Probing the isospin dependence of the in-medium nucleon-nucleon cross sections with radioactive beams

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Within a transport model we search for potential probes of the isospin dependence of the in-medium nucleon-nucleon (NN) cross sections. Traditional measures of the nuclear stopping power are found sensitive to the magnitude but they are ambiguous for determining the isospin dependence of the in-medium NN cross sections. It is shown that isospin tracers, such as the neutron/proton ratio of free nucleons, at backward rapidities/angles in nuclear reactions induced by radioactive beams in inverse kinematics is a sensitive probe of the isospin dependence of the in-medium NN cross sections. At forward rapidities/angles, on the other hand, they are more sensitive to the density dependence of the symmetry energy. Measurements of the rapidity/angular dependence of the isospin transport in nuclear reactions will enable a better understanding of the isospin dependence of in-medium nuclear effective interactions.

PACS numbers: 25.70.-z, 25.75.Ld., 24.10.Lx
I. INTRODUCTION

The isospin dependence of in-medium nuclear effective interactions is critical in determining both the nature of nucleonic matter and novel structures of radioactive nuclei [1]. Moreover, it determines the equation of state (EOS), especially the nuclear symmetry energy, and transport properties of isospin asymmetric nuclear matter. It is thus important for our understanding about many interesting questions about not only nuclei, but also neutron stars and supernovae [2,3]. Nuclear reactions induced by radioactive beams provide a unique opportunity to explore the isospin dependence of in-medium nuclear effective interactions.

While much attention has been given to finding experimental observables constraining the EOS of isospin asymmetric nuclear matter, little effort has been made so far to extract the isospin dependence of the in-medium nucleon-nucleon (NN) cross sections. The latter affects the transport properties of isospin asymmetric nuclear matter [4] and it depends on particularly the short-range part of nuclear effective interactions. Because both the iso-singlet and iso-triplet channels contribute to neutron-proton (np) scatterings, their cross sections ($\sigma_{np}^{free}$) in free space are higher than those for proton-proton (pp) or neutron-neutron (nn) scatterings ($\sigma_{pp}^{free}$) where only iso-triplet channels are involved. This is illustrated by the solid line in Fig. 1 where the ratio $\sigma_{np}/\sigma_{pp}$ is shown as a function of nucleon beam energy $E_{lab}$. More specifically, the $\sigma_{np}/\sigma_{pp}$ ratio changes from about 2.7 at $E_{lab} = 50$ MeV to 1.7 at $E_{lab} = 300$ MeV. How does the ratio $\sigma_{np}/\sigma_{pp}$ change with density and isospin asymmetry in asymmetric medium encountered often in heavy-ion reactions and astrophysical situations? This is an important question since its answer may reveal directly useful information about the isospin dependence of the in-medium nuclear effective interactions. However, very little work has been done so far about the isospin dependence of the in-medium NN cross sections in asymmetric nuclear matter although extensive studies have been carried out in symmetric matter based on various many-body theories and/or phenomenological approaches, see, e.g., refs. [5–8]. Therefore, one can find in the literature only some information about the density dependence of the $\sigma_{np}/\sigma_{pp}$ ratio in symmetric nuclear matter.
FIG. 1. (Color online) The ratio of np over pp scattering cross sections as a function of incident nucleon energy. The solid line is extracted from experimental data [17] while the dashed lines are extracted from calculations in symmetric matter using the Bonn A potential within the Dirac-Brueckner approach in ref. [6].

