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Experiment of constraining symmetry energy at supra-saturation density with π^-/π^+ at HIRFL-CSR*

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Abstract The possibility of the experiment for constraining the symmetry energy $E_{\rm sym}(\rho)$ at supra-densities via π^-/π^+ probe on the external target experiment of phase I (ETE(I)) with part coverage at forward angle at HIRFL-CSR is studied for the first time by using the isospin and momentum dependent hadronic transport model IBUU04. Based on the transport simulation with Au+Au collisions at 400 MeV/u, it is found that the differential π^-/π^+ ratios are more sensitive to $E_{\rm sym}(\rho)$ at forward angles in laboratory reference, compared with the total yield ratio widely proposed. The insufficient coverage at lower transverse momentum maintains the sensitivity of the dependence of π^-/π^+ ratio on the $E_{\rm sym}(\rho)$ at high density, indicating that the ETF (I) under construction in Lanzhou provides the possibility of performing the experiment for probing the asymmetric nuclear equation of state.

Key words nuclear symmetry energy, charged pion ratio, IBUU04 transport model, external target facility

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1 Introduction

One of the major motivations to study heavy ion collisions at high energies using radioactive beams is to determine the nuclear equation of state (EOS) of isospin-asymmetric nuclear matter [1, 2], which is very important in both nuclear physics [3–5] and astrophysics [6–8]. However, such information is still poorly understood, though great efforts have been made during the last few decades in both theory and experiment [9]. In particular, the key ingredient in EOS, namely the density dependence of nuclear symmetry energy $E_{\rm sym}(\rho)$ given by

$$e(\rho,\delta)=e(\rho,0)+E_{\rm sym}(\rho)\delta^2, \tag{1}$$

still has large uncertainties, especially at higher densities, even it keeps going with the increasing density or starts to decrease at some supra-saturation point, which is often controversial with different approaches in theory [9–11]. The deviation of $E_{\rm sym}(\rho)$ at higher densities will result in profound consequences for various studies in astrophysics [12]. Therefore, it stresses the importance of cross checking in both fields of nuclear physics and astrophysics.

The fundamental cause of the extremely uncertain high-density (HD) behavior of $E_{\rm sym}(\rho)$ is the complete lack of terrestrial laboratory data to constrain the model predictions directly. Indeed, during the last two decades, only the heavy ion collisions performed at the LBNL Bevalac facility and the GSI Schwerionen Synchrotron were used to produce hot and compressed neutron-rich nuclear matter to obtain the information about $E_{\rm sym}(\rho)$ at higher densities [13–15]. By analyzing the data [16] of the FOPI collaboration with the transport model IBUU04 [17], it has been found that a rather soft $E_{\rm sym}(\rho)$ is expected to be at work at $\rho \geqslant 2\rho_0$ [18]. However, the result is just very preliminarily circumstantial evidence and deserves more data from further experiments for confirmation.

This lack of experimental data should be reolved during the next decade, thanks to several new radioactive beam facilities with higher bombarding energy and larger intensity that are being built worldwide, such as FAIR/GSI [19], RIB/RIKEN [20] and FRIB/MSU [21]. All of the heavy-ion facilities will

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hopefully provide more useful data for constraining the HD behavior of $E_{\rm sym}(\rho)$. In addition, the cooling storage ring (HIRFL-CSR) in China, delivering heavy-ion beams up to 1 GeV/u, and which will be coupled with advanced detectors at the external target experiment (ETE), will contribute significantly to further studies of $E_{\rm sym}(\rho)$ [22].

Here, we will continue to study the differential behavior of the π^-/π^+ ratio and its dependence on the $E_{\rm sym}(\rho)$ in the whole phase space, aiming at the first stage feasibility study of measuring the π^-/π^+ at ETE(I). Head-on collision of Au+Au at 400 MeV/u is chosen because of the high degree of isospin fractionation achieved in this system. Very recently, a systematic analysis of π^-/π^+ has revealed that the π^-/π^+ ratio is indeed an effective probe to constrain the HD behavior of $E_{\rm sym}(\rho)$. Moreover, the π^-/π^+ ratio appears to be more sensitive in heavier systems, and the dependence of the sensitivity on system size is less pronounced when decreasing the beam energy to the threshold of pion production [23]. Therefore, here we perform the calculation of Au+Au at 400 MeV/u, which is reasonably typical for presenting a general feasibility study on the experiment of constraining $E_{\rm sym}(\rho)$ at higher densities at ETE (I) on HIRFL-CSR.

