A Transport Model for Nuclear Reactions Induced by Radioactive Beams

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Abstract. Major ingredients of an isospin and momentum dependent transport model for nuclear reactions induced by radioactive beams are outlined. Within the IBUU04 version of this model we study several experimental probes of the equation of state of neutron-rich matter, especially the density dependence of the nuclear symmetry energy. Comparing with the recent experimental data from NSCL/MSU on isospin diffusion, we found a nuclear symmetry energy of $E_{\text{sym}}(\rho) \approx 31.6(\rho/\rho_0)^{1.05}$ at subnormal densities. Predictions on several observables sensitive to the density dependence of the symmetry energy at supranormal densities accessible at GSI and the planned Rare Isotope Accelerator (RIA) are also made.

INTRODUCTION

The Equation of State (EOS) of isospin asymmetric nuclear matter can be written within the well-known parabolic approximation, which has been verified by all many-body theories, as

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

where $\delta \equiv (\rho_n - \rho_p)/(\rho_p + \rho_n)$ is the isospin asymmetry and $E_{\text{sym}}(\rho)$ is the density-dependent nuclear symmetry energy. The latter is very important for many interesting astrophysical problems[1], the structure of radioactive nuclei[2,3] and heavy-ion reactions[4,5,6,7]. Unfortunately, the density dependence of symmetry energy $E_{\text{sym}}(\rho)$, especially at supranormal densities, is still poorly known. Predictions based on various many-body theories diverge widely at both low and high densities. In fact, even the sign of the symmetry energy above $3\rho_0$ remains uncertain[8]. Fortunately, heavy-ion reactions, especially those induced by radioactive beams, provide a unique opportunity to pin down the density dependence of nuclear symmetry energy in terrestrial laboratories. Significant progress in determining the symmetry energy at subnormal densities has been made recently both experimentally and theoretically[8][10]. High energy radioactive beams to be available at GSI and RIA will allow us to determine the symmetry energy at supranormal densities.

To extract information about the EOS of neutron-rich matter from nuclear reactions induced by radioactive beams, one needs reliable theoretical tools. Transport models are especially useful for this purpose. Especially for central, energetic reactions at RIA and GSI, transport models are the most useful tool for understanding the role of isospin degree of freedom in the reaction dynamics and extract information about the EOS of neutron-rich matter. Significant progresses have been made recently in improving semi-classical transport models for nuclear reactions. While developing practically implementable quantum transport theories is a long term goal, applications of the semi-classical transport models have enabled us to learn a great deal of interesting physics from heavy-ion reactions. In the following we outline the major ingredients of an isospin and momentum dependent transport model applicable for heavy-ion reactions induced by both stable and radioactive beams[11]. This model has been found very useful in understanding a number

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of new phenomena associated with the isospin degree of freedom in heavy-ion reactions. Based on applications of this model, we highlight here the most recent progress in determining the symmetry energy at subnormal densities and present our predictions on several most sensitive probes of the symmetry energy at supranormal densities.

FIGURE 1. Density dependence of the symmetry energy for four \( x \) parameters.

IBUU04 VERSION OF THE MODEL

Crucial to the extraction of critical information about the \( E_{\text{sym}}(\rho) \) is to compare experimental data with transport model calculations. We outline here the major ingredients of the version IBUU04 of an isospin- and momentum-dependent transport model for nuclear reactions induced by radioactive beams\[^{11}\]. The single nucleon potential is one of the most important inputs to all transport models. Both the isovector (symmetry potential) and isoscalar parts of this potential should be momentum dependent due to the non-locality of strong interactions and the Pauli exchange effects in many-fermion systems. In the IBUU04, we use a single nucleon potential derived from the Hartree-Fock approximation using a modified Gogny effective interaction (MDI)\[^{12}\], i.e.,

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

(2)

In the above \( \tau = 1/2 \) (-1/2) for neutrons (protons) and \( \tau \neq \tau' \); \( \sigma = 4/3 \); \( f_\tau(\vec{r}, \vec{p}) \) is the phase space distribution function at coordinate \( \vec{r} \) and momentum \( \vec{p} \). The parameters \( A_u(x), A_l(x), B, C_\tau \tau, C_\tau \tau', \) and \( \Lambda \) were obtained by fitting the momentum-dependence of the \( U(\rho, \delta, \vec{p}, \tau, x) \) to that predicted by the Gogny Hartree-Fock and/or the Brueckner-Hartree-Fock calculations, the saturation properties of symmetric nuclear matter and the symmetry energy of 30 MeV at normal nuclear matter density \( \rho_0 = 0.16 \text{ fm}^{-3} \)\[^{12}\]. The incompressibility \( K_0 \) of symmetric nuclear matter at \( \rho_0 \) is set to be 211 MeV. The parameters \( A_u(x) \) and \( A_l(x) \) depend on the \( x \) parameter according to

\[
A_u(x) = -95.98 - x \frac{2B}{\sigma + 1}, \quad A_l(x) = -120.57 + x \frac{2B}{\sigma + 1}.
\]  

