High $p_t$ squeezed-out nucleons as a probe of $K_{\text{sym}}$ of the symmetry energy

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In the framework of the Isospin-dependent Boltzmann-Uehling-Uhlenbeck (IBUU) transport model, the effects of the curvature of nuclear symmetry energy at saturation density on the squeezed-out nucleons are demonstrated in the semi-central Au+Au reaction at 400 MeV/nucleon. It is clearly shown that the squeezed-out isospin-dependent nucleon emissions at high transverse momenta, i.e., the isospin-dependent nucleon elliptic flow and the squeezed-out free neutron to proton ratio at high transverse momenta are both sensitive to the curvature of nuclear symmetry energy at saturation density. The curvature of nuclear symmetry energy at saturation density thus can be directly probed by the high momentum squeezed-out nucleons from dense matter formed in the semi-central heavy-ion collisions.

Nowadays the study of the equation of state (EoS) of nuclear matter is one of the most hot topic in nuclear community [1–3]. The EoS at density $\rho$ and isospin asymmetry $\delta$ ($\delta = (\rho_n - \rho_p) / (\rho_n + \rho_p)$) is usually expressed as

$$E(\rho, \delta) = E(\rho, 0) + E_{\text{sym}}(\rho)\delta^2 + O(\delta^4), \quad (1)$$

where $E_{\text{sym}}(\rho)$ is the density-dependent nuclear symmetry energy. Currently the EoS of isospin symmetric nuclear matter $E(\rho, 0)$ is roughly determined [4] but the EoS of neutron-rich matter, especially the high-density symmetry energy, is still very controversial [5]. The high-density symmetry energy is closely related to the physics of neutron stars [6], such as their stellar radii and cooling rates [7–9], the gravitational-wave frequency [10, 11], the gamma-ray bursts [12], the r-process nucleosynthesis [13–15] in neutron star mergers [16, 17]. Experimentally, probing the high-density symmetry energy by the measurements of pion and nucleon, triton and $^3$He yields ratio in isotope Sn+Sn reactions at about 300 MeV/nucleon are being carried out at RIBF/RIKEN in Japan [18, 19]. Such projects are also being carried out/planned at FOPI/GSI and CSR/Lanzhou [20, 21], the Facility for Rare Isotope Beams (FRIB) in the United States [22] and the Rare Isotope Science Project (RISP) in Korea [23]. And some progress has been made by measuring nucleon and light charged cluster flows at FOPI/GSI [20].

The density-dependent symmetry energy around saturation can be Taylor expanded in terms of a few bulk parameters [24],

$$E_{\text{sym}}(\rho) = E_{\text{sym}}(\rho_0) + L \left( \frac{\rho - \rho_0}{3\rho_0} \right)^2 + K_{\text{sym}} \left( \frac{\rho - \rho_0}{3\rho_0} \right)^2, \quad (2)$$

where $E_{\text{sym}}(\rho_0)$ is the value of the symmetry energy at saturation point and the quantities $L$, $K_{\text{sym}}$ are related to its slope and curvature, respectively, at the same density point,

$$L = 3\rho_0 \left. \frac{\partial E_{\text{sym}}(\rho)}{\partial \rho} \right|_{\rho = \rho_0}, \quad K_{\text{sym}} = 9\rho_0^2 \left. \frac{\partial^2 E_{\text{sym}}(\rho)}{\partial \rho^2} \right|_{\rho = \rho_0}. \quad (3)$$

Over the last two decades the most probable magnitude $E_{\text{sym}}(\rho_0) = 31.7\pm3.2$ MeV and slope $L = 58.7\pm28.1$ MeV of the nuclear symmetry energy at saturation density have been found through surveys of 53 analyses [25, 26]. The updated Isospin-dependent Boltzmann-Uehling-Uhlenbeck (IBUU) transport model, we studied the isospin-dependent nucleon elliptic flow and the squeezed-out free neutron to proton ratio at high transverse momenta in the semi-central Au+Au reaction at 400 MeV/nucleon and find they are both sensitive to the curvature of nuclear symmetry energy at saturation density. The curvature of nuclear symmetry energy at saturation density thus can be directly probed by the high $p_t$ squeezed-out nucleons in heavy-ion collisions.