As an example, shown in Fig. 1 with the dashed lines are the $\sigma_{np}/\sigma_{pp}$ ratio in symmetric matter extracted from predictions using the Bonn A potential within the Dirac-Brueckner approach of ref. [6]. Efforts are currently being made to extend the above calculations to isospin asymmetric matter within the same approach, and the preliminary results are indeed very interesting [9]. In this approach not only the in-medium NN cross sections are reduced compared to their values in free-space, the ratio $\sigma_{np}/\sigma_{pp}$ is also predicted to decreases with increasing density. However, several other microscopic studies have concluded just the opposite, i.e., the $\sigma_{np}/\sigma_{pp}$ ratio increases in symmetric medium, see, e.g., [10–12].
It is therefore imperative to have experimental information about the isospin dependence of the in-medium NN cross sections. Experimentally, strong evidences supporting reduced in-medium NN cross sections have been found in heavy-ion collisions, see, e.g., refs. [13–15]. However, all analyses have been done so far assume some overall reduction of all NN scattering channels. Thus, no information about the isospin dependence of the in-medium NN cross sections has been extracted from the experiments. Given the opportunities provided by the radioactive beams, it now becomes more important to find sensitive experimental observables practically useful for extracting the isospin dependence of the in-medium NN cross sections. In this work we demonstrate within a transport model that isospin tracers, such as the neutron/proton ratio of free nucleons, at backward rapidities/angles in nuclear reactions induced by radioactive beams in inverse kinematics is such an observable.

II. THE TRANSPORT MODEL AND ITS MOST IMPORTANT INPUTS USED IN THIS WORK

In this exploratory study, we use an isospin dependent but momentum independent transport model [16]. This is perfectly sufficient for the purpose of this work while being computationally efficient. The default values of the differential and total NN cross sections are taken from the experimental data giving the solid line in Fig. 1 [17,18]. We explore effects of the isospin dependence of the in-medium NN cross sections by changing the ratio $\sigma_{np}/\sigma_{pp}$ without changing the angular distributions of elementary NN scatterings. Besides the NN cross sections, another input to the model important for the following discussions is the symmetry energy $E_{sym}(\rho)$. The density dependence of the symmetry energy is rather strongly model dependent, see, e.g., refs. [18–21]. We adopt here a parameterization used by Heiselberg and Hjorth-Jensen in their studies of neutron stars [22] $E_{sym}(\rho) = E_{sym}(\rho_0) \cdot (\rho/\rho_0)^\gamma$, where $E_{sym}(\rho_0)$ is the symmetry energy at normal nuclear matter density $\rho_0$ and $\gamma$ is a parameter. By fitting earlier predictions of the variational many-body calculations by Akmal et al [23], they obtained the values of $E_{sym}(\rho_0) = 32$ MeV and $\gamma = 0.6$. However, recent analyses of
isospin diffusions in heavy-ion collisions at intermediate energies favor strongly a $\gamma$ value between 1 and 2 [24,25] depending on whether the momentum dependence of the symmetry potential is taken into account. In the following we use $E_{\text{sym}}(\rho_0) = 30$ MeV and compare results obtained with $\gamma = 1$ and 2. By construction, the symmetry energies with $\gamma = 1$ and 2 come to cross each other at $\rho_0$. At subnormal densities the softer symmetry energy with $\gamma = 1$ leads to more repulsive/attractive symmetry potentials for neutrons/protons than the stiffer one with $\gamma = 2$. While it is the opposite at supranormal densities. The initial nucleon density distributions in the projectile $^{100}$Zn were calculated by using the Hartree-Fock-Bogoliubov method and were provided to us by J. Dobaczewski [26]. Other details about the model can be found in earlier publications [16,18].

![FIG. 2. (Color online) Quadruple moment as a function of beam energy in head-on collisions of $^{100}$Zn + $^{40}$Ca with the three choices of nucleon-nucleon cross sections.](image-url)
III. THE GLOBAL STOPPING POWER AS A MEASURE OF THE ISOSPIN
DEPENDENCE OF THE IN-MEDIUM NN CROSS SECTIONS

First, it is worth mentioning that we have examined several observables that are known to be sensitive to the in-medium NN cross sections. These include the quadruple moment $Q_{zz}$ of nucleon momentum distribution, the linear momentum transfer (LMT) and the ratio of transverse to longitudinal energies (ERAT) which have all been used traditionally as measures of the nuclear stopping power. We found that these observables are sensitive only to the magnitude but not the isospin dependence (measured by the $\sigma_{np}/\sigma_{pp}$ ratio) of the in-medium NN cross sections. The quadruple moment $Q_{zz}$ was previously proposed by Liu et al. as a measure of the isospin dependence of the in-medium NN cross sections based on their IQMD model calculations [27]. This seems to be in contradiction to our findings here. We thus examine here this measure in detail and discuss the origin of the seemingly different conclusions.

