Correlation and isospin dynamics of participant-spectator matter in neutron-rich colliding nuclei at 50 MeV/nucleon

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The sensitivities of isospin asymmetry and collision geometry dependencies of participant (overlapping region)-spectator (quasiprojectile and quasitarget region) matter towards the symmetry energy using the isospin quantum molecular dynamical model are explored. Particularly, the difference of the number of nucleons in the overlapping zone to the quasi-projectile-target matter is found to be quite sensitive to the symmetry energy at semiperipheral geometries compared to the individual yield. It gives us a clue that this quantity can be used as a measure of isospin migration. Further, the yield of neutrons (charge of the second-largest fragment) is provided as a tool for overlapping region (quasi-projectile-target) matter to check the sensitivity of the above-mentioned observable towards the symmetry energy experimentally.

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I. INTRODUCTION

The primary goal of isospin physics is to obtain a better understanding of the properties of asymmetric nuclear matter or, in other words, isospin dependence of the nuclear equation of state (NEOS). Over three decades, the NEOS of symmetric nuclear matter is well understood by the study of giant dipole resonances, collective flow, multifragmentation, etc. [1–5]. The compressibility $\kappa_0 = 9\rho_0^2 \frac{\partial(E/A)}{\partial\rho}|_{\rho=\rho_0}$, which describes so-called stiffness of the symmetric nuclear matter has been determined to 235 ± 14 MeV. The NEOS of isospin asymmetric nuclear matter is recently under way, particularly in regard to the density dependence of symmetry energy, which is critically important also in many astrophysical processes, such as structural and dynamical evolution of neutron star, the critical density for the direct cooling process, etc. [6].

Considerable progress has been made in determining the sub- and suprasaturation density behavior of the symmetry energy [7–16]. The latter part is still an unanswered question in spite of recent findings in terms of neutron-proton elliptic flow ratio and difference [13,14]. However, the former one is understood to some extent [7–11], although more efforts are needed for precise measurements. In this contest, in the year 2011, the Symmetry Energy project (SEP) is started at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University (MSU) in collaboration with European as well as Asian countries. The aim of project is (1) to revisit the results of isospin sensitive observables, such as double ratio and isospin diffusion with more accuracy; (2) to search new observables for the determination of symmetry energy with minimum uncertainities, as the uncertainities in the literature are from soft to linear one [7,9,10]. Here we try to search for a new observable whose importance in intermediate-energy heavy-ion collisions is discussed below.

Recently, the role of isospin degree of freedom has been investigated using collective flow and its balance energy (at which flow disappears) [16]. The collective flow is proven as an indicator for the symmetry energy. At balance energy, the attractive interactions owing to mean field are balanced by the repulsive interactions owing to nucleon-nucleon (NN) collisions. This counterbalancing is reflected in quantities such as participant-spectator matter [17]. Recently, the participant-spectator matter at balance energy is found to be quite insensitive towards the mass and N/Z of the colliding system and hence can act as a barometer for the study of vanishing flow [17,18]. The interdependence of collective flow with symmetry energy and collective flow with participant-spectator matter gives us a clue to check the sensitivity of participant-spectator matter towards the symmetry energy in asymmetric colliding nuclei.

Second, the elliptic flow is also shaped by the interplay of collisions and mean field [19]. In addition, the elliptic flow pattern of the participant matter is affected by the presence of cold spectator matter [20]. The spectator can especially inhibit the collective transverse expansion of the decompressing participant matter and effectively shadow particle emission directed towards the reaction plane. This study indicates that elliptic flow is influenced strongly by participant-spectator matter distributions. As we have discussed earlier, the elliptic flow ratio and difference from neutrons and protons was used as an indicator for the symmetry energy [13,14]. It is the another insight or clue to check the sensitivity of participant-spectator matter towards the symmetry energy.

Apart from collective transverse and elliptic flow, the participant-spectator matter also plays an important role in understanding multifragmentation as well as nuclear stopping. In recent years, the correlation between nuclear stopping and light charged particles (LCPs) is investigated by using quantum molecular dynamics (QMD) and isospin-QMD (IQMD) [21]. The relationship among nuclear stopping, directed flow, and elliptic flow is established [22]. Further, participant matter is declared as an indicator to nuclear stopping [17]. All the correlation studies indicate some indirect correlation of participant-spectator matter with different kinds of fragments. So it also becomes our prime duty to correlate the participant-spectator matter with different kinds of fragments and then

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provide specific types of fragments as an experimental measure for participant-spectator matter.

