The neutron/proton ratio of squeezed-out nucleons and the high density behavior of the nuclear symmetry energy

Gao-Chan Yong [a,b,c], Bao-An Li [c], Lie-Wen Chen [c,d,e]

[a] *Institute of Modern Physics, Chinese Academy of Science, Lanzhou 730000, China*

[b] *Graduate School,Chinese Academy of Science, Beijing 100039, P.R. China*

[c] *Department of Physics, Texas A&M University-Commerce, Commerce, TX 75429, USA*

[d] *Institute of Theoretical Physics, Shanghai Jiao Tong University, Shanghai 200240, China*

[e] *Center of Theoretical Nuclear Physics, National Laboratory of Heavy Ion Accelerator, Lanzhou 730000, China*

Abstract

Within a transport model it is shown that the neutron/proton ratio of squeezed-out nucleons perpendicular to the reaction plane, especially at high transverse momenta, in heavy-ion reactions induced by high energy neutron-rich nuclei can be a useful tool for studying the high density behavior of the nuclear symmetry energy.

Key words: Equation of state, neutron-rich matter, symmetry energy, heavy-ion reactions, transport theory, radioactive beams.
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The equation of state (EOS) of neutron-rich nuclear matter is not only important for nuclear physics but also crucial for many phenomena and processes in astrophysics and cosmology, see, e.g., Refs. [1,2] for a recent review. Heavy-ion reactions induced by neutron-rich nuclei, especially radioactive beams, provide a unique opportunity to constrain the symmetry energy term in the EOS of isospin asymmetric nuclear matter [3,4,5]. Though considerable progress has been made recently in determining the density dependence of the nuclear symmetry energy at sub-normal densities, probing the high density behavior of the nuclear symmetry energy remains a major challenge. As an illustration of the current situation, in Fig. 1 several typical theoretical model predictions [6,7,8] are compared with some phenomenological constraints obtained from model analyses of experimental data (those labeled $x = 0$, $x = -1$ and FSU-Gold). The constraints labeled $x = 0$ and $x = -1$ were extracted recently from studying isospin diffusion in the reaction of ^{124}Sn $+^{112}$Sn at $E_{beam}/A = 50$ MeV within a transport model [9,10,11,12]. For this particular reaction the maximum density reached is about $1.2\rho_0$. Moreover, it was shown that the neutron-skin thickness in ^{208}Pb calculated within the Hartree-Fock approach using the same underlying Skyrme interactions as the ones labeled $x = 0$ and $x = -1$ is consistent with the available experimental data [13,14,15]. The symmetry energy labeled as FSU-Gold was calculated within a Relativistic Mean Field Model (RMF) using a parameter set such that it reproduces both the giant monopole resonance in ^{90}Zr and ^{208}Pb, and the isovector giant dipole resonance of ^{208}Pb [16]. It is also interesting to mention that the constraint obtained recently from isoscaling analyses is consistent with the FSU-Gold and the $x = 0$ case [17]. These results all together represent the best phenomenological constraints available on the symmetry energy at sub-normal densities. The various predictions at supra-normal densities diverge widely although they are all close to the existing constraints at low densities. The lines labeled $x = 0$, $x = -1$ and FSU-Gold are all extended into the supra-saturation regions where they are not constrained by any experimental data at all. The situation summarized in Fig. 1 signifies clearly the need for more work to determine the high density behavior of the nuclear symmetry energy.

Of particular interest is to identify experimental observables that are sensitive to the high density behavior of the nuclear symmetry energy. However, it is very challenging to find such observables since the high density phase is formed only transiently in heavy-ion reactions. Moreover, most hadronic observables are affected by both the isospin symmetric and asymmetric parts of the EOS at all densities throughout the whole dynamical evolution of the reaction. Thus rather delicate observables have to be selected to probe the high density behavior of the nuclear symmetry energy. The π^-/π^+ ratio [18,19,20,21], the neutron-proton differential flow [22,23] and the K^0/K^+ ratio [24] are among the most promising observables identified so far for this purpose. In this Letter, it is shown that the neutron/proton ratio of squeezed-out nucleons, especially at high transverse momenta, in heavy-ion reactions induced by high energy neutron-rich nuclei is another useful, complementary but more direct tool for studying the high density behavior of the nuclear symmetry energy.