The updated Isospin-dependent Boltzmann-Uehling-Uhlenbeck (IBUU) transport model originates from the IBUU04 model [27, 28]. In this model, effects of the short-range-correlations are appropriately taken into account [29, 30]. The neutron and proton density distributions in nucleus are given by the Skyrme-Hartree-Fock with Skyrme M* force parameters [31]. In colliding nuclei, the proton and neutron momentum distributions with high-momentum cutoff $p_{\text{max}} = 2$ $pf$ are employed [31, 32, 33–36]. The isospin- and momentum-dependent single nu-
cleon mean-field potential reads

\[
U(\rho, \delta, \vec{p}, \tau) = A_u(x) \frac{\rho^\prime}{\rho_0} + A_1(x) \frac{\rho\tau}{\rho_0}
+ B \left( \frac{\rho}{\rho_0} \right)^\sigma (1 - x\delta^2) - 8x\tau B \frac{\rho^{\sigma - 1}}{\rho_0^\sigma} \delta \rho_\tau - 2C_{\tau,\tau} \int \frac{d^3 p'}{\rho_0} \frac{f_\tau(\vec{r}, \vec{p}')}{1 + (\vec{p} - \vec{p}')^2/\Lambda^2} \nonumber
+ 2C_{\tau,\tau'} \int \frac{d^3 p'}{\rho_0} \frac{f_{\tau'}(\vec{r}, \vec{p}')}{1 + (\vec{p} - \vec{p}')^2/\Lambda^2},
\]

where \( \rho_0 \) is the saturation density, \( \tau, \tau' = 1/2(-1/2) \) is for neutron (proton), \( \delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) \) is the isospin asymmetry, and \( \rho_n, \rho_p \) denote neutron and proton densities, respectively. The parameter values \( A_u(x) = 33.037 - 125.34x \text{ MeV}, A_1(x) = -166.963 + 125.34x \text{ MeV}, B = 141.96 \text{ MeV}, C_{\tau,\tau} = 18.177 \text{ MeV}, C_{\tau,\tau'} = -138.365 \text{ MeV}, \sigma = 1.265, \) and \( \Lambda = 630.24 \text{ MeV} \). Note here that in the single particle potential, the parameter \( x \) can change with density (while the empirical values of nuclear matter at normal density are kept) to mimic different density-dependent symmetry energy. And in the model the isospin-dependent baryon-baryon scattering cross section in medium is reduced compared with their free-space value. More details on the present used model can be found in Ref. [31].

To probe the curvature \( K_{sym} \) of neutron-rich matter at saturation density and keep the parameters \( E_{sym}(\rho_0) \) and slope \( L \) fixed, we in Eq. (4) use two density-dependent \( x \) parameters to plot two density-dependent symmetry energies by fixing \( E_{sym}(\rho_0) = 30 \text{ MeV} \) and \( L = 60 \text{ MeV} \) but letting curvatures \( K_{sym} = 0 \) and \( K_{sym} = -400 \text{ MeV} \), respectively. For \( K_{sym} = 0 \) case,

\[
x = -0.3688 \left( \frac{\rho}{\rho_0} \right)^5 + 3.1516 \left( \frac{\rho}{\rho_0} \right)^4
- 10.379 \left( \frac{\rho}{\rho_0} \right)^3 + 16.59 \left( \frac{\rho}{\rho_0} \right)^2
- 13.39 \left( \frac{\rho}{\rho_0} \right) + 4.9229.
\]

For \( K_{sym} = -400 \) case,

\[
x = 0.2374 \left( \frac{\rho}{\rho_0} \right)^3 - 1.1231 \left( \frac{\rho}{\rho_0} \right)^2
+ 2.0456 \left( \frac{\rho}{\rho_0} \right) - 0.539.
\]

With these settings, employing the density and momentum dependent single particle potential Eq. (4), the density-dependent symmetry energies (shown with symbols) for curvatures \( K_{sym} = 0 \) and \( K_{sym} = -400 \text{ MeV} \) with \( E_{sym}(\rho_0) = 30 \text{ MeV} \) and \( L = 60 \text{ MeV} \) are shown in Fig. 1. One can see that, in the density range \( 0.2 - 2\rho_0 \), the symmetry energies derived from Eq. (2) with \( E_{sym}(\rho_0) = 30 \text{ MeV} \) and \( L = 60 \text{ MeV} \) fit quite well. Since in the semi-central Au+Au reaction at 400 MeV/nucleon, the maximum compression density is about \( 2\rho_0 \), we show in Fig. 1 the density only up to \( 2\rho_0 \).

