Isospin dependence of nucleon emission and radial flow in heavy-ion collisions induced by high energy radioactive beams

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Abstract

Using an isospin- and momentum-dependent transport model we study the emission of free nucleons and the nuclear radial flow in central heavy-ion collisions induced by high energy radioactive beams. The midrapidity neutron/proton ratio and its transverse momentum dependence are found very sensitive to the high density behavior of nuclear symmetry energy. The nuclear radial flow, however, depends only weakly on the symmetry energy.

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The density dependence of nuclear symmetry energy $E_{\text{sym}}(\rho)$ is very important for understanding many interesting questions in astrophysics \cite{1, 2, 3, 4, 5}, the novel structures of radioactive nuclei \cite{6, 7, 8, 9}, and many observables of heavy-ion reactions \cite{3, 10, 11, 12}. However, it is still very poorly known both theoretically and experimentally, especially at supranormal densities, see e.g., refs.\cite{4, 13}. Fortunately, nuclear reactions induced by radioactive beams provide a unique opportunity to pin down the symmetry energy in a broad density range \cite{14}. Moreover, they also allow us to explore the role of isospin degree of freedom in various phenomena and the dynamics of nuclear reactions. In particular, central heavy-ion reactions induced by high energy radioactive beams up to 400 MeV/nucleon at the planned Rare Isotope Accelerator (RIA) will enable us to probe the high density behavior of nuclear symmetry energy. While a number of experimental observables constraining the $E_{\text{sym}}(\rho)$ at subnormal densities have been identified recently, see e.g., refs. \cite{3, 10, 12} for reviews, very few observables sensitive to the high density behavior of $E_{\text{sym}}(\rho)$, except the $\pi^-/\pi^+$ ratio \cite{15, 16}, are currently known. In this work, we examine midrapidity nucleons and the radial flow in central heavy-ion reactions induced by high energy radioactive beams as potential probes of the symmetry energy at high densities.

Our study is based on the isospin- and momentum-dependent transport model IBUU04 \cite{17}. In this model a parameter $x$ was introduced in the single nucleon potential to mimic various density dependences of the symmetry energy as predicted by different microscopic many-body theories \cite{18}. Shown in Fig. 1 are examples of the symmetry energy with the parameter $x$ going from 1 (softer) to -2 (stiffer). The recent data from NSCL/MSU on isospin diffusion in mid-central $^{124}Sn + ^{112}Sn$ reactions at 50 MeV/nucleon was used to constrain the symmetry energy at subnormal densities \cite{19}. Within the IBUU04 model, a symmetry energy $E_{\text{sym}}(\rho) \approx 31.6(\rho/\rho_0)^{1.05}$ corresponding to $x = -1$ was found to reproduce the isospin diffusion data very nicely \cite{20}. In the present study we use the same model and parameter set to study nucleon emissions and the radial flow for central $^{132}Sn + ^{124}Sn$ reactions at a beam energy of 400 MeV/nucleon. In this reaction a compressed matter of about twice normal nuclear matter density is formed and lasts for about 15 fm/c \cite{16}. This particular reaction system will be studied experimentally using the Time Projection Chamber with beams from the fast fragmentation line at RIA.

Shown in Fig. 2 are the rapidity distributions of free nucleons identified as those having local baryon densities less than $\rho_0/8$ at 30 fm/c when the dynamical freeze-out for particle
emission is reached. It is seen that mid-rapidity nucleons are very sensitive to the symmetry energy. With the symmetry energy changing from being softer ($x=1$) to stiffer ($x=-2$) more (less) neutrons (protons) are emitted at midrapidity. This is a direct consequence of the higher repulsive (attractive) symmetry potential for neutrons (protons) with the stiffer symmetry energy at supranormal densities. Moreover, neutrons appear to be more sensitive to the variation of the symmetry energy than protons. This is because for protons the repulsive Coulomb potential works against the symmetry potential. It is also interesting to point out that the effects of the symmetry potential on nucleon emissions observed here are just opposite to those at intermediate energies around 50 MeV/nucleon where a softer symmetry energy causes more (less) emissions of neutrons (protons)\[21\]. This is because of the crossover of the symmetry energy functions with different density dependences at $\rho_0$ as shown in Fig. 1. Thus it is very important to carry out excitation function studies of particle emissions in order to map out the symmetry energy in a broad range of density.