Our study is based on the transport model IBUU04. Details of the model and its applications in studying the density dependence of the nuclear symmetry energy can be found in Refs. [25,26]. The most important input relevant to this work is the momentum- and isospin-dependent single nucleon potential (MDI) [27], i.e.

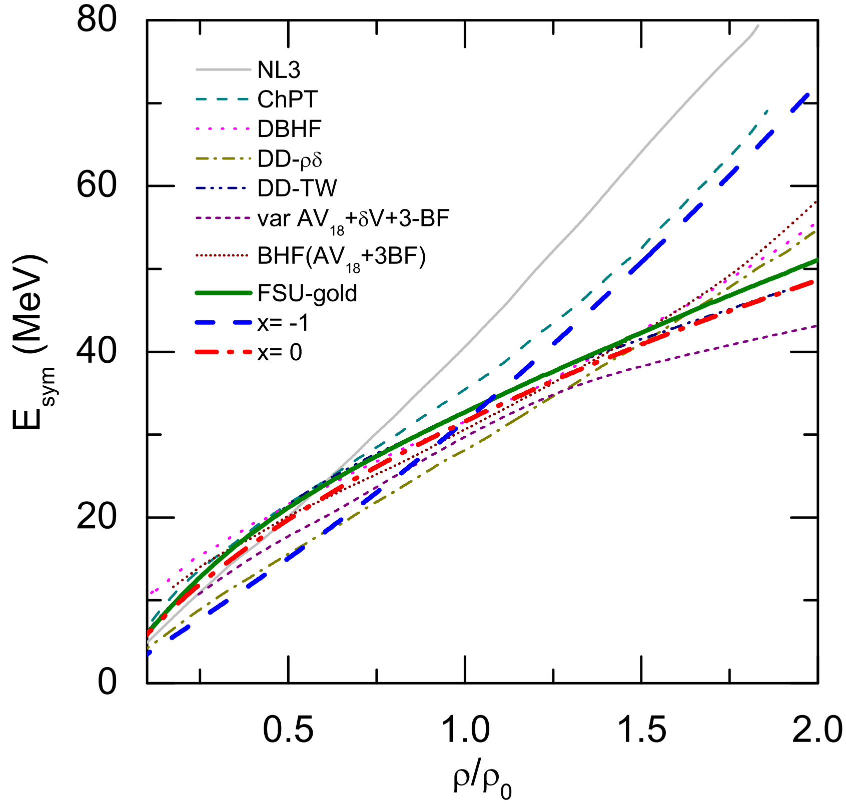

Fig. 1. (Color online) Density dependence of the nuclear symmetry energy using the MDI interaction with $x = 0$ and $x = -1$ and other many-body theories predictions (data are taken from [7,8,16]).

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

The detailed values of the parameters can be found in Ref. [11,12,27]. The parameter x in Eq. (1) was introduced to mimic various forms of the density dependence of the symmetry energy. For a given value x, one can readily calculate the symmetry energy $E_{\rm sym}(\rho)$ as a function of density [27]. As we have stressed earlier, while the symmetry energy at sub-normal densities is constrained approximately between $x = 0$ and $x = -1$, there is still no experimental indication about the symmetry energy at supra-normal densities. Assuming the continuity of the model to higher densities we use in the present work the MDI interaction with $x = 0$ and $x = -1$ at all densities.

