π^-/π^+ ratio with significant more events are in progress.

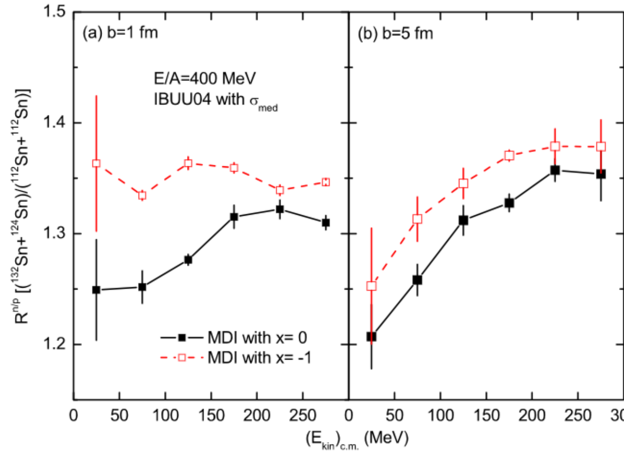

Fig. 4. (Color online.) The double neutron/proton ratio of free nucleons taken from the reactions of $^{132}Sn + ^{124}Sn$ and $^{112}Sn + ^{112}Sn$ at 400 MeV/nucleon and an impact parameter of 1 fm (left window) and 5 fm (right window), respectively.

4. Summary

In summary, within the transport model IBUU04 we investigated the double neutron/proton ratio of nucleon emissions taken from two reaction systems using three Sn isotopes at the beam energy of 50 MeV/nucleon and 400 MeV/nucleon, respectively. It is found that the double neutron/proton ratio has about the same sensitivity to the density dependence of symmetry energy as the single neutron/proton ratio in the more neutron-rich system of the two reactions. Since the double neutron/proton ratio has the advantage of reducing systematically the influence of the Coulomb force and has smaller systematic errors, it is more useful than the single neutron/proton ratio of nucleon emissions for further constraining the symmetry energy of neutron-rich matter.

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