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 to be 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 and angles in nuclear reactions induced by radioactive beams in inverse kinematics are a sensitive probe of the isospin dependence of the in-medium *NN* cross sections. At forward rapidities and angles, in contrast, they are more sensitive to the density dependence of the symmetry energy. Measurements of the rapidity and angular dependence of the isospin transport in nuclear reactions will enable a better understanding of the isospin dependence of in-medium nuclear effective interactions.

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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 of many interesting questions about not only nuclei but also neutron stars and supernove [2,3]. Nuclear reactions induced by radioactive beams provide a unique opportunity to explore the isospin dependence of in-medium nuclear effective interactions.

Although 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 particularly on 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 ($\sigma_{np}^{\rm free}$) in free space are higher than those for proton-proton (*pp*) or neutron-neutron (*nn*) scatterings ($\sigma_{pp}^{\rm free}$) where only iso-triplet channels are involved. This is illustrated by the solid line in Fig. 1, where the ratio σ_{np}/σ_{pp} is shown as a function of nucleon beam energy $E_{\rm lab}$. More specifically, the σ_{np}/σ_{pp} ratio changes from about 2.7 at $E_{\rm lab} = 50$ MeV to 1.7 at $E_{\rm lab} = 300$ MeV. How does the ratio σ_{np}/σ_{pp} change with density and isospin asymmetry in the asymmetric medium often encountered 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 on 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 little information in the literature about the density dependence of the σ_{np}/σ_{pp} ratios in symmetric nuclear matter.

As an example, shown in Fig. 1 with the dashed lines are the σ_{np}/σ_{pp} ratios 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 these calculations to isospin asymmetric matter within the same approach, and the preliminary results are indeed very interesting [9]. In this approach not only are the in-medium *NN* cross sections reduced compared to their values in free space, but the ratio σ_{np}/σ_{pp} is also predicted to decreases with increasing density. However, several other microscopic studies have concluded just the opposite, that is, that the σ_{np}/σ_{pp} ratio increases in a symmetric medium (see, e.g. [10–12]). It is therefore imperative to have experimental information on the isospin dependence of the in-medium *NN* cross sections. Experimentally, strong evidence supporting reduced in-medium *NN* cross sections has been found in heavy-ion collisions (see, e.g., Refs. [13–15]). However, thus far all analyses have assumed some overall reduction of all *NN* scattering channels. Thus, no information on the isospin dependence of the in-medium *NN* cross sections has been extracted from the experiments. Given the opportunities provided by radioactive beams, it becomes even more important to find sensitive experimental observables that are 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 and angles in nuclear reactions induced by radioactive beams in inverse kinematics comprise such an observable.

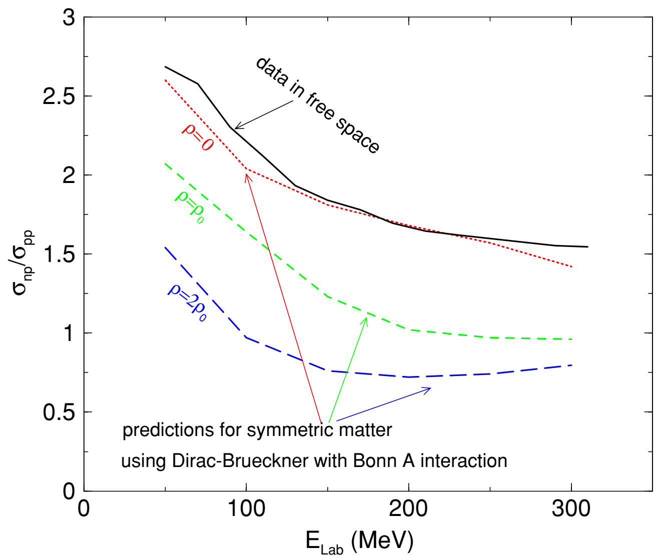

FIG. 1. (Color online) The ratio of *np* to *pp* scattering cross sections as a function of incident nucleon energy. The solid line is extracted from experimental data [17]; the dashed lines are extracted from calculations in symmetric matter using the Bonn A potential within the Dirac-Bruckner approach in Ref. [6].