Shown in Fig. 2 are the quadruple moment per nucleon $Q_{zz}/A \equiv \frac{1}{A} \sum_{i=1}^{A} (2p_{iz}^2 - p_{ix}^2 - p_{iy}^2)$ as a function of beam energy for the head-on collisions of $^{100}Zn + ^{40}Ca$ with three choices of the in-medium NN cross sections. In agreement with ref. [27] we found that the $Q_{zz}$ is almost independent of the symmetry energy simply because the isoscalar interaction overwhelmingly dominates over the isovector interaction for the globe thermalization of the system. Also in agreement with ref. [27], by setting artificially the cross section for neutron-proton scatterings to be the same as that for proton-proton scatterings in free-space (long dashed line), thus the ratio $\sigma_{np}/\sigma_{pp}$ is one, the $Q_{zz}$ increases significantly compared to the calculations using the free-space np and pp scattering cross sections $\sigma_{np}^{free}$ and $\sigma_{pp}^{free}$ (solid line). Based on this observation, it was proposed in ref. [27] that the stopping power measured by the $Q_{zz}$ can be used as a sensitive probe of the isospin dependence of the in-medium NN cross sections. However, we point out that the observed increase of the $Q_{zz}$ is simply due to the reduction of the np scattering cross sections although the $\sigma_{np}/\sigma_{pp}$ ratio is indeed also changed. In fact, the $Q_{zz}$ is insensitive to the $\sigma_{np}/\sigma_{pp}$ ratio if one keeps the total number of...
NN collisions to be about the same. We demonstrate the ambiguity of using the \( Q_{zz} \) probe by comparing the above calculations with the ones using \( \sigma_{np} = \sigma_{pp} = (\sigma_{np}^{\text{free}} + \sigma_{pp}^{\text{free}})/2 \). In the latter the ratio \( \sigma_{np}/\sigma_{pp} \) is also one, however, the \( Q_{zz} \) is about the same as the calculations using the free-space NN cross sections up to about \( E_{\text{beam}}/A = 220 \) MeV. This observation can be understood qualitatively from the total number of NN collisions \( N_{\text{coll}} \) that essentially determines the nuclear stopping power. Neglecting the Pauli blocking, the \( N_{\text{coll}} \) scales according to

\[
N_{\text{coll}} \propto N_{np} \sigma_{np} + (N_{pp} + N_{nn}) \sigma_{pp},
\]

where the \( N_{np} \) and \( N_{pp} \) are the number of np and pp colliding pairs. Assuming only the first chance NN collisions contribute, the ratio \( N_{np}/(N_{pp} + N_{pp}) \approx (1 - \delta_1 \delta_2)/(1 + \delta_1 \delta_2) \approx 1 - 2\delta_1 \delta_2 \) is about one to the second order in isospin asymmetry even for the very neutron-rich systems, where \( \delta_1 \equiv (N_1 - Z_1)/A_1 \) and \( \delta_2 \equiv (N_2 - Z_2)/A_2 \) are the isospin asymmetries of the two colliding nuclei. Thus one has \( N_{\text{coll}} \propto N_{np} (\sigma_{np} + \sigma_{pp}) \). With either \( \sigma_{np} = \sigma_{pp} = (\sigma_{np}^{\text{free}} + \sigma_{pp}^{\text{free}})/2 \) or \( \sigma_{np} = \sigma_{np}^{\text{free}} \) and \( \sigma_{pp} = \sigma_{pp}^{\text{free}} \) the numbers of NN collisions \( N_{\text{coll}} \) are then the same leading to approximately the same \( Q_{zz} \). At higher energies, however, secondary collisions are expected to become gradually more important. The above arguments become less valid. Our discussions here indicates clearly that the nuclear stopping power is indeed sensitive to the in-medium NN cross sections. However, the stopping power alone is insufficient to determine simultaneously both the magnitude and the isospin dependence of the in-medium NN cross sections. In a nutshell, one needs at least two observables to determine two unknowns. An additional observable sensitive to the ratio \( \sigma_{np}/\sigma_{pp} \) is thus absolutely necessary.