The degree of isospin equilibrium or translucency can be measured by the rapidity distribution of nucleon isospin asymmetry $\delta_{\text{free}} \equiv (N_n - N_p)/(N_n + N_p)$ where $N_n$ ($N_p$) is the multiplicity of free neutrons (protons)\[22\]. Although it might be difficult to measure directly $\delta_{\text{free}}$ because it requires the detection of neutrons, similar information can be extracted from ratios of light clusters, such as, $^3H/^3He$, as demonstrated recently within a coalescence model\[23, 24\]. Shown in Fig. 3 are the rapidity distributions of $\delta_{\text{free}}$ with (upper window) and without (lower window) the Coulomb potential. It is interesting to see that the $\delta_{\text{free}}$ at midrapidity is particularly sensitive to the symmetry energy. As the parameter $x$ increases from $-2$ to 1 the $\delta_{\text{free}}$ at midrapidity decreases by about a factor of 2. Moreover, the forward-backward asymmetric rapidity distributions of $\delta_{\text{free}}$ with all four $x$ parameters indicates the apparent nuclear translucency during the reaction. Comparing the results shown in the upper and lower windows, one sees that the Coulomb potential is to reduce the value of $\delta_{\text{free}}$, while the sensitivity to the symmetry energy remains about the same.

Concentrating on nucleons at midrapidity, we examine in Fig. 4 the differential neutron/proton ratio $dN_n/dN_p$ as a function of transverse momentum $p_t$. The solid line in the figure is the average $(n/p)_{\text{sys}}$ ratio of the reaction system. In the low (high) $p_t$ part the $dN_n/dN_p$ is significantly higher (lower) than the $(n/p)_{\text{sys}}$. Moreover, the low $p_t$ part of the $dN_n/dN_p$ ratio is more sensitive to the symmetry energy than the high $p_t$ part. Both observations are due to the momentum dependence of the symmetry potential. As shown
earlier by one of us the symmetry potential decreases with increasing nucleon momentum in
agreement with the Lane potential extracted from nucleon-nucleus scattering data \[17, 25\].
Of course, the symmetry potential is also density dependent. Generally, high $p_t$ particles
are more likely to come from high density regions where the symmetry potential is stronger.
However, if effects of the momentum dependence are stronger than those of the density de-
pendence, the low $p_t$ particles are then more sensitive to the symmetry potential as observed
here.

It is also seen from Fig. 4 that the $dN_n/dN_p$ ratios with different $x$ parameters are almost
parallel with each other except in the high $p_t$ region. It is well known within the blast wave
picture of central heavy-ion reactions that the inverse slope of the particle spectra, i.e., the
apparent temperature, reflects the combined effects of the true temperature and the radial
flow velocity of the compressed matter in the exploding fireball \[26\]. Our observation here
about the slopes of the $dN_n/dN_p$ ratios indicates that the symmetry energy has a weak
influence on the overall thermalization and the radial flow. To be more specific we study
in the following the isospin dependence of radial flow. It is worth noting that to our best
knowledge this kind of study has never been carried out before. In anticipation of the coming
experiments at RIA, it is important to identify what role the isospin degree of freedom may
play in the radial flow which is in its own right an interesting phenomenon. We extract the
average radial flow velocity at radius $r$ from