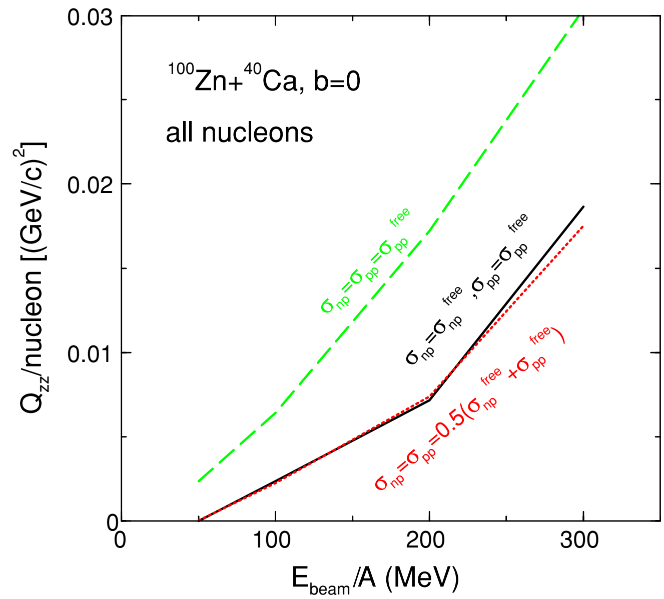

FIG. 2. (Color online) Quadruple moment as a function of beam energy in head-on collisions of ^{100}Zn+^{40}Ca with the three choices of nucleon-nucleon cross sections.

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 plotted as a 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 σ_{np}/σ_{pp} without changing the angular distributions of elementary *NN* scatterings. Besides the *NN* cross sections, another input to the model important for the following discussion is the symmetry energy $E_{\rm sym}(\rho)$. The density dependence of the symmetry energy is rather strongly model dependent (see, e.g., Refs. [18–21]). We adopt here the following parametrization used by Heiselberg and Hjorth-Jensen in their studies of neutron stars [22]: $E_{\rm sym}(\rho) = E_{\rm sym}(\rho_0)\,.\,(\rho/\rho_0)^\gamma$, where $E_{\rm sym}(\rho_0)$ is the symmetry energy at normal nuclear matter density ρ_0 and γ is a parameter. By fitting earlier predictions of the variational many-body calculations by Akmal and Pandharipande [23], they obtained values of $E_{\rm sym}(\rho_0) = 32$ MeV and $\gamma = 0.6$. However, recent analyses of isospin diffusion in heavy-ion collisions at intermediate energies strongly favor a γ 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 $E_{\rm sym}(\rho_0) = 30$ MeV and compare results obtained with $\gamma = 1$ and 2. By construction, the symmetry energies with $\gamma = 1$ and 2 cross each other at ρ_0. At subnormal densities the softer symmetry energy with $\gamma = 1$ leads to more repulsive (respectively attractive) symmetry potentials for neutrons (respectively protons) than the stiffer one with $\gamma = 2$. Whereas at supranormal densities the opposite is true. 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 Dobaczewski [26]. Other details of the model can be found in earlier publications [16,18].