In the literature, mostly participant-spectator terminology is used, which is most suitable at higher incident energies, where the dynamics is almost fully accounted for by NN collisions. In the energy region of the present paper, the reaction proceeds through the interplay of both NN collisions and mean field. We prefer to use quasiprojectile (QP) or quasitarget (QT) for spectator matter and overlap region (OR) for the participant matter.

In the present work, the IQMD model is used, which is discussed in detail in our recent publications [11,23], originally developed by Hartnack and collaborators [24]. The model is modified by the authors for the density dependence of symmetry energy, having the form

$$E_{\mathrm{Sym}}(\rho) = \frac{C_{s,k}}{2}\left(\frac{\rho}{\rho_0}\right)^{2/3} + \frac{C_{s,p}}{2}\left(\frac{\rho}{\rho_0}\right)^{\gamma_i},$$

with the parameters of $C_{s,k} = 25$ MeV and $C_{s,p} = 35.2$ MeV. When we set $\gamma_i = 0.5$ and 1.5, respectively, it corresponds to the soft and stiff symmetry energy [11].

II. RESULTS AND DISCUSSION

The present OR and QP + QT matter demonstration is based on the fireball model [25] as reported in Ref. [17]. All nucleons having experienced at least one collision are supposed to originate from OR matter (labeled as N_{OR}). The remaining matter is called QP,QT matter (labeled as $N_{\mathrm{QP+QT}}$). N_{Tot} is the total number of nucleons in the reaction system. This concept gives results similar to those demonstrated in the fireball model of Gaitanos *et al.* [25] and further verified by QMD in last couple of years to date [17,18]. There is another way to define the OR, QP, and QT matter on the basis of different rapidity cuts [8,17]. However, both these definitions have been reported to give the same results [8,17]. In the present study, we use the first definition to construct the OR and QP + QT matter. During the expansion stage, this definition will lead to the production of two matters with different densities. The OR must have relatively low density compared to QP, QT matter. This density gradient must increase when one goes towards the peripheral collisions. Owing to the density gradient, the transfer of particles from the high- to the low-density region is found to relate with the phenomenon known as isospin migration [26].

Mathematically, isospin migration can be understood as $D_n^{\rho} - D_p^{\rho} \propto 4\delta\frac{\partial E_{\mathrm{sym}}}{\partial \rho}$, with $D_{p/n}^{\rho}$ the mass coefficients, which are directly given by the variation of n, p chemical potentials with respect to density and asymmetry (for more detail, see Ref. [26]). From the above equation, it is clear that isospin migration depends on the slope of the symmetry energy or the symmetry pressure. When one moves towards the semiperipheral collisions, QP or QT of about normal density are in contact with the OR, where the density is quite lower than saturation density. In this region of density, a stiff symmetry energy has a smaller value but a larger slope in comparison with a soft symmetry energy. In brief, this definition can help us to find the observable for isospin migration.

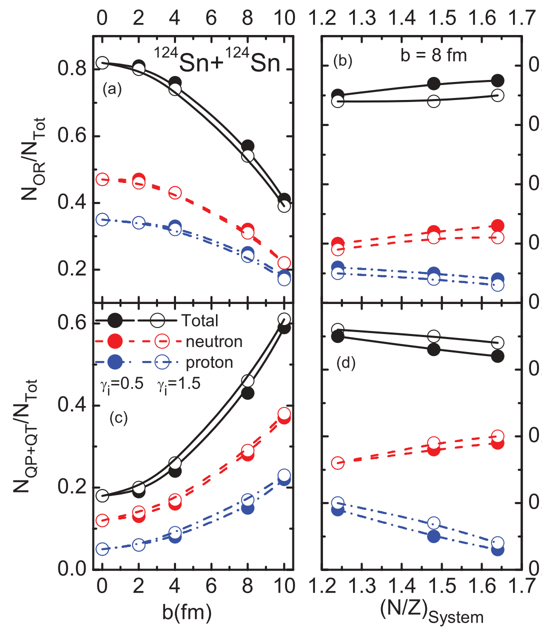

FIG. 1. (Color online) Impact parameter (left panels) and isospin asymmetry (right panels) dependencies of nucleons in OR (a),(b) and QP + QT (c),(d) matter, including the contributions from neutrons and protons. The solid (open) symbols represent soft (stiff) symmetry energies.

A. Theoretical probe for isospin migration

In the present study, thousand of events are simulated using static soft equation of state and energy-dependent NN cross section for the isotopes of Sn, namely ^{112}Sn + ^{112}Sn, ^{124}Sn + ^{124}Sn, and ^{132}Sn + ^{132}Sn at incident energy 50 MeV/nucleon along the whole collision geometry.