The transport model used in the present work is IBUU04, with the isospin effects and the momentum dependence in both the isoscalar and the isovector potentials having been modeled in single particle potential U. In particular, for a nucleon with momentum $\vec{p}$ and isospin τ,

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

where the isospin $\tau=1/2$ ($-1/2$) for neutrons (protons). Parameter x is introduced to mimic different forms of $E_{\rm sym}(\rho)$ predicted by various many-body theories while keeping other properties of the nuclear equation of state fixed. For details of the model and other parameters in Eq. 2, we refer to Ref. [17, 24]. With $U(\rho,\delta,\vec{p},\tau)$, one can readily calculate $E_{\rm sym}(\rho)$ for a given x. Fig. 1 is shows the symmetry energy $E_{\rm sym}(\rho)$ varying with the baryon density. One can find that, with $x=1$, $E_{\rm sym}(\rho)$ starts to decrease the above saturation density, closely following the Hartree-Fock prediction with the original Gogny force [25], while with $x=0$, $E_{\rm sym}(\rho)$ continues to increase and recovers the well-known APR prediction, which is widely used in astrophysics [26]. In the following section, we will comprehensively analyse and then discuss the π^-/π^+ ratio with different forms of $E_{\rm sym}(\rho)$ by fixing the parameter at $x=1$ and $x=0$, respectively.

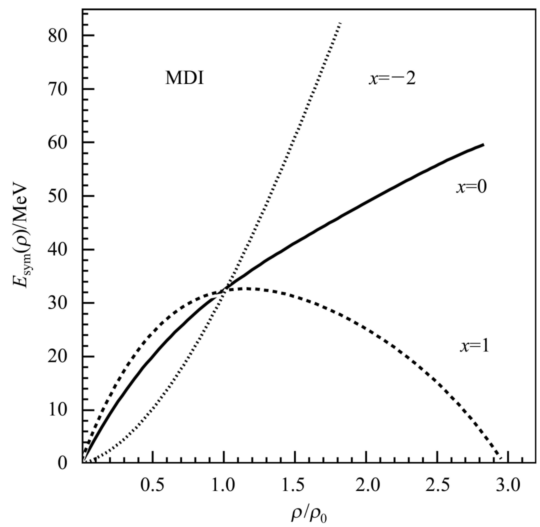

Fig. 1. The density dependence of the symmetry energy with $x=-2$, 0 and 1, respectively.

Let us start by studying the differential π^-/π^+ ratio as a function of angle in a laboratory system. The motivation for such a study is that the measured momentum space distributions of charged pions do not cover the completed 4π phase space for the limited polar angle covered by detectors in most laboratories, so they must be complemented by interpolations and extrapolations. Such procedures will introduce systematic uncertainties to the multiplicity of charged pions, thus the total yield ratio is π^-/π^+. Moreover, if the differential π^-/π^+ ratio has a very sensitive dependence on the nuclear symmetry energy $E_{\rm sym}(\rho)$ at some certain polar angles, it can also suggest related experiments on constraining the HD behavior of $E_{\rm sym}(\rho)$ in the laboratories without 4π coverage. Fig. 2 shows the calculated differential π^-/π^+ ratios with the $E_{\rm sym}(\rho)$ of $x=1$ and $x=0$ as a function of polar angle in a lab system. First, one finds that the calculated π^-/π^+ ratios with the $E_{\rm sym}(\rho)$ of $x=1$ are globally higher than those with $x=0$. The distinction is in accordance with the total yield π^-/π^+ ratio due to the isospin fractionation during the reaction. Also, it is interesting to see that the differential π^-/π^+ ratios are much more sensitive at smaller polar angles in a lab system, compared with the ratios at larger angles. The quality to describe the sensitivity of π^-/π^+ has been introduced in Ref. [23] and denoted by the double ratio of π^-/π^+ obtained with the $E_{\rm sym}(\rho)$ of $x=1$ over that with $x=0$. The comparison between $x=1$ and 0 indicates that the sensitivity of π^-/π^+ on $E_{\rm sym}(\rho)$ is enhanced at forward angle.