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 σ_{np}/σ_{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 is 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 head-on collisions of ^{100}Zn+^{40}Ca with three choices of in-medium *NN* cross sections. In agreement with Ref. [27] we found that Q_{zz} is almost independent of the symmetry energy simply because the isoscalar interaction overwhelmingly dominates over the isovector interaction for the global thermalization of the system. Also in agreement with Ref. [27], by artificially setting the cross section for neutron-proton scattering to be the same as that for proton-proton scattering in free space (long dashed line), thus making the ratio σ_{np}/σ_{pp} equal to one, Q_{zz} increases significantly compared to calculations using the free space *np* and *pp* scattering cross sections $\sigma_{np}^{\text{free}}$ and $\sigma_{pp}^{\text{free}}$ (solid line). Based on this observation, it was proposed in Ref. [27] that the stopping power measured by 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 Q_{zz} is simply due to the reduction of the *np* scattering cross sections, although the σ_{np}/σ_{pp} ratio is indeed also changed. In fact, Q_{zz} is insensitive to the σ_{np}/σ_{pp} ratio if one keeps the total number of *NN* collisions about the same. We demonstrate the ambiguity of using the Q_{zz} probe by comparing these calculations with the ones using $\sigma_{np} = \sigma_{pp} = (\sigma_{np}^{\text{free}} + \sigma_{pp}^{\text{free}})/2$. In the latter the ratio σ_{np}/σ_{pp} is also one; however, Q_{zz} is about the same as in 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_{coll} which essentially determines the nuclear stopping power. Neglecting Pauli blocking, we find that N_{coll} scales according to $N_{\text{coll}} \propto N_{np}\sigma_{np} + (N_{pp} + N_{nn})\sigma_{pp}$, where N_{np} and N_{pp} are the number of *np* and *pp* colliding pairs, respectively. If one assumes that only the first chance *NN* collisions contribute, then 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 second order in isospin asymmetry even for 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_{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 and these arguments become less valid. Our discussion 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 σ_{np}/σ_{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 δ 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 and 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 and 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 that the symmetry potential can change the direction of motion of nucleons. Thus at backward rapidities and 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 and 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 cannot be avoided completely.

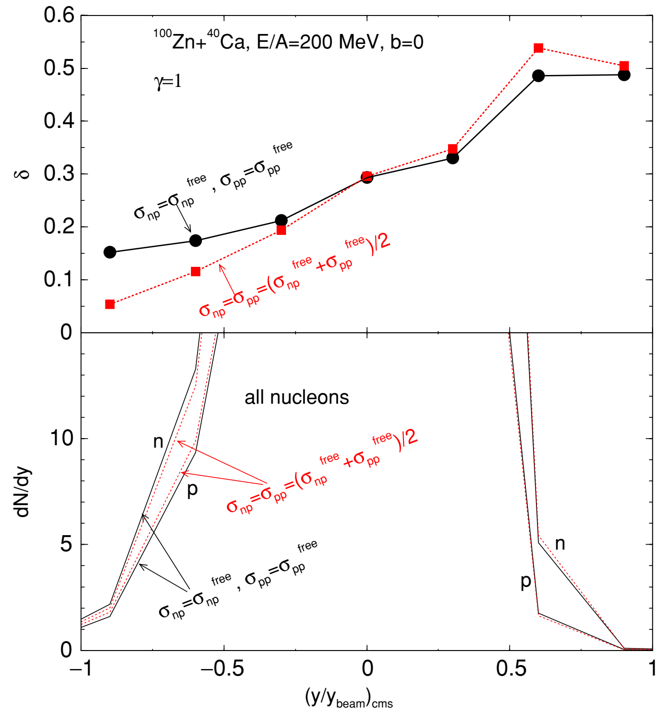

FIG. 3. (Color online) Rapidity distributions (lower panel) of all nucleons and their isospin asymmetries (upper panel) in head-on collisions of ^{100}Zn+^{40}Ca at a beam energy of 200 MeV/*A* using a γ parameter of 1.

Shown in Figs. 3 and 4 are the rapidity distributions of all nucleons (lower panels) and their isospin asymmetries (upper