Figure 1 displays the impact parameter (b) and isospin asymmetry of the system [$(N/Z)_{\mathrm{system}}$] dependencies of OR and QP + QT, including the neutron and proton contributions. With the increase of impact parameter, the number of nucleons in OR (QP + QT) matter decreases (increases). Similar behavior is followed by the impact parameter dependence of neutrons and protons. In contrast, there is more sensitivity for the difference in the numbers of neutrons and protons near the central (peripheral) geometries from OR (QP + QT) matter, which is attributable to the dominance of more NN collisions (many fewer collisions) near the respective collision geometries.

In semiperipheral collisions, the isospin asymmetry dependence of OR and QP + QT matter along with neutron and proton contribution have dramatic behavior. With the increase in isospin asymmetry, the number of nucleons in OR (QP + QT) matter increases (decreases). Furthermore, the neutron (proton) contribution from OR as well as QP + QT matter increases (decreases). Interestingly, the sensitivity is stronger for QP + QT matter at higher isospin asymmetry. This is attributable to the fact that (1) with isospin asymmetry, there emerges a sharp increase in neutron content inside QP + QT of about 4–5 times compared to the decrease of QP + QT matter (see the red circles vs black circles in right bottom panel); (2) because the proton content is constant for all the isotopes of

Sn and while the QP + QT matter is decreasing, it will eventually lead to a decrease in proton content in the QP + QT matter.

Last, the effect of symmetry energy is relatively weak on the impact parameter and isospin asymmetry dependencies on the nucleons originated from OR and QP + QT matter. This difference is true as the error bars are smaller than the size of the symbols. The soft (stiff) symmetry energy contributes more for OR (QP + QT) matter. This is attributable to the gradient in densities of two matters, which can be explained by slope of symmetry energy rather than magnitude. The slope (magnitude) of symmetry energy changes its behavior below (at) the saturation density for the soft and stiff symmetry energy. Owing to the large slope (less magnitude) for the stiff symmetry energy even below the saturation density, the QP + QT is more neutron-rich with the stiff symmetry energy, which is true with the soft symmetry energy for OR matter because the density at freeze-out time in comparison to QP + QT is very low.

From the above discussions, it is clear that the number of nucleons contributed from OR and QP + QT matter is a good candidate to explore the isospin physics, but not a potential candidate for symmetry energy (owing to weak dependence). However, the density gradient of symmetry energy gives us some preliminary clues of isospin migration between the nucleons of OR and QP + QT matter.

To reveal the effect of symmetry energy in terms of isospin migration, in Fig. 2, we display the difference of nucleon number between OR and QP + QT ($\frac{N_{\mathrm{OR}}-N_{\mathrm{QP+QT}}}{N_{\mathrm{Tot}}}$) as a function of the kinetic energy of nucleons at different impact parameters and for two neutron-rich systems. In central collisions, no effect of symmetry energy is observed. However, with the increase of the impact parameter, sensitivity of symmetry energy towards the observable seems to be increasing. This indicates that the effect of symmetry energy on the observable under study depends weakly on the isospin asymmetry, but strongly on the density gradient. As discussed earlier, the density gradient increases strongly (weakly) with the impact parameter (isospin asymmetry). The effect of symmetry energy on the observable ($\frac{N_{\mathrm{OR}}-N_{\mathrm{QP+QT}}}{N_{\mathrm{Tot}}}$) mainly originates from the density difference and not from the isospin asymmetry. We further know that the density difference is a direct measure of the isospin migration. The findings also support the results of the Ref. [26].

From the study, we can conclude that the difference in the number of nucleons from OR to QP + QT can act as a probe to the slope of symmetry energy versus the density in terms of isospin migration at subsaturation densities.