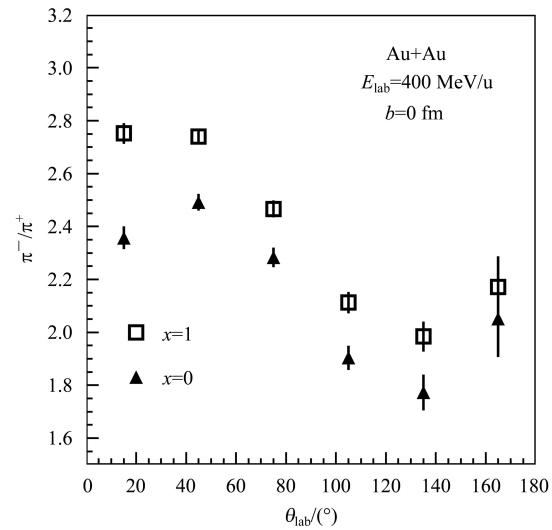

Fig. 2. The differential π^-/π^+ ratio as a function of polar angle in a lab system with the $E_{\rm sym}(\rho)$ of $x=1$ and $x=0$.

We further present in Fig. 3 the distributions of π^-/π^+ ratios as functions of transverse momentum and reduced rapidity. It is seen that, in lower transverse momentum, the π^-/π^+ ratios exhibit larger sensitivity and the two forms of $E_{\rm sym}(\rho)$ are distinguishable in this region. On the rapidity distribution, it is also shown that the sensitivity is slightly enhanced in the large rapidity region ($|y^{(0)}|>1$) compared with the overall rapidity range. This is consistent with the observations in Fig. 2, because the products emitted at forward angle in the laboratory mainly contribute to the phase space with lower transverse momentum and larger rapidity. The reason for the larger sensitivity at low transverse momentum and larger rapidity (corresponding to a smaller angle in the laboratory) is partly attributed to the pions emitted in the forward region, which experience less re-scattering. In more detail, the production of charged pions that carry the information about $E_{\rm sym}(\rho)$ can be viewed as a two-stage process. One is the isospin transport between the high density and low density region: due to the isospin fractionation mechanism, more neutrons transfer to the HD region. The other, consequent to the isospin transport, is the production of pions via Δ resonances. It is already found that, due to a larger degree of isospin fractionation, heavier systems at lower beam energies are preferential for the study of $E_{\rm sym}(\rho)$ with a pion probe [23]. For a given system at fixed beam energy, the reabsorption of pions partly erases the memory of the initial HD phase where the pions are produced is less modified. In this sense the sensitivities of probing HD $E_{\rm sym}(\rho)$ with π^-/π^+ is reduced. Therefore, the pions emitted at forward angle in the laboratory experience less re-scattering and the carried information of the initial HD phase where the pions are produced is less modified.

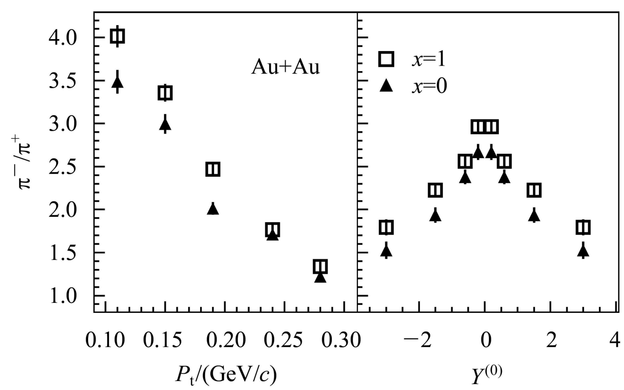

Fig. 3. The differential π^-/π^+ ratios as functions of transverse momentum (left window) and reduced rapidity (right window) with $E_{\rm sym}(\rho)$ of $x=1$ and $x=0$.