(3)
The parameter \( x \) can be adjusted to mimic predictions on the \( E_{\text{sym}}(\rho) \) by microscopic and/or phenomenological many-body theories. The last two terms contain the momentum-dependence of the single-particle potential. The momentum dependence of the symmetry potential stems from the different interaction strength parameters \( C_{\tau',\tau} \) and \( C_{\tau,\tau'} \) for a nucleon of isospin \( \tau \) interacting, respectively, with unlike and like nucleons in the background fields. More specifically, we use \( C_{\text{unlike}} = -103.4 \) MeV and \( C_{\text{like}} = -11.7 \) MeV. As an example, shown in Fig. 1 is the density dependence of the symmetry energy for \( x = -2, -1, 0 \) and 1.

**FIGURE 2.** Symmetry potential as a function of momentum and density for MDI interaction with \( x = -1 \).

Systematic analyses of a large number of nucleon-nucleus and (p,n) charge exchange scattering experiments at beam energies below about 100 MeV indicate undoubtedly that the symmetry potential at \( \rho_0 \), i.e., the Lane potential, decreases approximately linearly with increasing beam energy \( E_{\text{kin}} \) according to

\[
U_{\text{Lane}} = a - b E_{\text{kin}}
\]

where \( a \approx 22 - 34 \) MeV and \( b \approx 0.1 - 0.2 \). This provides a stringent constraint on the symmetry potential. The potential in eq. 2 meets this requirement very well as seen in Fig. 2 where the symmetry potential \( (U_n - U_p)/2\delta \) as a function of momentum and density for the parameter \( x = -1 \) is displayed.

One characteristic feature of the momentum dependence of the symmetry potential is the different effective masses for neutrons and protons in isospin asymmetric nuclear matter, i.e.,

\[
m^*_\tau/m_\tau = \left\{ 1 + m_\tau \left[ \frac{dU_\tau}{h^2 k} \right]^{-1} \right\}_{k = k^F_\tau},
\]

where \( k^F_\tau \) is the nucleon Fermi wave number. With the potential in eq. 2 since the momentum-dependent part of the nuclear potential is independent of the parameter \( x \), the nucleon effective masses are independent of the \( x \) parameter too. Shown in Fig. 3 are the nucleon effective masses as a function of density (upper window) and isospin asymmetry (lower window). It is seen that the neutron effective mass is higher than the proton effective mass and the splitting between them increases with both the density and isospin asymmetry of the medium. We notice here that the momentum dependence of the symmetry potential and the associated splitting of nucleon effective masses in isospin asymmetric matter is still highly controversia\[15, 16\]. The experimental determination of both the density and momentum dependence of the symmetry potential is required. Please see also ref. [17] on this point.

Since both the incoming current in the initial state and the level density of the final state in nucleon-nucleon (NN) scatterings depend on the effective masses of colliding nucleons in medium, the in-medium nucleon-nucleon cross sections are expected to be reduced by a factor

\[
\sigma_{\text{NN}}^{\text{medium}}/\sigma_{\text{NN}} = (\mu_{\text{NN}}^*/\mu_{\text{NN}})^2
\]

where \( \mu_{\text{NN}}^* \) and \( \mu_{\text{NN}} \) are the reduced mass of the colliding nucleon pairs in free-space and in medium, respectively [18, 19, 20]. Effective masses is consistent with predictions based on more microscopic many-body theories [21]. Thus, be-
cause of the reduced in-medium nucleon effective masses and their dependence on the density and isospin asymmetry of the medium, the in-medium NN cross sections are not only reduced compared to their free-space values, the nn and pp cross sections are split and the difference between them grows in more asymmetric matter as shown in Fig. 3. The in-medium NN cross sections are also independent of the parameter $x$. The isospin-dependence of the in-medium NN cross sections is expected to play an important role in nuclear reactions induced by neutron-rich nuclei. The other details, such as the initialization of colliding nuclei in phase space, Pauli blocking, etc can be found in our earlier publication.

