Effect of isospin dependence of radius on transverse flow and fragmentation in isobaric pairs

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We study the role of nuclear structure effects through radius in reaction dynamics via transverse flow and multifragmentation of isobaric colliding pairs. Our study reveals that isospin-dependent radius [proposed by Royer and Rousseau [Eur. Phys. J. A **42**, 541 (2009)] has significant effect towards isospin effects. The collective flow behavior and fragmentation pattern of neutron-rich system with respect to neutron-deficient system is found to get reversed with isospin-dependent radius compared to that with liquid drop radius.

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The nuclear charge radius is known with less uncertainty because of the highly precise elastic electron-nucleus and muon-nucleus scattering experiments. For a long time, it has been known that the root mean square (rms) radius of a charge distribution increases slower than $A^{1/3}$. The finite thickness of nuclear surface along with the assumption of equal distribution of neutrons and protons (with constant central density) fits the experimental data on elastic electron scattering well and it deviates from the $A^{1/3}$ law by an amount as produced by surface effects. Similarly, the discovery of halo nuclei has also shown that $A^{1/3}$ behavior of radius is no more valid for those nuclei [1]. In this direction, various parametrizations of radii have been proposed during the last three to four decades that have modifications over the liquid drop radii [2–4]. On the other hand, knowledge about the neutron distribution is still lacking. In this context, the availability of radioactive nuclear beams facilities provides an opportunity to study the nuclei far from the line of stability [5] and various studies have been carried out in this direction [6]. Such facilities have made it possible to determine the nuclear interaction radii of β-unstable nuclei. In addition to it, the study of proton and neutron density distributions and the neutron thickness (difference between the proton and neutron root mean square radii) has also become possible. These properties provide fundamental information about the nuclear structure. The neutron skin thickness is a very sensitive probe of the measure of the pressure difference that exists between neutrons and protons and is found to be sensitive to the symmetry energy and equation of state of asymmetric nuclear matter [7–9].

Only a few studies exist in the literature where the role of nuclear structure effect (via radius) on the reaction dynamics has been studied. In low energy reactions, the effect of various forms of radii was found to be less significant in fusion reactions [10]. On the other hand, cluster-decay studies did indicate a quite significant effect on the half-life of emitted clusters [11]. At intermediate energies, in Ref. [12], it has been shown that neutron skin thickness affects the reaction cross section, neutron or proton removal cross section, as well as their ratios. In another recent study by Bansal and collaborators [13], the role of the structural effect on the collective flow has been investigated, where the radii chosen are those which have been incorporated in different theoretical models. The study revealed a strong dependence of the flow on the radius of the colliding nuclei. From all the above reported investigations, it is clear that the radius of the colliding nucleus is an important factor that can affect the reaction dynamics throughout the energy range. Some of the proposed radius parametrizations have different radii for protons and neutrons and thus have explicit isospin dependence in them. Among all these, for the present study, we use the recent one which has modifications over the liquid drop radius and also has isospin dependence. This additional isospin dependence through the nuclear structure effect may alter the isospin physics. Therefore, the aim of this Brief Report is at least twofold:

(i) to see the role of different radii on the reaction dynamics,
(ii) and to study the role of isospin dependence of radius on isospin effects in collective flow and fragmentation.

The present study is carried out within the framework of the isospin-dependent quantum molecular dynamics (IQMD) model [14], which has been widely used to study isospin effects in reaction studies at intermediate energies [15].

We simulate the reactions of isobaric pairs (having the same liquid drop radius) of $^{60}\mathrm{Ca} + {}^{60}\mathrm{Ca}$ and $^{60}\mathrm{Zn} + {}^{60}\mathrm{Zn}$ at incident energy of 100 MeV/nucleon using the soft equation of state throughout the range of colliding geometry. We use the standard isospin- and energy-dependent nucleon-nucleon (nn) cross section $\sigma = 0.8\ \sigma_{NN}{}^{\mathrm{free}}$. The details about the elastic and inelastic cross sections for proton-proton and proton-neutron collisions can be found in Ref. [14]. The cross sections for the neutron-neutron collisions are assumed to be equal to the proton-proton cross sections. For transverse flow, we use "*directed transverse momentum* $\langle p_x^{\mathrm{dir}}\rangle$". To study the effect of radius and its isospin dependence, we use, apart from the liquid drop radius, the recent parametrized form of the radius proposed by Royer and Rousseau in 2009 that reads as

$$R = 1.2332A^{1/3} + 2.8961A^{-2/3} - 0.18688A^{1/3}I \text{ fm} \qquad (1)$$

with

$$I = \frac{N - Z}{A}, \qquad (2)$$

that has isospin dependence through the last term.