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Nucleon directed and elliptic flows in heavy-ion collisions can be derived from the Fourier expansion of the azimuthal distribution [33, 34], i.e.,

\[
\frac{dN}{d\phi} \propto 1 + 2 \sum_{i=1}^{n} v_n \cos(n\phi).
\]
The nucleon elliptic flow \( v_2 \) is obtained from
\[
v_2 = \langle \cos(2\phi) \rangle = \frac{\langle p_t^2 - p_t^2 \rangle}{p_t^4}
\]
and can be a potential observable to probe the density-dependent nuclear symmetry energy. Fig. 2 shows nucleon elliptic flow as a function of transverse momentum in the semi-central Au+Au reaction at 400 MeV/nucleon with \( K_{sym} = 0 \) and \( K_{sym} = -400 \) MeV, respectively. It is first seen that, due to the Coulomb repulsion, the strength of proton elliptic flow is larger than that of neutron. Because the gradient of the high-density symmetry energy with \( K_{sym} = 0 \) case is larger than that with \( K_{sym} = -400 \) MeV (as shown Fig. 1) and the symmetry energy is repulsive for neutrons and attractive for protons, the larger effects of the high-density symmetry energy with \( K_{sym} = 0 \) increase (decrease) the strength of neutron (proton) elliptic flow. It is thus seen that for neutron elliptic flow, the strength is larger for \( K_{sym} = 0 \) than that for \( K_{sym} = -400 \) MeV whereas for proton elliptic flow the strength is smaller for \( K_{sym} = 0 \) that for \( K_{sym} = -400 \) MeV. The latter is qualitatively consistent with that founding in Ref. [39].

To enlarge the effects of the curvature \( K_{sym} \) of the symmetry energy at saturation density, it is good to make a difference of neutron and proton elliptic flows. Fig. 3 shows the difference of neutron and proton elliptic flows as a function of transverse momentum in the semi-central Au+Au reaction at incident beam energy of 400 MeV/nucleon with \( K_{sym} = 0 \) and \( K_{sym} = -400 \) MeV, respectively. It is shown that at lower transverse momenta, the difference of neutron and proton elliptic flows is less sensitive to the curvature \( K_{sym} \) of the symmetry energy. At high transverse momenta, however, the effects of the curvature \( K_{sym} \) of the symmetry energy on the difference of neutron and proton elliptic flows are quite evident. The difference of neutron and proton elliptic flows with \( K_{sym} = -400 \) MeV is larger than that with \( K_{sym} = 0 \). The \( v_2^n - v_2^p \) at high \( p_t \) thus can be a potential probe of the curvature \( K_{sym} \) of the symmetry energy at saturation density.

\begin{align}
\text{FIG. 3: (Color online) Difference of neutron and proton elliptic flows } v_2^n - v_2^p \text{ as a function of transverse momentum in the semi-central Au+Au reaction (b= 7 fm, } |y_{beam}| \leq 0.5) \text{ at incident beam energy of 400 MeV/nucleon with } K_{sym} = 0 \text{ and } K_{sym} = -400 \text{ MeV, respectively.}
\end{align}

\begin{align}
\text{FIG. 4: (Color online) Effects of the curvature of nuclear symmetry energy at saturation density on the transverse momentum distribution of the ratio of mid-rapidity (}|y_{beam}| \leq 0.5) \text{ neutrons to protons emitted in the reaction of Au+Au at incident beam energy of 400 MeV/nucleon and impact parameter of b= 7 fm. The azimuthal angle cut is } 75^\circ \leq \phi \leq 105^\circ \text{ and } 255^\circ \leq \phi \leq 285^\circ, \text{ to make sure that the free nucleons are from the direction perpendicular to the reaction plane (so called squeezed-out nucleons).}
\end{align}