APPLICATION OF THE MODEL

The model outlined above have many applications in heavy-ion reactions induced by both stable and radioactive beams. In this section, we illustrate several examples of studying the role of isospin degree of freedom in the reaction dynamics and extracting the density dependence of nuclear symmetry energy. Besides probes of symmetry energy at subnormal densities, several probes sensitive to the high density behavior of the symmetry energy have been also proposed largely based on transport model simulations.
Probing the symmetry energy at subnormal densities with isospin diffusion

Tsang et al.\textsuperscript{[9]} recently studied the degree of isospin diffusion in the reaction $^{124}\text{Sn} + ^{112}\text{Sn}$ by measuring\textsuperscript{[23]}

$$R_i = \frac{2X_{^{124}\text{Sn} + ^{112}\text{Sn}} - X_{^{124}\text{Sn} + ^{124}\text{Sn}} - X_{^{112}\text{Sn} + ^{112}\text{Sn}}}{X_{^{124}\text{Sn} + ^{124}\text{Sn}} - X_{^{112}\text{Sn} + ^{112}\text{Sn}}}$$

(6)

where $X$ is the average isospin asymmetry $\langle \delta \rangle$ of the $^{124}\text{Sn}$-like residue. The data are indicated in Fig. 5 together with the IBUU04 predictions about the time evolutions of $R_i$ and the average central densities calculated with $x = -1$ using both the MDI and the soft Bertsch-Das Gupta-Kruse (SBKD) interactions. It is seen that the isospin diffusion process occurs mainly from about 30 fm/c to 80 fm/c corresponding to an average central density from about $1.2\rho_0$ to $0.3\rho_0$. The experimental data from MSU are seen to be reproduced nicely by the MDI interaction with $x = -1$, while the SBKD interaction with $x = -1$ leads to a significantly lower $R_i$ value\textsuperscript{[10]}.

Effects of the symmetry energy on isospin diffusion were also studied by varying the parameter $x$\textsuperscript{[10]}. Only with the parameter $x = -1$ the data can be well reproduced. The corresponding symmetry energy can be parameterized as $E_{\text{sym}}(\rho) \approx 31.6(\rho/\rho_0)^{1.05}$. In the present study on isospin diffusion, only the free-space NN cross sections are used and thus effects completely due to the different density dependence of symmetry energy are investigated. As the next step we are currently investigating effects of the in-medium NN cross sections on the isospin diffusion.
FIGURE 5. The degree of isospin diffusion as a function of time with the MDI and SBKD interactions. The corresponding evolutions of central density are also shown.

Isospin asymmetry of dense matter formed in high energy heavy-ion reactions

What are the maximum baryon density and isospin asymmetry that can be achieved in central heavy-ion collisions at the highest beam energy expected at RIA? This is an interesting question relevant to the study of the EOS of asymmetric nuclear matter. To answer this question we show in Fig. 6 the central baryon density (upper window) and the average \((n/p)_{p \geq \rho_0}\) ratio (lower window) of all regions with baryon densities higher than \(\rho_0\) in the reaction of \(^{132}\text{Sn} + ^{124}\text{Sn}\) at a beam energy of 400 MeV/nucleon and an impact parameter of 1 fm. It is seen that the maximum baryon density is about 2 times normal nuclear matter density. Moreover, the compression is rather insensitive to the symmetry energy because the latter is relatively small compared to the EOS of symmetric matter around this density. The high density phase lasts for about 15 fm/c from 5 to 20 fm/c for this reaction. It is interesting to see that the isospin asymmetry of the high density region is quite sensitive to the symmetry energy. The soft (e.g., \(x = 1\)) symmetry energy leads to a significantly higher value of \((n/p)_{p \geq \rho_0}\) than the stiff one (e.g., \(x = -2\)). This is consistent with the well-known isospin fractionation phenomenon. Because of the \(E_{\text{sym}}(\rho)\delta^2\) term in the EOS of asymmetric nuclear matter, it is energetically more favorable to have a higher isospin asymmetry \(\delta\) in the high density region with a softer symmetry energy functional \(E_{\text{sym}}(\rho)\). In the supranormal density region, as shown in Fig. 1, the symmetry energy changes from being soft to stiff when the parameter \(x\) varies from 1 to -2. Thus the value of \((n/p)_{p \geq \rho_0}\) becomes lower as the parameter \(x\) changes from 1 to -2. It is worth mentioning that the initial value of the quantity \((n/p)_{p \geq \rho_0}\) is about 1.4 which is less than the average n/p ratio of 1.56 of the reaction system. This is because of the neutron-skins of the colliding nuclei, especially that of the projectile \(^{132}\text{Sn}\). In the neutron-rich nuclei, the n/p ratio on the low-density surface is much higher than that in their interior. It is clearly seen that the dense region can become either neutron-richer or neutron-poorer with respect to the initial state depending on the symmetry energy functional \(E_{\text{sym}}(\rho)\) used.