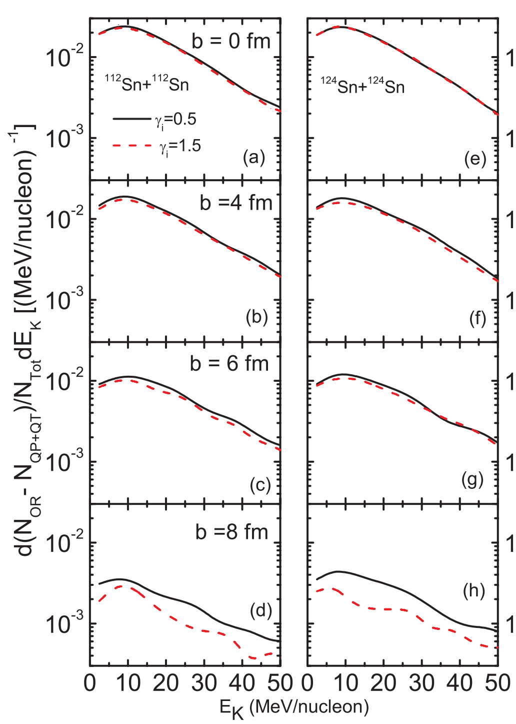

FIG. 2. (Color online) The kinetic energy spectra of the $\frac{N_{\mathrm{OR}}-N_{\mathrm{QP+QT}}}{N_{\mathrm{Tot}}}$ at different colliding geometries. The solid (dashed) lines represent the contribution with soft and stiff symmetry energy. Panels (a),(b),(c),(d) and (e),(f),(g),(h) are for ^{112}Sn + ^{112}Sn and ^{124}Sn + ^{124}Sn systems, respectively.

B. Correlation with fragments and observables for experiments

The second aspect of this paper is to correlate the number of nucleons in OR and QP + QT matter with fragmentation process and then provide some observables to test the above observable as a sensitive probe for symmetry energy.

To this end, we displayed the impact parameter and isospin asymmetry dependencies of different kinds of fragments in Fig. 3, which is similar to Fig. 1. The multiplicity of different

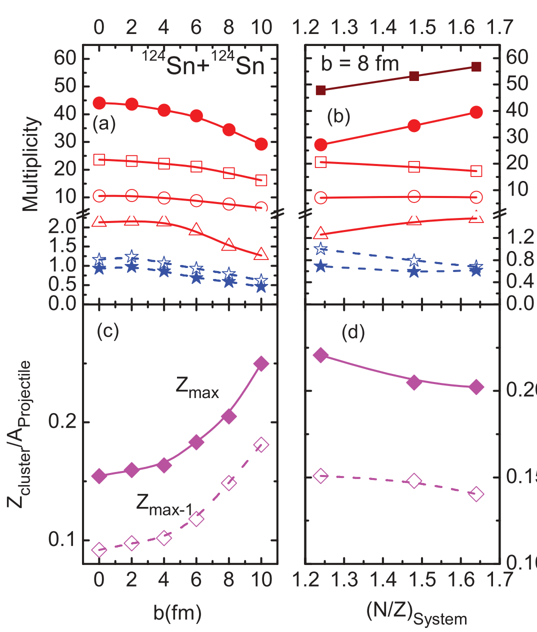

FIG. 3. (Color online) Same as Fig. 1, but for the multiplicity of different kinds of fragments from lighter to the heavier ones. In panels (a) and (b), the solid squares represent free nucleons, solid circles (open squares) free neutrons (protons), circles (open triangles) deuteron (triton), open stars (solid stars) ^{3}He (^{4}He). In panels (c) and (d), solid and open diamonds represent the heaviest fragment and second-heaviest fragment, respectively.

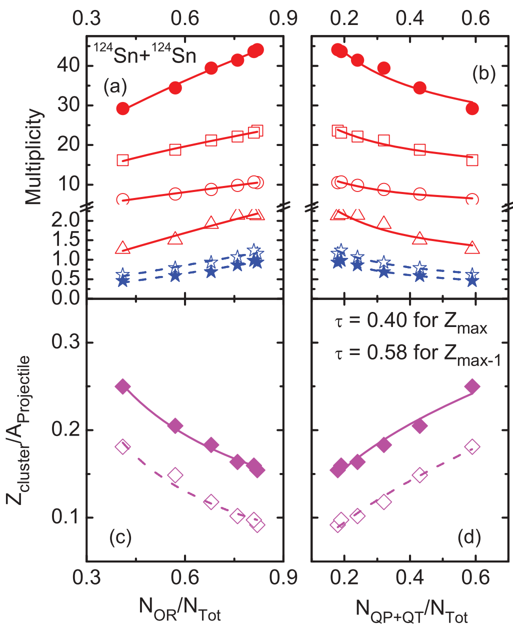

FIG. 4. (Color online) Correlation between the nucleons of OR and QT + QT matter with different kinds of fragments. The lines are fitted with the power-law form $Y = CX^{\tau}$. Symbols are the same as in Fig. 3.

kinds of LCPs goes on decreasing with the increase of impact parameter as well as size of the fragments. This type of the behavior has already been observed many times in the literature [21]. However, $Z_{max-1}/A_{projectile}$ (charge of the second-largest fragment normalized by the mass number of the projectile) and $Z_{max}/A_{projectile}$ (charge of the largest fragment normalized by the mass number of the projectile) increase with impact parameter. These two left panels are similar those in the left panels in Fig. 1, indicating some clues to the correlation for the measure of number of nucleons in OR(QP + QT) using the LCPs (charge of the heavier fragments).