It is known that the squeezed-out nucleons (emitted in the direction perpendicular to the reaction plane) in semi-central collisions carry more direct information about the high density phase of the reaction [43–49]. Fig. 4 shows the squeezed-out neutron to proton ratio of nucleons emitted in the direction perpendicular to the reaction plane in Au+Au at 400 MeV/nucleon. It is clearly seen that the effects of the curvature of the symmetry energy on the squeezed-out neutron to proton ratio \( n/p \) are quite evident, especially at high transverse momenta. Since the slope of the high-density symmetry energy with \( K_{sym} = 0 \) is larger than that with \( K_{sym} = -400 \) MeV, one sees the values of the squeezed-out \( n/p \) with \( K_{sym} = 0 \) are higher than that with \( K_{sym} = -400 \) MeV. Around \( p_t = 0.8 \) GeV/c, the effects of the curvature of the symmetry energy on the squeezed-out \( n/p \) reach about 40%, which is much larger than the ratio of integrating neutron and proton elliptic flows [50]. The squeezed-out \( n/p \) thus can be one of the most potential probe of the
curvature of the symmetry energy and in fact can be carried out on the rare isotope reactions worldwide, such as the Facility for Rare Isotope Beams (FRIB) in the United States [22], the Radioactive Isotope Beam Facility (RIBF) at RIKEN in Japan [18, 19], or the GSI Facility for Antiproton and Ion Research (FAIR) in Germany [20], the Cooling Storage Ring on the Heavy Ion Research Facility at IMP (HIRFL-CSR) in China [21] and the Rare Isotope Science Project (RISP) in Korea [23].

Note here that, although the effects of the curvature of the symmetry energy on the high $p_t$ squeezed-out $n/p$ reach about 40%, the effects of the slope $L$ on this observable still reach about 7-10% when changing the slope $L$ from 60 to 40 MeV. At density reaches only about $2\rho_0$, affections of the slope $L$ on the $K_{sym}$ sensitive observable are inevitable since there is no way to differentiate the contributions from $L$ or $K_{sym}$ terms in Eq. (2). At very high densities, although the $K_{sym}$ term may contribute more than the $L$ term, it is hard to find a $K_{sym}$ sensitive observable in heavy-ion collisions due to the high temperature of the dense matter formed in energetic heavy-ion collisions.

Since the slope $L$ is more related to the symmetry energy around saturation density than the $K_{sym}$, considering complexity of the transport model, it is better to constrain the slope $L$ of the symmetry energy at saturation density using properties of neutron-rich nuclei or matter at ground state [5][6][16]. Because $K_{sym}$ is related to the high order of Taylor expansion of the symmetry energy, constraining $K_{sym}$ by properties of neutron-rich nuclei or matter at ground state would cause larger uncertainties. While probing $K_{sym}$ by neutron star properties relating dense matter is recommendable but the physics relevant neutron stars in heaven has more conjecture than heavy-ion collisions in terrestrial laboratory. Therefore, probing $K_{sym}$ by high $p_t$ squeezed-out dense matter in semi-central heavy-ion collisions in terrestrial laboratory is one of the best avenues. Unfortunately, currently there is no suitable experimental data used to constrain $K_{sym}$ at saturation density. So far FOPI and FOPI-LAND data provided by GSI-asym collaboration cannot be used to constrain $K_{sym}$ at saturation density effectively [50]. To constrain $K_{sym}$ at saturation density more effectively, it seems that one has to make high $p_t$ squeezed-out neutron and proton measurements in heavy-ion collisions.

To summarize, the value and the slope of nuclear symmetry energy at saturation density have been roughly pinned down. While the curvature of the symmetry energy at saturation density is still largely uncertain. The curvature of the symmetry energy at saturation density is closely related to the properties of neutron-rich matter such as the incompressibility of neutron-rich matter and the high-density behavior of the symmetry energy. It is hard to constrain the curvature of the symmetry energy at saturation density by the properties of neutron-rich nuclei at ground state. Present existed experimental data in heavy-ion collisions at several hundred MeV incident beam energy cannot be used to constrain $K_{sym}$ at saturation density effectively. High $p_t$ squeezed-out $n/p$ in semi-central heavy-ion collisions seems to be one of the most effective avenues to constrain the $K_{sym}$ at saturation density.

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