IV. THE NEUTRON/PROTON RATIO AS A MEASURE OF THE ISOSPIN DEPENDENCE OF THE IN-MEDIUM NN CROSS SECTIONS

Now we turn to the rapidity and angular distributions of isospin tracers as potential probes of the isospin dependence of the in-medium NN cross sections. Several observables can be used as isospin tracers, such as, the neutron/proton ratio or isospin asymmetry \( \delta \) of free nucleons and fragments. The rapidity and angular distributions of the isospin tracers
measure directly the isospin transport in reactions especially below the pion production threshold. These observables were previously used also to study the momentum stopping power and the nucleon translucency [28–33] in heavy-ion collisions, see, e.g., [18,34] for a review. We use the isospin tracers at backward rapidities/angles in central collisions induced by highly asymmetric projectiles on symmetric targets in inverse kinematics to probe the isospin dependence of the in-medium NN cross sections. In these reactions the deviation of neutron/proton ratio from one at backward rapidities/angles reflects the strength of isospin transfer from the projectile to the target. Our proposal is based on the consideration that only large angle and/or multiple np scatterings are effective in transporting the isospin asymmetry from forward to backward angles. With inverse kinematics nucleons in the lighter target moving backward with higher velocities in the center of mass frame of the reaction are more likely to induce multiple np scatterings. It is well known that the symmetry potential is also important for isospin transport in heavy-ion collisions [35–38]. However, it is unlikely for the symmetry potential to change the directions of motion of nucleons. Thus at backward rapidities/angles, the isospin tracers are less affected by the symmetry potential. Nevertheless, the relative importance and interplay of the symmetry potential and the in-medium NN cross sections on the rapidity/angular distributions of isospin tracers have to be studied quantitatively within a transport approach. We look for observables in special kinematic or geometrical regions where the dual sensitivity to both the symmetry potential and the isospin dependence of the in-medium NN cross sections is a minimum if it can not be avoided completely.

Shown in Fig. 3 and Fig. 4 are the rapidity distributions of all nucleons (lower windows) and their isospin asymmetries (upper windows) at 100 fm/c in head-on collisions of $^{100}Zn+^{40}Ca$ at a beam energy of 200 MeV/A using $\gamma = 1$ and 2, respectively.
FIG. 3. (Color online) Rapidity distributions (lower window) of all nucleons and their isospin asymmetries (upper window) in head-on collisions of $^{100}\text{Zn}+^{40}\text{Ca}$ at a beam energy of 200 MeV/A using a $\gamma$ parameter of 1.

We first compare nucleon rapidity distributions using the free-space NN cross sections and $\sigma_{np} = \sigma_{pp} = (\sigma_{np}^{\text{free}} + \sigma_{pp}^{\text{free}})/2$. As discussed earlier and shown in Fig. 2 these two choices of the in-medium NN cross sections lead to identical quadruple moment $Q_{zz}$ at $E_{\text{beam}} = 200$ MeV/A. It is seen that the effects of the in-medium NN cross sections on the overall nucleon rapidity distributions are rather small with both values of the $\gamma$ parameter. Moreover, the symmetry energy also has very little effect on the nucleon rapidity distributions. These observations are consistent with those obtained from studying other global measures of the nuclear stopping power. Concentrating on the forward and backward nucleons, however, it
is clearly seen that the larger $\sigma_{np}/\sigma_{pp}$ ratio in the case of using $\sigma_{np} = \sigma_{np}^{\text{free}}$ and $\sigma_{pp} = \sigma_{pp}^{\text{free}}$ leads to more (less) transfer of neutrons (protons) from forward to backward rapidities. Since the effect is opposite on neutrons and protons, it is much more pronounced on the isospin asymmetry $\delta$ as shown in the upper windows.

![Graph showing isospin asymmetry and nucleon distribution](image)

FIG. 4. (Color online) The same as fig. 3 but using a $\gamma$ parameter of 2.