To further strengthen the correlation, the right panels of Fig. 3 give us some interesting features. Just like the isospin asymmetry dependence of nucleons in OR (QP + QT) matter, the multiplicity of free nucleons (charge of the heavier fragments) is increasing (decreasing). Moreover, with the isospin asymmetry, the increasing (decreasing) trend of neutron (proton) contribution in OR matter (Fig. 1) is similar to the behavior of the multiplicity of neutrons (protons) (Fig. 3). In addition, the isospin asymmetry dependence of charges of heavier fragments is also similar to the contribution of protons from the QP + QT (Fig. 1). These represent strong evidence for correlation. The important point to check here is the sensitivity of yield of different kinds of fragments and charges of the heavier fragments with nucleons of OR and QP + QT matter, which are further checked in Fig. 4 by using the power-law fitting method.

From the LCPs, interesting isospin effects are observed with isospin asymmetry of the system. With the increase in the one neutron in the LCPs, that is, from ^{1}H → ^{2}H → ^{3}H and ^{3}He → ^{4}He, the multiplicity changes its trend from decreasing ^{1}H, ^{3}He to increasing for ^{3}H, ^{4}He, respectively. However, with the

TABLE I. τ value extracted from Fig. 4, showing the positive (negative) slope of LCPs with participant (spectator) matter.

Particles	n	p	^{2}H	^{3}H	^{3}He	^{4}He
τ for OR	0.605	0.546	0.815	0.831	1.022	1.180
τ for QP + QT	−0.317	−0.288	−0.423	−0.418	−0.524	−0.599

increase of one proton from ^{3}H to ^{3}He, the multiplicity reveals a sharp change from increasing to decreasing. The neutron-proton distributions within the LCPs are also satisfying the neutron-proton distributions from the OR zone. This indicates the strong correlation between LCPs and OR matter, but the point of interest is which type of LCPs are perfect indicators for OR matter, which is discussed in Fig. 4.

In Fig. 4, the sensitivity of number of nucleons in OR and QP + QT matter with the multiplicity of LCPs, as well as charge of the heavier fragments is checked by fitting the power law of the form $Y = CX^{\tau}$. Positive correlation is observed between OR (QP + QT) nucleons and a multiplicity of LCPs (Z_{max} and Z_{max-1}). Interestingly, from the power-law slope, it is found that, although the multiplicity decreases with the size of light fragments, the slope parameter or sensitivity increases with the fragment size (shown in Table I). This type of prediction is also true for the second-largest fragment and the largest fragment for the QP + QT nucleons. The slope parameters for neutrons (0.6) with nucleons of OR matter (also shown in Table I) and for $Z_{max-1}/A_{projectile}$ with nucleons of QP + QT matter (0.58) (Fig. 4) are almost the same, which reveals the similar sensitivity of the respective matter towards the respective fragments. From here, one can say that if one uses the neutron as a measure for the nucleons of OR matter and $Z_{max-1}/A_{projectile}$ as a measure for the nucleons of QP + QT matter, then the difference of two parameters at semiperipheral geometry, just like in Fig. 2, can act as a probe for the isospin migration or slope of symmetry energy. From Table I, we also observed that there is a linear correlation between the nucleons of OR matter and ^{3}He fragments (i.e., having τ very close to one), which indicates that the ^{3}He can be taken as a direct measure for the nucleons of OR matter.

III. CONCLUSION

In summary, we tried to find an observable to measure density dependence of symmetry energy or its slope by studying the OR and QP + QT matter in intermediate-energy heavy-ion collisions. The difference in the numbers of nucleons of OR to QP + QT matter is particularly sensitive towards the slope of symmetry energy at semiperipheral geometries. This gives us a clue that this observable can act as a probe for the isospin migration. Principally, the yield of neutrons and charge of the second-largest fragment ($Z_{max-1}/A_{projectile}$) could be provided as experimental tools to check the sensitivity of nucleons in OR and QP + QT matter towards the symmetry energy in terms of isospin migration. Interestingly, the nucleons of OR matter have a linear correlation with the yield of ^{3}He (τ close to 1).

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