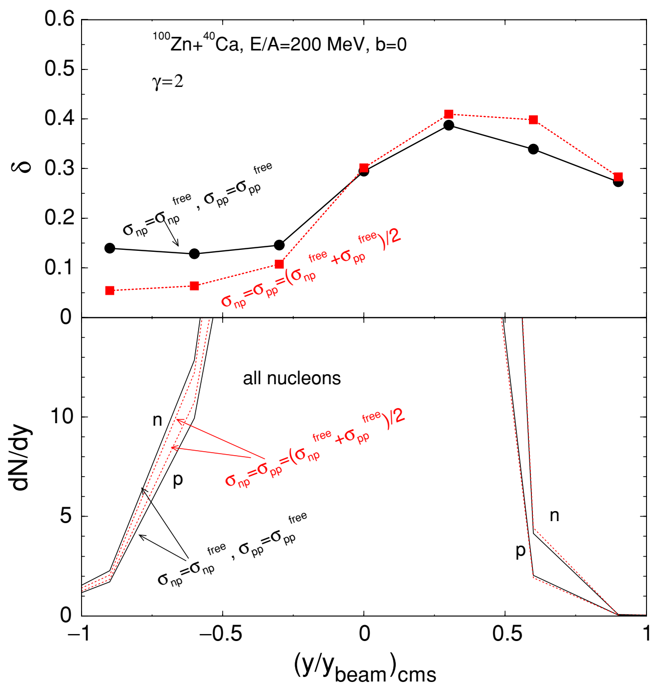

FIG. 4. (Color online) The same as Fig. 3 but using a γ parameter of 2.

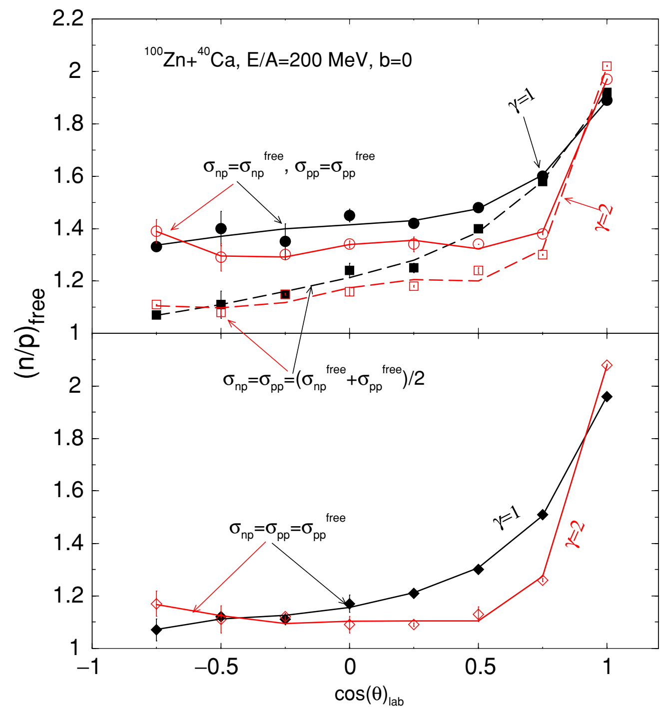

FIG. 5. (Color online) Angular distributions of the free neutron to proton ratio $(n/p)_{\rm free}$ in head-on collisions of ^{100}Zn+^{40}Ca at a beam energy of 200 MeV/nucleon.

panels) at 100 fm/c in head-on collisions of ^{100}Zn+^{40}Ca at a beam energy of 200 MeV/nucleon using $\gamma = 1$ and 2, respectively.

We first compare nucleon rapidity distributions using the free space NN cross sections and $\sigma_{np} = \sigma_{pp} = (\sigma_{np}^{\rm free} + \sigma_{pp}^{\rm free})/2$. As discussed earlier and shown in Fig. 2 these two choices of in-medium NN cross section lead to identical quadruple moment Q_{zz} at $E_{\rm beam} = 200$ MeV/nucleon. 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 γ 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, we clearly see that the larger σ_{np}/σ_{pp} ratio in the case of using $\sigma_{np} = \sigma_{np}^{\rm free}$ and $\sigma_{pp} = \sigma_{pp}^{\rm free}$ 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 δ, as shown in the upper panels.

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 panels of Figs. 3 and 4, we see that at forward rapidities the softer symmetry potential with $\gamma = 1$ leads to slightly higher isospin asymmetry, as one expects. This effect is compatible with that due to the isospin dependence of the in-medium NN cross sections. 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 δ resulting from the isospin dependence of the in-medium NN cross sections discussed here 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 $t/^3$He ratio, or the isoscaling parameters.