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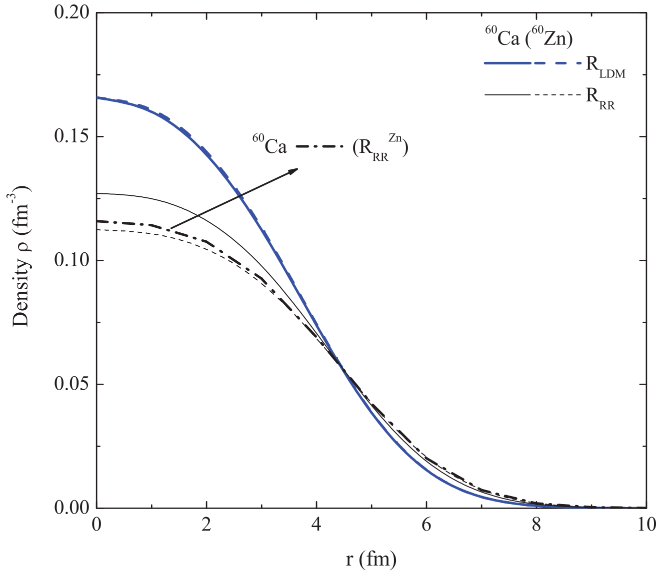

FIG. 1. (Color online) The density profile $\rho(r)$ for a ^{60}Ca and ^{60}Zn nucleus initialized in IQMD with liquid drop radius (thick lines) and Royer and Rousseau radius (thin lines) at time $t = 0$ fm/c. Dash-dotted line represents the case of ^{60}Ca nucleus initialized with same Royer and Rousseau radius without isospin dependence.

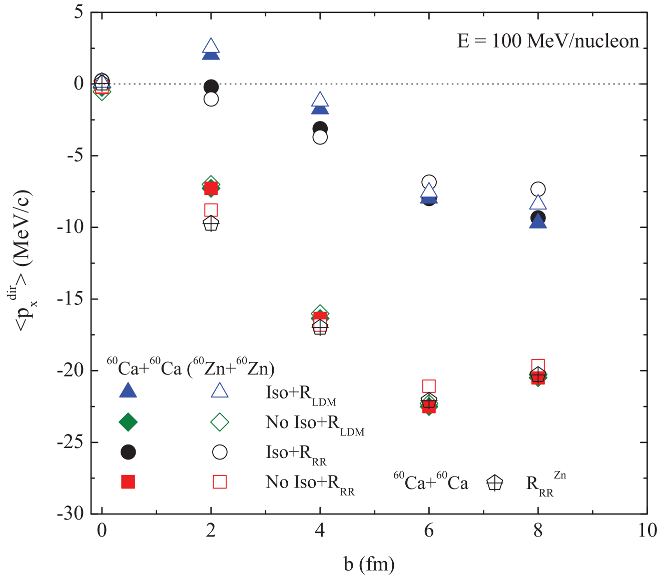

FIG. 2. (Color online) The transverse in-plane flow $\langle p_x^{dir}\rangle$ as a function of impact parameter for the reactions of ^{60}Ca + ^{60}Ca and ^{60}Zn + ^{60}Zn at incident energy of 100 MeV/nucleon. Various symbols are explained in text and in the figure.

