Probing the momentum-dependence of the symmetry potential by the free n/p ratio of preequilibrium emission

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Based on an isospin and momentum-dependent transport model, we studied the effect of momentum-dependent symmetry potential on the free neutron to proton ratio of preequilibrium nucleon emission. It is found that for \(^{132}\)Sn + \(^{124}\)Sn reaction at 400 MeV/nucleon incident beam energy, free n/p ratio of preequilibrium nucleon emission mainly probe the momentum-dependence of symmetry potential at nucleon momentum around 400 \(\sim\) 600 MeV/c. Whereas for 200 MeV/nucleon incident beam energy, this observable mainly probe the momentum-dependence of symmetry potential at nucleon momentum around 200 \(\sim\) 400 MeV/c. To probe the symmetry energy/potential using free n/p ratio, not all the details of the momentum-dependence of the symmetry potential are important, the values of symmetry potential at only certain momentum range are crucial for an observable. It is important to input reasonable density- and momentum-dependence of the symmetry potential according to the magnitude of incident beam energy of heavy-ion collisions. The present experimental data on the symmetry potential are not enough for probing the density-dependent symmetry energy. More experimental data (such as nucleon and nuclei’s scattering experiments at different nucleonic momenta and densities) on the symmetry potential are therefore needed to pin down the density-dependent symmetry energy.

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Heavy-ion collisions induced by neutron-rich nuclei have been used as the unique means to probe the density dependence of nuclear symmetry energy \([1–7]\), as well as the properties of neutron stars \([10, 11]\). Nowadays, the density dependence of nuclear symmetry energy/potential is still not well known especially at suprasaturation densities \([12]\) and high momentum \([13]\). Few progress has been made until recently \([14]\). And reducing the uncertainties on the constraints of \(E_{\text{sym}}(\rho)\) is of critical importance and remains a big challenge.

The momentum-dependence of the symmetry potential is important to determine the symmetry energy \([12, 13]\). However, except the old experimental data \([17]\), no new related experiments on the symmetry potential were carried out in recent 30 years. Nowadays the determination of the density-dependent symmetry energy is one of the most important question in nuclear community, therefore it needs urgently to study the momentum-dependence of the symmetry potential more detailedly.

Very recently, the authors have done a work of decomposition of the sensitivity of symmetry energy/potential observables in density region \([18]\) and found that the symmetry-energy-sensitive observables (including charged pion ratio \(\pi^-/\pi^+\) and free neutron-proton ratio \(n/p\)) mainly probe the symmetry energy/potential around \(1.25\rho_0\) (for pion emission) or \(1.5\rho_0\) (for preequilibrium nucleon emission). As a further consideration, for the momentum-dependent symmetry potential, one would like to know which momentum region does free n/p ratio reflect. To find out the answer, in this report, we decompose the sensitivity of the frequently used symmetry energy observable pre-equilibrium free n/p in momentum region. Such study is surely crucial to pin down the momentum-dependence of symmetry potential as well as the density-dependent symmetry energy. In the following, we show how to decompose the sensitivity of free n/p to the symmetry potential in momentum space.

The present study is based on an isospin and momentum-dependent transport model IBUU04 \([13, 20]\).
In the model, the initial proton and neutron density distributions are given by the relativistic mean-field theory \[21\]. We use the experimental nucleon-nucleon scattering cross section in free space and consider the Pauli blockings for fermions. The potential adopted here is an isospin and momentum-dependent single nucleon potential (MDI) \[22\], i.e.,

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U(\rho, \delta, \mathbf{p}, \tau) = A_u(x) \frac{\rho_{\tau'}}{\rho_0} + A_l(x) \frac{\rho_{\tau}}{\rho_0} + B \left( \frac{\rho_{\tau'}}{\rho_0} \right)^2 \left( 1 - x \delta^2 \right) - 8 x \tau \left( \frac{\rho_{\tau}}{\rho_0} \right)^{-1} \delta \rho_{\tau'} + C \left( \frac{\rho_{\tau'}}{\rho_0} \right) \int d^3 \mathbf{p'} \frac{f_{\tau'}(\mathbf{r}, \mathbf{p'})}{1 + (\mathbf{p} - \mathbf{p'})^2 / \Lambda^2} + C \left( \frac{\rho_{\tau}}{\rho_0} \right) \int d^3 \mathbf{p'} \frac{f_{\tau}(\mathbf{r}, \mathbf{p'})}{1 + (\mathbf{p} - \mathbf{p'})^2 / \Lambda^2},
\]