It is seen that the isospin asymmetries are rather sensitive to the isospin dependence of the in-medium NN cross sections especially at backward rapidities in both cases. Comparing the two upper windows of Figs. 3 and 4, one can notice a small effect of the symmetry potential especially at forward rapidities. At backward rapidities, however, the influence of the isospin dependence of the in-medium NN cross sections dominates overwhelmingly over that due to the symmetry potential. The effects on $\delta$ due to the isospin dependence

10
of the in-medium NN cross sections discussed above are clearly measurable, especially at backward rapidities. In principle, the effect can be extracted experimentally, for instance, by studying the free neutron/proton ratio, the $t/3 \, H e$ ratio or the isoscaling parameters. As an illustration, we now turn to the polar angle distributions of the neutron/proton ratio $(n/p)_{free}$ of free nucleons identified as those having local baryon densities less than $\rho_0/8$.

![Angular distributions of the free neutron to proton ratio $(n/p)_{free}$](chart.png)

**FIG. 5.** (Color online) Angular distributions of the free neutron to proton ratio $(n/p)_{free}$ in head-on collisions of $^{100}Zn + ^{40}Ca$ at a beam energy of 200 MeV/A.

These are shown in Fig. 5 for the three choices of the in-medium NN cross sections with both $\gamma = 1$ and 2. In the upper window we compare results obtained by using the free-space NN cross sections and the choice $\sigma_{np} = \sigma_{pp} = (\sigma_{np}^{free} + \sigma_{pp}^{free})/2$, the same choices as those in Figs. 3 and 4. It is clearly seen that the $(n/p)_{free}$ ratio at backward angles is
rather insensitive to the symmetry energy but very sensitive to the isospin dependence of the in-medium NN cross sections. While at forward angles it is the opposite. Moreover, by comparing results using all three choices considered for the in-medium NN cross sections, it is interesting to see that the choices of $\sigma_{np} = \sigma_{pp} = (\sigma_{np}^{free} + \sigma_{pp}^{free})/2$ and $\sigma_{np} = \sigma_{pp} = \sigma_{pp}^{free}$ lead to about the same $(n/p)^{free}$ value at very backward angles. The latter value is significantly less than the one obtained by using the free np and pp cross sections. In other words, at these very backward angles the $(n/p)^{free}$ is sensitive only to the $\sigma_{np}/\sigma_{pp}$ ratio but not the absolute values of the individual nn and np cross sections nor the symmetry energies. Thus it would be very valuable to measure the $(n/p)^{free}$ ratio at large backward angles. On the other hand, at very forward angles the $(n/p)^{free}$ ratio is very sensitive to the symmetry potential but not much to the in-medium NN cross sections.

To further illustrate and test our proposal we study in Fig. 6 the $(n/p)^{free}$ ratio as a function of nucleon kinetic energy in the laboratory frame. We set a limit of $\cos(\theta) \leq -0.25$ for backward (upper window) and $\cos(\theta) > 0.5$ for forward (lower window) angles. Most nucleons emitted to the backward angles have energies less than about 100 MeV for the reaction considered. Only few nucleons in the backward regions have higher energies and our calculations using 12,000 events in each case do not have enough statistics to show a meaningful $(n/p)^{free}$ ratio. In the backward angles the $(n/p)^{free}$ ratio is significantly higher than one which is the neutron/proton ratio of the target considered here. The value of $(n/p)^{free}$ is larger with the higher $\sigma_{np}/\sigma_{pp}$ ratio and the effect of the isospin dependence of the in-medium NN cross section is most pronounced at very low energies. This is understandable because transferring relatively more neutrons from the forward-going projectile to the backward direction requires more np scatterings.
FIG. 6. (Color online) The \((n/p)_{\text{free}}\) as a function of nucleon kinetic energy at backward (upper window) and forward (lower window) angles in head-on collisions of \(^{100}\text{Zn} + ^{40}\text{Ca}\) at a beam energy of 200 MeV/A.