Pions yields and \(\pi^-/\pi^+\) ratio as a probe of the symmetry energy at supranormal densities

At the highest beam energy at RIA, pion production is significant. Pions may thus carry interesting information about the EOS of dense neutron-rich matter.\(^{24, 25}\) Shown in Fig. 7 are the \(\pi^-\) and \(\pi^+\) yields as a function of the \(x\) parameter. It is interesting to see that the \(\pi^-\) multiplicity depends more sensitively on the symmetry energy. The \(\pi^-\) multiplicity increases by about 20% while the \(\pi^+\) multiplicity remains about the same when the \(x\) parameter is changed from -2 to 1. The multiplicity of \(\pi^-\) is about 2 to 3 times that of \(\pi^+\). This is because the \(\pi^-\) mesons are mostly produced from neutron-neutron collisions. Moreover, with the softer symmetry energy the high density region is more neutron-rich due to isospin fractionation.\(^{25}\) The \(\pi^-\) mesons are thus more sensitive to the isospin asymmetry of the reaction system and the symmetry energy. However, one should notice that it is well known that pion yields are also sensitive to the symmetric part of the nuclear EOS. It is thus hard to get reliable information about the symmetry...
FIGURE 6. Central baryon density (upper window) and isospin asymmetry (lower window) of high density region for the reaction of $^{132}{\text{Sn}} + ^{124}{\text{Sn}}$ at a beam energy of 400 MeV/nucleon and an impact parameter of 1 fm.

FIGURE 7. The $\pi^-$ and $\pi^+$ yields as functions of the $x$ parameter.

energy from $\pi^-$ yields alone. Fortunately, the $\pi^-/\pi^+$ ratio is a better probe since statistically this ratio is only sensitive to the difference in the chemical potentials for neutrons and protons [26]. This expectation is well demonstrated in Fig. 8. It is seen that the pion ratio is quite sensitive to the symmetry energy, especially at low transverse momenta. Thus, it is promising that the high density behavior of nuclear symmetry energy $E_{\text{sym}}(\rho)$ can be probed using the $\pi^-/\pi^+$ ratio.

**Isospin fractionation and n-p differential flow at RIA and GSI**

The degree of isospin equilibration or translucency can be measured by the rapidity distribution of nucleon isospin asymmetry $\delta_{freec} \equiv (N_n - N_p)/(N_n + N_p)$ where $N_n$ ($N_p$) is the multiplicity of free neutrons (protons) [27]. Although it might be difficult to measure directly $\delta_{freec}$ 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 [28, 29]. Shown in Fig. 9 are the rapidity distributions of $\delta_{freec}$ with (upper window) and without (lower window) the Coulomb
FIGURE 8. The $\pi^-/\pi^+$ ratio as a function of transverse momentum.

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 [30].

FIGURE 9. Isospin asymmetry of free nucleons with and without the Coulomb force.
Another observable that is sensitive to the high density behavior of symmetry energy is the neutron-proton differential flow \[ F_{n-p}(y) \equiv \frac{N(y)}{\sum w_i p_i^i w_i} / N(y), \] where \( w_i = 1 \) for neutrons (protons) and \( N(y) \) is the total number of free nucleons at rapidity \( y \). The differential flow combines constructively effects of the symmetry potential on the isospin fractionation and the collective flow. It has the advantage of maximizing the effects of the symmetry potential while minimizing those of the isoscalar potential. Shown in Fig. 10 is the n-p differential flow for the reaction of \(^{132}\text{Sn} + ^{124}\text{Sn}\) at a beam energy of 400 MeV/nucleon and an impact parameter of 5 fm. Effects of the symmetry energy are clearly revealed by changing the parameter \( x \).

**FIGURE 10.** Neutron-proton differential flow at RIA and GSI energies

**CONCLUSIONS**

Transport models are powerful tools for investigating especially central heavy-ion reactions induced by neutron-rich nuclei. Applications of these models will help us understand the isospin dependence of in-medium nuclear effective interactions. Comparing with the experimental data, we can extract the isospin dependence of thermal, mechanical and transport properties of asymmetric nuclear matter playing important roles in nuclei, neutron stras and supernovae. Currently, the most important issue is the density dependence of the nuclear symmetry energy. The latter is very important for both nuclear physics and astrophysics. Significant progress has been made recently by the heavy-ion community in determining the density dependence of the nuclear symmetry energy. Based on transport model calculations, a number of sensitive probes of the symmetry energy have been found. The momentum dependence in both the isoscalar and isovector parts of the nuclear potential was found to play an important role in extracting accurately the density dependence of the symmetry energy. Comparing with recent experimental data on isospin diffusion from NSCL/MSU, we have extracted a symmetry energy of \( E_{\text{sym}}(\rho) \approx 31.6(\rho/\rho_0)^{1.05} \) at subnormal densities. It would be interesting to compare this conclusion with those extracted from studying other observables. More experimental data including neutrons with neutron-rich beams in a broad energy range are needed. Looking forward to experiments at RIA and GSI with high energy radioactive beams, we hope to pin down the symmetry energy at supranormal densities in the near future. Theoretically, the development of a practically implementable quantum transport theory for nuclear reactions induced by radioactive beams remains a big challenge.

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