It is well known that the squeeze-out of nuclear matter in the participant region perpendicular to the reaction plane occurs in noncentral heavy-ion collisions. In mid-central collisions, high density nuclear matter in the participant region has larger density gradient in the direction perpendicular to the reaction plane. Moreover, in this direction nucleons emitted from the high density participant region have a better chance to escape without being hindered by the spectators. These nucleons thus carry more direct information about the high density phase of the reaction. They have been widely used in probing the EOS of dense matter, see, e.g., Refs. [28,29,30,31,32,33] for a review. We explore here whether the squeeze-out of nucleons can be used to constrain the high density behavior of the nuclear symmetry energy. As an example, we consider here the reaction of ^{132}Sn+^{124}Sn at a beam energy of 400 MeV/nucleon and an impact parameter of 5 fm. In this reaction the maximal baryon density reached is about twice the normal nuclear matter density[23].

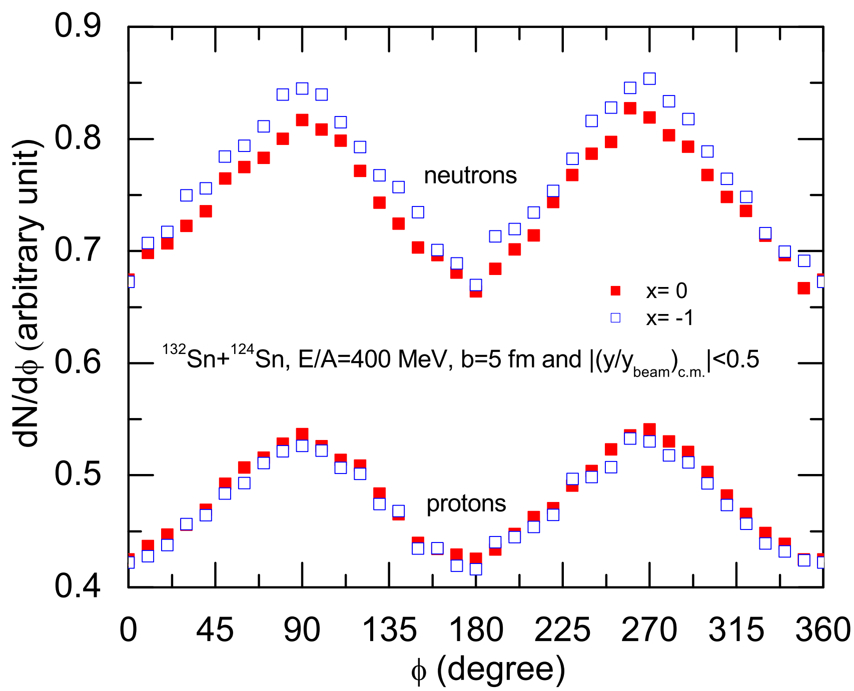

Fig. 2. (Color online) Azimuthal distribution of midrapidity nucleons emitted in the reaction of ^{132}Sn+^{124}Sn at an incident beam energy of 400 MeV/nucleon and an impact parameter of $b = 5$ fm.

Shown in Fig. 2 are the azimuthal distributions of free nucleons in the midrapidity region ($|(y/y_{beam})_{c.m.}| < 0.5$). A preferential emission of nucleons perpendicular to the reaction plane is observed clearly for both neutrons and protons as one expects. Most interestingly, neutrons emitted perpendicular to the reaction plane show clearly an appreciable sensitivity to the variation of the symmetry energy compared to protons. This is mainly because the symmetry potential is normally repulsive for neutrons and attractive for protons. For the latter, the additional repulsive Coulomb potential works against the attractive symmetry potential. Overall, one thus expects the neutron emission to be more sensitive to the variation of the symmetry energy. Since the symmetry potential is relatively small compared to the isoscalar potential, it is always necessary and challenging to find obervables that are delicate enough to be useful for extracting information about the symmetry potential/energy. Fortunately, the squeeze-out of neutrons appears to be promising.