Once these neutrons are converted backward through possibly multiple scatterings they then have less energies left. Moreover, since these neutrons have experiences multiple np scatterings they are therefore more sensitive to the \(\sigma_{np}/\sigma_{pp}\) ratio. In the forward angles selected here the \((n/p)_{\text{free}}\) ratio is more affected by the symmetry energy. As an example, we show in the lower window of Fig. 6 the results obtained by using the free NN cross sections. Results with other choices of the in-medium NN cross sections are qualitatively the same. But with the still relatively large angular range of \(-60^0 \leq \theta \leq 60^0\) selected by the cut \(\cos(\theta) > 0.5\), the in-medium NN cross sections still have some effects on the \((n/p)_{\text{free}}\)
ratio at forward angles as indicated in Fig. 5. It is seen that the influence of the symmetry energy depends strongly on the nucleon energy as one expects. Since the low energy nucleons are more likely emitted at subnormal densities where the repulsive/attractive symmetry potentials are stronger with the softer symmetry energy, the \((n/p)_{\text{free}}\) ratio is higher with \(\gamma = 1\) for low energy nucleons. The high energy nucleons mostly emitted forward, however, more likely have gone through the supranormal density region in the earlier stage of the reaction. The stiffer symmetry energy with \(\gamma = 2\) thus results in higher values of \((n/p)_{\text{free}}\) for these nucleons.

FIG. 7. (Color online) Rapidity (upper window) and angular (lower window) dependences of isospin asymmetries of all nucleons in the reaction of \(^{100}\text{Zn} + ^{40}\text{Ca}\) at a beam energy of 200 MeV/A and impact parameter of 4 fm using a \(\gamma\) parameter of 1.
The above discussions are all based on results of head-on collisions. We find that the conclusions remain qualitatively the same but with reduced effects at finite impact parameters. As an example, shown in Fig. 7 are the rapidity and angular distributions of the isospin asymmetry $\delta$ of all nucleons (upper window) and the $(n/p)_{\text{free}}$ of free ones at an impact parameter of 4 fm. The effects of the in-medium NN cross sections are still clearly observable but smaller than those in head-ion collisions. One can also notice that memories of the n/p ratio of the projectile and target are now more clear as one expects. Besides the reactions at 200 MeV/A, we have also studied the reactions at 100 and 300 MeV/A but with less events so far. Our conclusions do not seem to change qualitatively in the energy range considered. It will be interesting to extend the study down to the Fermi energy range and examine the influence of the size of the colliding nuclei. Also, an investigation based on a momentum dependent transport model [39] using isospin-dependent in-medium NN cross sections and the mean field evaluated consistently in asymmetric matter from the same nuclear effective interactions [40] is in progress.

V. SUMMARY

In summary, within a transport model for nuclear reactions induced by neutron-rich nuclei, we searched for potential probes of the isospin dependence of the in-medium NN cross sections. The traditional probes of the nuclear stopping power are found sensitive to the magnitude of the in-medium NN cross sections. They are, however, ambiguous for determining the isospin dependence of the in-medium NN cross sections. In particular, we found that an earlier conclusion that the nucleon quadruple moment can be used as a probe of the isospin dependence of the in-medium NN cross sections is premature. We also studied the relative importance and interplay of the symmetry energy and the in-medium NN cross sections on the rapidity and angular distributions of isospin tracers. We found that the isospin tracers, such as the neutron/proton ratio of free nucleons, at backward rapidities/angles in nuclear reactions induced by radioactive beams in inverse kinematics is
a sensitive probe of the isospin dependence of the in-medium NN cross sections. At forward rapidities/angles, on the other hand, the neutron/proton ratio is more sensitive to the density dependence of the symmetry energy. It is thus very useful to measure experimentally the rapidity and angular distributions of isospin tracers to study the transport properties and the EOS of isospin asymmetric matter. Ultimately, these studies will enable us to better understand the isospin dependence of the in-medium nuclear effective interactions.

B.A. Li would like to thank the nuclear theory group at Michigan State University for the kind hospitality he received there during his summer visit when this work started. The work is supported in part by the National Science Foundation under Grant No. PHY-0245009, PHY-01-10253, PHY-0354572, and the NASA-Arkansas Space Grants Consortium.
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