In Fig. 1, we display the density profile of ^{60}Ca (solid lines) and ^{60}Zn (dashed lines) nuclei that are generated in IQMD using the liquid drop radius (labeled by R_{LDM}) (thick lines) and Royer and Rousseau radius (labeled by R_{RR}) (thin lines) at time $t = 0$ fm/c. From the figure, we see that the density profile is the same for both the nuclei using the liquid drop radius initialization, as it should be. On the other hand, the density profile gets extended for the ^{60}Zn nucleus compared to the ^{60}Ca nucleus when the isospin-dependent radius is used. This happens as the radius for ^{60}Zn gets larger compared to that for the ^{60}Ca nucleus. Thus, we see that with isospin dependence of radius, neutron-rich nucleus becomes compact compared to the neutron-deficient one and this may lead to different reaction dynamics. The Royer and Rousseau radius, having isospin dependence, changes the radius of the isospin symmetric nucleus (^{60}Zn, in the present case) also. Therefore, to see the role of isospin in the radius explicitly, we also plot the density profile of the ^{60}Ca nucleus by initializing it with the same R_{RR} as that of ^{60}Zn (i.e, without isospin dependence). We now see that density profile of ^{60}Ca gets extended compared to that with actual R_{RR} for ^{60}Ca (compare dash-dotted and thin solid lines) and also becomes close to that of ^{60}Zn (compare dash-dotted and dashed lines) because of the same radii of both. Therefore, by incorporating the isospin dependence of the radius, the neutron-rich nucleus becomes compact and, thus, can affect the dynamics.

In Fig. 2, we display the impact parameter dependence of $\langle p_x^{\mathrm{dir}}\rangle$ for the reactions of ^{60}Ca + ^{60}Ca (solid symbols) and ^{60}Zn + ^{60}Zn (open) using a normal liquid drop radius as well as with the Royer and Rousseau parametrization. From the figure, we see that transverse flow increases for semicentral reactions and then again decreases (see triangles). We find that transverse flow is higher for the reactions of ^{60}Zn + ^{60}Zn compared to ^{60}Ca + ^{60}Ca reactions with liquid drop radius (see triangles). This is because of the dominance of the Coulomb potential in isospin effects compare to the symmetry energy and *nn* scattering cross section, as has been predicted in Ref. [16], where the Coulomb potential dominates in the isospin effects for isobaric colliding pairs. To be sure of this, we also calculated the transverse flow by neglecting the Coulomb potential, symmetry potential, and isospin independent *nn* scattering cross section (see diamonds). We notice that transverse flow decreases at all the colliding geometries due to the weakening of repulsive forces (because of the absence of Coulomb and symmetry potential). Also, the transverse flow now becomes almost equal in both the reactions, thus, signifying the dominance of the Coulomb potential in isospin degree of freedom. It is worth mentioning that to explicitly see the dominance of Coulomb repulsion in isospin effects, only the Coulomb potential should be turned off (and not the symmetry potential and with isospin dependence of *nn* scattering cross section as done in Ref. [16]). Had we switched off only the Coulomb potential, the behavior of isospin effects in the transverse flow for the reactions of ^{60}Ca + ^{60}Ca and ^{60}Zn + ^{60}Zn gets reversed with a significant difference between the two. But, since we have neglected all the isospin effects, therefore, the difference between the two systems vanishes (because of a counteracting symmetry potential and scattering cross section). A similar dominance of the Coulomb potential in the fusion cross section has been found for fusion reactions of isotonic pairs [17]. Next, to see the role of isospin dependence of the radius, we initialized the nucleus of ^{60}Ca and ^{60}Zn by the Royer and Rousseau parametrization and then calculated the transverse flow (circles). We find that for semicentral reactions, the above-mentioned trend gets reversed, the flow now becomes higher for the ^{60}Ca + ^{60}Ca reaction. This is due