As an illustration, we now turn to the polar angle distributions of the neutron/proton ratio $(n/p)_{\rm free}$ of free nucleons identified as those having local baryon densities less than $\rho_0/8$. These are shown in Fig. 5 for three choices of in-medium NN cross section with both $\gamma = 1$ and 2. In the upper panel we compare results obtained by using the free space NN cross sections and the choice $\sigma_{np} = \sigma_{pp} = (\sigma_{np}^{\rm free} + \sigma_{pp}^{\rm free})/2$, the same choices as those in Figs. 3 and 4. It is clearly seen that the $(n/p)_{\rm free}$ 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, whereas at forward angles the opposite is true. Moreover, comparing results using all three choices considered for the in-medium NN cross sections, we see that the choices of $\sigma_{np} = \sigma_{pp} = (\sigma_{np}^{\rm free} + \sigma_{pp}^{\rm free})/2$ and $\sigma_{np} = \sigma_{pp} = \sigma_{pp}^{\rm free}$ lead to about the same $(n/p)_{\rm free}$ 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 $(n/p)_{\rm free}$ is sensitive only to the σ_{np}/σ_{pp} ratio but not to the absolute values of the individual nn and np cross sections nor the symmetry energies. Thus it would be very valuable to measure the $(n/p)_{\rm free}$ ratio at large backward angles. However, at very forward angles the $(n/p)_{\rm free}$ ratio is very sensitive to the symmetry potential but is rather insensitive to the in-medium NN cross sections.

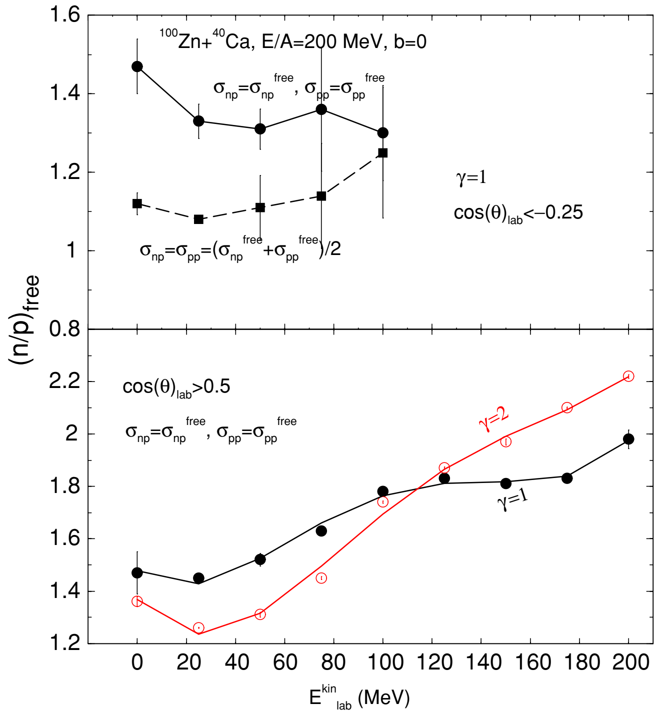

FIG. 6. (Color online) The $(n/p)_{\text{free}}$ ratio as a function of nucleon kinetic energy at backward (upper panel) and forward (lower panel) angles in head-on collisions of ^{100}Zn+^{40}Ca at a beam energy of 200 MeV/nucleon.