where \( \rho = \rho_n + \rho_p \) is the baryon density, \( \rho_n \) and \( \rho_p \) denote the neutron (\( \tau = 1/2 \)) and proton (\( \tau = -1/2 \)) density, respectively. \( \delta = (\rho_n - \rho_p) / \rho \) is the isospin asymmetry of nuclear medium. The variable \( x \) is introduced to reflect different forms of \( E_{\text{sym}}(\rho) \). More details of the parameters in the above equation can be found in Refs. \[19, 20, 22\]. With the above single particle potential \( U(\rho, \delta, \mathbf{p}, \tau) \), one can give the symmetry energy \( E_{\text{sym}}(\rho) \) for a given parameter \( x \). In this study, we choose \( x = 0 \) for example. Fig. 1 shows the isovector potential \( (U_u - U_p)/2\delta \) at different densities using the MDI interaction with \( x = 0 \). The shaded region can be described by \( U = a - bE_{\text{kin}} \) with \( a \simeq 22 - 34 \text{MeV} \) and \( b \simeq 0.1 - 0.2 \) from experimental data \[17, 23, 24\]. Here \( E_{\text{kin}} \) can be expressed as a function of nucleonic momentum \( E_{\text{kin}} = 1000 \times \left( [p^2 + 0.93893^2]^{1/2} - 0.93893 \right) \text{MeV} \) (here nucleonic momentum \( p \) is in GeV/c). It is seen that the experimental data of symmetry potential reach about 450 MeV/c in momentum space.

In order to know in which momentum region does the frequently used symmetry energy/potential sensitive observable free n/p ratio shows maximal sensitivity, in the whole momentum region we use Eq. 1 with \( x = 0 \) as the standard calculation. We then make calculations by turning off this symmetry potential from high to low momentum regions step by step. At each step, we get a new result. Through comparing these new computing results at each step with the standard calculation, one can obtain the sensitivity of a symmetry energy/potential observable in certain momentum region.

Shown in Fig. 2 is the relative sensitivity of pre-equilibrium free n/p ratio to the symmetry potential in different momentum regions at the beam energy of 400 MeV/nucleon in \( ^{132}\text{Sn} + ^{124}\text{Sn} \) collision with an impact parameter \( b = 1 \text{fm} \). One can clearly see that the maximal sensitivity of n/p ratio to the symmetry potential in the momentum region is no longer sensitive. Therefore, to study the effect of nuclear symmetry energy using heavy-ion collisions at incident beam energies around 400 MeV/nucleon, the values of symmetry potential in momentum range 400 ~ 600 MeV/c play crucial role in determination the value of the final observable.

Since related experiments with incident beam energies around 100 ~ 350 MeV/nucleon are planning/doing at facilities that offer fast radioactive beams such as the National Superconducting Cyclotron Laboratory (NSCL) and the Facility for Rare Isotope Beams (FRIB) in the USA, the Radioactive Isotope Beam Facility (RIBF) in Japan, it is necessary to make a similar study at incident beam energy below 400 MeV/nucleon. Shown in Fig. 3 is the relative sensitivity of pre-equilibrium free n/p ratio to the symmetry potential in different momentum regions at beam energy of 200 MeV/nucleon. However, one can see that the maximal sensitivity of free n/p ratio to the symmetry potential is in the momentum

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\text{FIG. 2: Relative sensitivity of pre-equilibrium free n/p ratio to the symmetry potential in different momentum regions at the beam energy of 400 MeV/nucleon in } ^{132}\text{Sn} + ^{124}\text{Sn} \text{ collision with an impact parameter } b = 1 \text{ fm.}
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\text{FIG. 3: Same as Fig. 2 but at the beam energy of 200 MeV/nucleon.}
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regions. While the maximal baryon number locates in the region of 200 ~ 400 MeV/c at the incident beam energy of 200 MeV/nucleon. Maximal baryon number location in certain momentum space should be also maximally affected by the symmetry potential at that momentum space, thus we see different sensitivity of free n/p ratio to symmetry potential in momentum space.

It is known to all that the symmetry energy has kinetic and potential parts \[23\]. However, in transport model simulations of heavy-ion collisions, the symmetry potential corresponding to a given potential symmetry energy is a direct input but the kinetic symmetry energy does not directly enter transport model simulations \[26\]. Because observables are sensitive to the symmetry potential mainly at certain density and momentum ranges, to probe the symmetry energy using heavy-ion collisions, it is important to input reasonable density- and momentum-dependence of the symmetry potential \[13, 20\] according to the magnitude of incident beam energy of heavy-ion collisions.

In summary, based on the IBUU04 transport model, we decomposed the sensitivity of pre-equilibrium free n/p ratio to the momentum-dependent symmetry potential in momentum region. It is found that the free n/p ratio mainly probe the symmetry potential in the momentum region 400 ~ 600 MeV/c for the incident beam energy of 400 MeV/nucleon and 200 ~ 400 MeV/c for 200 MeV/nucleon beam energy. This study can help us to constrain the momentum-dependence of the symmetry potential more detailedly. Since observables are sensitive to the symmetry potential mainly at certain density and momentum ranges, to probe the symmetry energy using heavy-ion collisions, it is important to input reasonable density- and momentum-dependence of the symmetry potential according to the magnitude of incident beam energy of heavy-ion collisions. Our study also shows that, the present experimental data on symmetry potential are not enough for probing the density-dependent symmetry energy. More experimental data (such as nucleon and nuclei’s scattering experiments at different nucleonic momenta and densities) on the symmetry potential are needed to pin down the density-dependent symmetry energy.

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