$$\beta(r) = \frac{1}{N(r)} \sum_i \frac{\vec{p}_i \cdot \vec{r}_i}{E_i},$$

where $N(r)$ is the number of particles including bound ones in the spherical shell between
radius $r$ and $r + dr$, $\vec{p}_i, \vec{r}_i$ and $E_i$ are the momentum, coordinate and energy of the particle
$i$. As an example, we show in Fig 5 the radial flow velocities of neutrons and protons and
their densities as functions of radius $r$ measured from the center of mass of the reaction with
$x = -1$. It is seen that the radial flow velocity increases with the radius $r$ similar to the
Hubble expansion of the universe. This observation is consistent with other studies on the
radial flow in heavy-ion reactions, see, e.g., refs. \[27, 28\]. Protons, especially at larger radii,
are flowing with a slightly higher velocity due to the Coulomb repulsion, although they have
about the same density profile as neutrons. To explore effects of the symmetry energy on
the radial flow we show in Fig. 6 the position-averaged nucleon radial flow velocity $<\beta>$
with and without the Coulomb potential as a function of the parameter $x$. The value of
<β> can be readily extracted experimentally from the particle spectra using the Siemens-Rasmussen formula\[26\]. In our calculations it is obtained from eq.1 by setting \( r = 0 \) and \( dr = \infty \). Formally, <β> is related to \( \beta(r) \) via

\[
<\beta> = \frac{1}{N_{\text{total}}} \int_{0}^{\infty} \beta(r) \rho(r) 4\pi r^2 dr,
\]

where \( N_{\text{total}} \) is the total number of neutrons or protons. Without the Coulomb potential, the radial flow of neutrons is faster than that of protons because of the repulsive (attractive) symmetry potential for neutrons (protons). The difference in <β> for neutrons and protons is the largest for the stiffest symmetry energy considered here as one expects. As the symmetry energy becomes softer the difference disappears gradually. However, the overall effect of the symmetry energy on the radial flow is small, even for the stiffest symmetry energy with \( x = -2 \) the effect is only about 4%. This is because the pressure of the fireball is dominated by the kinetic contribution. Moreover, the compressional contribution to the pressure is overwhelmingly dominated by the isoscalar interactions. For protons, however, as the Coulomb potential is turned on, because of its dominance over the symmetry potential the whole picture changes. In fact, the Coulomb potential almost cancels out the effect of the symmetry potential at \( x = -2 \). As the symmetry energy becomes softer, the radial flow for protons becomes higher than that for neutrons. With the softest symmetry energy considered here, i.e, with the parameter \( x = 1 \), the Coulomb potential results in a higher radial flow velocity for protons than neutrons by about 3%. The radial flow for neutrons is only weakly affected through a secondary effect because the reaction dynamics is slightly modified by the Coulomb interaction.

In summary, using an isospin- and momentum-dependent transport model we have studied nucleon emissions and the nuclear radial flow as potential probes of the symmetry energy at high densities. We found that the isospin asymmetry of midrapidity nucleons and its transverse momentum dependence are very sensitive to the high density behavior of nuclear symmetry energy. These observables together with the \( \pi^-/\pi^+ \) ratio reported earlier will be very useful for studying the equation of state of dense neutron-rich matter at RIA. We have also studied the isospin dependence of nuclear radial flow. Our findings clearly indicate that the isospin degree of freedom plays an important role in the nuclear radial flow through the competition between the Coulomb and the symmetry potential. However, the net effect of the symmetry energy on the radial flow is small.
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FIG. 1: (color online) Nuclear symmetry energy as a function of density with different $x$ parameter.
FIG. 2: (color online) Rapidity distributions of free neutrons and protons in the reaction of $^{132}\text{Sn} + ^{124}\text{Sn}$ at $E_{\text{beam}}/A = 400$ MeV and an impact parameter of 1 fm.

FIG. 3: (color online) Rapidity distribution of isospin asymmetry of free nucleons in the same reaction as in Fig. 2 with (upper window) and without (lower window) the Coulomb potential.
FIG. 4: (color online) Transverse momentum dependence of the differential neutron/proton ratio at mid-rapidity in the same reaction as in Fig. 2.

FIG. 5: (color online) Nuclear radial flow velocity and density as a function of position for the same reaction as in Fig. 2.
FIG. 6: (color online) Symmetry energy dependence of the position-averaged radial flow velocity for the same reaction as in Fig.2.