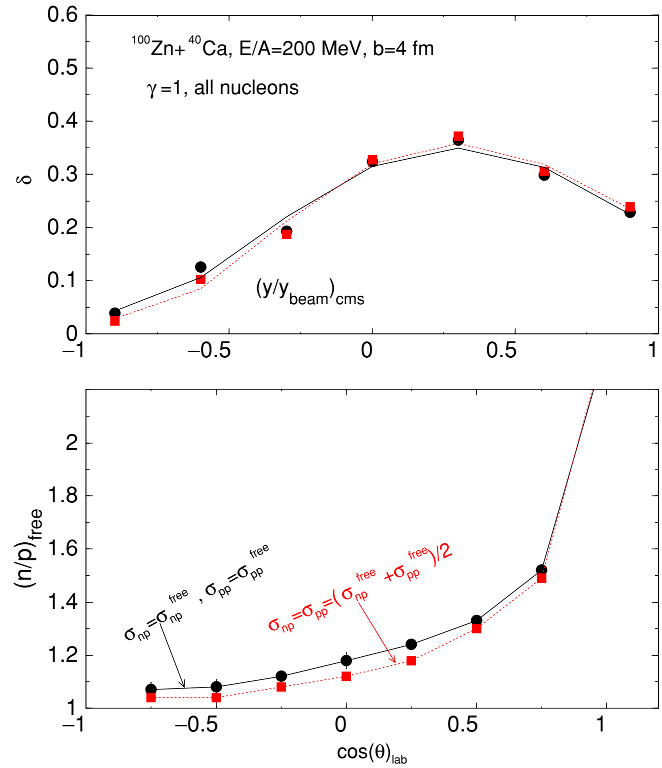

FIG. 7. (Color online) Rapidity (upper panel) and angular (lower panel) dependences of isospin asymmetries of all nucleons in the reaction of ^{100}Zn+^{40}Ca at a beam energy of 200 MeV/nucleon and impact parameter of 4 fm using a γ parameter of 1.

To further illustrate and test our proposal we study in Fig. 6 the $(n/p)_{\text{free}}$ ratio as a function of nucleon kinetic energy in the laboratory frame. We set a limit of $\cos(\theta) \leqslant -0.25$ for backward (upper panel) and $\cos(\theta) > 0.5$ for forward (lower panel) angles. Most nucleons emitted to the backward angles have energies less than about 100 MeV for the reaction considered. Only a few nucleons in the backward region have higher energies and our calculations using 12,000 events in each case do not have sufficient statistics to show a meaningful $(n/p)_{\text{free}}$ ratio. For the backward angles the $(n/p)_{\text{free}}$ ratio is significantly higher than one, which is the neutron/proton ratio of the target considered here. The value of $(n/p)_{\text{free}}$ is larger with higher σ_{np}/σ_{pp} ratio and the effect of 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.

Once these neutrons are converted backward through possibly multiple scatterings they then have less energy. Moreover, since these neutrons have experienced multiple *np* scatterings they are therefore more sensitive to the σ_{np}/σ_{pp} ratio. For 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 panel of Fig. 6 the results obtained using free *NN* cross sections. Results with other choices of in-medium *NN* cross sections are qualitatively the same. However, with the still relatively large angular range of $-60^\circ \leqslant \theta \leqslant 60^\circ$ selected by the cut $\cos(\theta) > 0.5$, the in-medium *NN* cross sections still have some effect 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 low-energy nucleons are more likely emitted at subnormal densities where the repulsive or attractive symmetry potentials are stronger with softer symmetry energy, the $(n/p)_{\text{free}}$ ratio is higher with $\gamma = 1$ for low-energy nucleons. The high-energy nucleons, which are mostly emitted forward, however, are more likely to 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.

All of the preceding discussion is 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 δ of all nucleons (upper panel) 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 are 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 clearer, as one expects. Besides the reactions at 200 MeV/nucleon, we have also studied the reactions at 100 and 300 MeV/nucleon but with fewer 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. In progress is an investigation based on a *momentum-dependent* transport model [39] using isospin-dependent in-medium *NN* cross sections and a mean field evaluated consistently in asymmetric matter from the same nuclear effective interactions [40].

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 to be 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 and angles in nuclear reactions induced by radioactive beams in inverse kinematics are a sensitive probe of the isospin dependence of the in-medium *NN* cross sections. At forward rapidities and angles, in contrast, the neutron/proton ratio is more sensitive to the density dependence of 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.

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