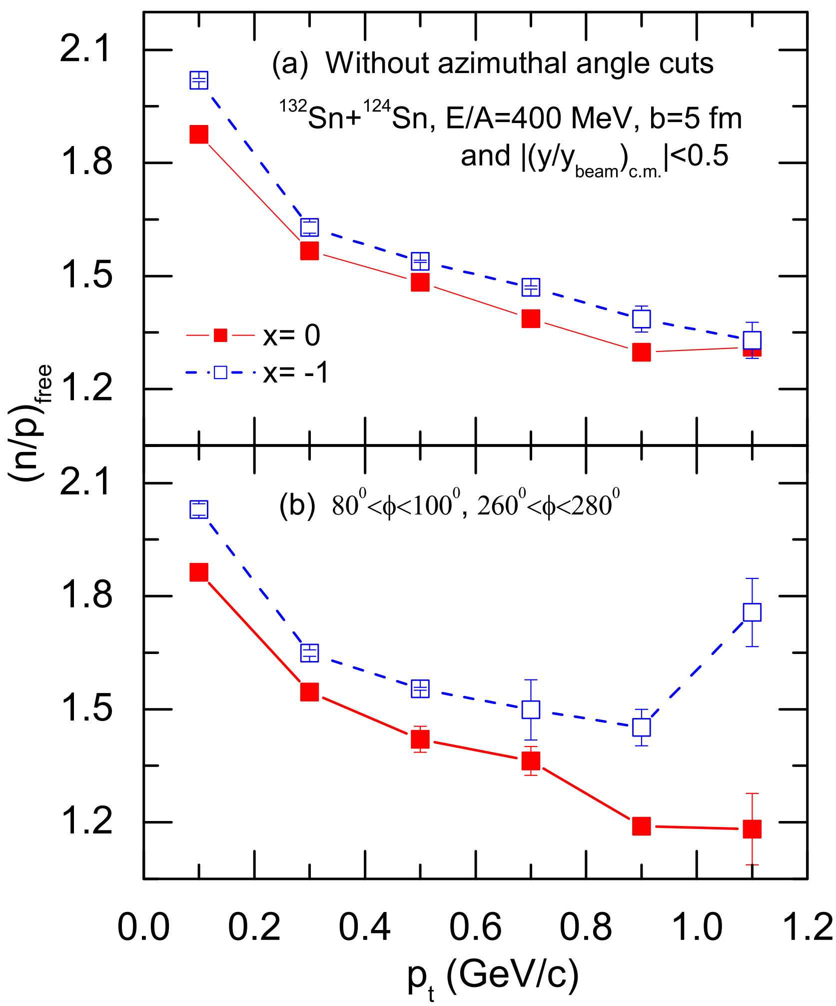

Fig. 3. (Color online) Transverse momentum distribution of the ratio of midrapidity neutrons to protons emitted in the reaction of ^{132}Sn+^{124}Sn at the incident beam energy of 400 MeV/nucleon and impact parameter of $b = 5$ fm. For the lower panel, we make an azimuthal angle cut of $80° < \phi < 100°$ and $260° < \phi < 280°$ to make sure that the free nucleons are from the direction perpendicular to the reaction plane, i.e., to analyze the squeezed-out nucleons only.

Since our main focus in this work is to probe the high density behavior of the symmetry energy, we would like to avoid as much as possible all remaining uncertainties associated with the EOS of symmetric nuclear matter. For this purpose we examine in the lower window of Fig. 3 the transverse momentum dependence of the neutron/proton (n/p) ratio of midrapidity nucleons emitted in the direction perpendicular to the reaction plane. It is known from previous studies [3,25] that the n/p ratio is determined mostly by the density dependence of the symmetry energy and almost not affected by the EOS of symmetric nuclear matter. It is interesting to see in the lower window that the symmetry energy effect on the n/p ratio increases with the increasing transverse momentum p_t. At a transverse momentum of 1 GeV/c, the effect can be as high as 40%. The high p_t particles most likely come from the high density region in the early stage during heavy-ion collisions and they are just more sensitive to the high density behavior of the symmetry energy. Without the cut on the azimuthal angle, the n/p ratio of free nucleons in the midrapidity region is shown in the upper window. This ratio is much less sensitive to the symmetry energy in the whole range of transverse momentum. It is worth mentioning that the n/p ratio of free nucleons perpendicular to the beam direction in the CMS frame in ^{124}Sn+^{124}Sn reactions at 50 MeV/nucleon was recently measured at the NSCL/MSU [34]. This measurement was useful for studying the density dependence of the symmetry energy at sub-normal densities.