Although the differential π^-/π^+ ratios at smaller polar angles in the laboratory reference are more sensitive to the HD behavior of $E_{\rm sym}(\rho)$, the charged pions with lower transverse momentum are very difficult to detect efficiently, particularly in a solenoid type field, because the trajectory of the pions with small transverse momentum forms circles of too small radii to be detected. This problem will be overcome greatly if a dipole magnet is used at the forward angle. It is thus necessary to survey the differential π^-/π^+ and its sensitivity on $E_{\rm sym}(\rho)$ at smaller polar angles in a laboratory system. To make the proposal clearer, we calculate the π^-/π^+ ratios as functions of transverse momentum and kinetic energy only for forward coverage. Fig. 4 shows the π^-/π^+ as functions of transverse momentum (left) and kinetic energy (right) for $\theta_{\rm lab}$ less than 35° (upper) and 50° (lower), respectively. Indeed, it can be clearly seen that the π^-/π^+ ratios at lower transverse momentum and the whole kinetic energy regions still exhibit a sensitive dependence on the HD behavior of $E_{\rm sym}(\rho)$. Especially for the kinetics energy spectrum, the π^-/π^+ ratios appear to be clearly separated through the kinetic energy region considered here. In other words, the differential π^-/π^+ ratios as a function of kinetic

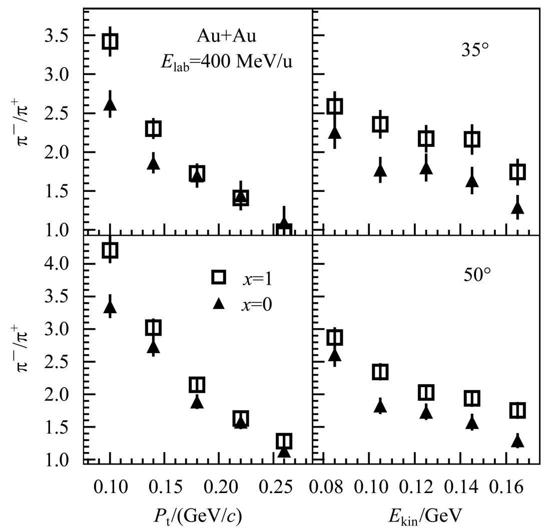

Fig. 4. The π^-/π^+ ratios as functions of transverse momentum (left) and kinetic energy (right) for θ_{lab} less than 35° (upper) and 50° (lower), respectively.

energy in limited coverage at forward region is still a reliable probe to constrain the $E_{sym}(\rho)$ at supra-saturation densities. Thus, the external target experiment [22], covering part of the forward angle, is applicable to the study of the HD behavior of $E_{sym}(\rho)$ with π^-/π^+.

In summary, an external target experiment (Phase I) at HIRFL-CSR with part coverage at forward angles in the laboratory is to be constructed at HIRFL-CSR. It is of significant interest to start a pion program and investigate the asymmetric nuclear EOS at supra-densities, which arouses the attention of nuclear physicists around the world as one of the most uncertain properties of nuclear matter. Using the IBUU04 transport model, it is found that the calculated π^-/π^+ ratios produced in Au+Au collisions at 400 MeV/u exhibit higher sensitivity in the HD behavior of $E_{sym}(\rho)$ at small polar angles in a laboratory system. Moreover, the transverse momentum spectrum and kinetic energy spectrum on π^-/π^+ ratios, limited at forward region, serve as further probes to constrain the form of $E_{sym}(\rho)$ at higher densities. Thus we note here that ETE(I) is a suitable means to carry out further experiments to constrain the EOS of asymmetric nuclear matter with a π^-/π^+ probe. This initiates a full simulation based GEANT package, for instance, for a further feasibility study.

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