Compared to other potentially powerful probes of the symmetry energy at supra-normal densities, such as, the π^-/π^+ and K^0/K^+ ratios, the n/p ratio of squeezed-out nucleons carries directly information of the symmetry potential/energy since it acts directly on nucleons. Pions and kaons are mostly produced through nucleon-nucleon and pion-nucleon inelastic scatterings, they thus carry indirectly and often secondary or even higher order effects of the symmetry energy [44]. Moreover, nucleonic observables such as the n/p ratio are essentially free of uncertainties associated with the production mechanisms of pions and kaons.

While it is very tough to measure neutrons, both the transverse flow and the squeeze-out of neutrons were measured at the BEVALAC by Madey et al.[35,36] and at the SIS/GSI by the TAPS and the Land collaborations[37,38,39]. The measurements were accurate enough to extract reliable information about the EOS of symmetric nuclear matter and the reaction dynamics. The analyses of the experimental data and the associated theoretical calculations, see, e.g., Refs. [40,41], however, have all focused on extracting only information about the EOS of symmetric nuclear matter without paying any attention to the symmetry energy. In all of these experiments, it was essential to measure simultaneously charged particles together with neutrons. To study the symmetry energy at high densities using the n/p ratio of squzzed-out nucleons, similar experimental setups are necessary. Especially, to construct the reaction plane, 4π charged particle detectors are necessary. For determining the momenta of neutrons, the TOF (Time of Flight) of neutrons can be measured with neutron walls or other neutron detectors. The squeeze-out of nucleons can then be studied with respect to the reaction plane determined by using the charged particles on the event-by-event basis.

The symmetry energy effects on the n/p ratio of squeezed-out nucleons are large enough to be measured with some of the existing detectors[42]. This optimistic view and the past success in studying neutron squeeze-out make us feel confident that the predicted effects can be studied realistically. Especially, with the new development in detector technologies, the next generation of detectors for both charged particles and neutrons are being planned and/or constructed. For instance, the Modular Neutron Array (MoNA) or the neutron walls existing at the NSCL/MSU may be coupled with one of the available charged particle detectors there. However, it is beyond the scope of this work to estimate the technical requirements for the detectors to measure the predicted symmetry energy effects on the n/p ratio of squeezed-out nucleons. Nevertheless, it is still exciting to mention that the nuclear reaction community is currently considering the construction of a new TPC (Time-Projection-Chamber) for studying reactions induced by high energy radioactive beams[43]. To study the n/p ratio of squeezed-out nucleons in these reactions, an advanced neutron detector must be used together with the TPC. The present study adds to the importance of constructing the TPC and an advanced neutron detector at the site of an isotope science facility capable of providing high energy radioactive beams.

In summary, it has been a challenging task for the intermediate energy heavy-ion community to identify experimental observables that are sensitive to the high density behavior of the nuclear symmetry energy. Within a transport model, we found that the neutron/proton ratio of squeezed-out nucleons perpendicular to the reaction plane, especially at high transverse momenta, is such an observable. Compared to other potential probes identified earlier in the literature, the n/p ratio of squeezed-out nucleons is complementary but carries more direct information about the symmetry energy at high densities. The sensitivity to the high density behavior of the nuclear symmetry energy observed in the n/p ratio of squeeze-out nucleons is probably the highest found so far among all observables studied within the same transport model.

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