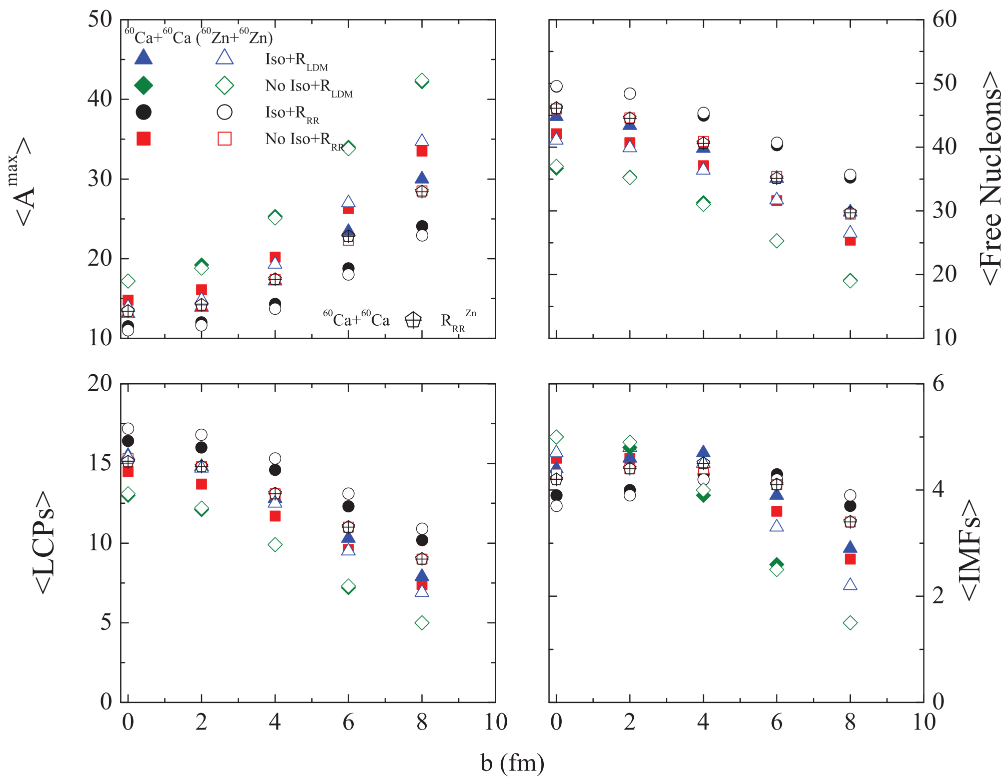

FIG. 3. (Color online) The heaviest fragment A^{max}, free nucleons, light charged particles (LCPs), and intermediate mass fragments (IMFs) as a function of impact parameter for the reactions of ^{60}Ca + ^{60}Ca and ^{60}Zn + ^{60}Zn. Symbols have the same meaning as in Fig. 2.

to the fact that the R_{RR} radius is more for the ^{60}Zn nucleus compared to ^{60}Ca. Due to this enhanced radius, the density profile gets extended, which in turn, will lead to weak repulsive forces, and thus, transverse flow decreases. On the other hand, flow behavior remains the same at peripheral collisions and radius effect does not come into the picture. This is because of the less overlapping region in peripheral collisions, so the density achieved will be less and therefore, density-dependent interactions would not dominate and the Coulomb potential still dominates. To further strengthen our point, we increase the normal liquid drop radius in IQMD by 30% and 60% and calculate the flow for the reactions of ^{60}Ca + ^{60}Ca. Again, we found that by increasing the radius, flow decreases (results not shown here). Similarly, when all isospin effects are neglected (by switching off the Coulomb and symmetry potential and with isospin independent scattering cross section) with R_{RR} parametrization, the transverse flow is higher for the reactions of ^{60}Ca + ^{60}Ca (solid squares) compared to the reactions of ^{60}Zn + ^{60}Zn at semicentral reactions (which otherwise was the same for both with a liquid drop radius, see diamonds). Thus, we see that the isospin dependence of radius has significant effect on transverse flow. As we have mentioned earlier, the size of the ^{60}Zn nucleus gets modified with R_{RR} (because of modifications over the liquid drop radius). Therefore, to see explicitly the role of the isospin-dependent radius, we calculate the flow for the reactions of ^{60}Ca + ^{60}Ca by initializing the nucleus of ^{60}Ca with the Royer and Rousseau radius, but without isospin dependence. From the figure, we see that for semicentral reactions, flow decreases further compared to that with actual R_{RR} having isospin dependence (compare solid squares and cross pentagons). Thus, we see that the radius and its isospin dependence plays a significant role in isospin effects of transverse flow.

Next, we investigate the role of the radius and its isospin dependence on the fragmentation pattern. Figure 3(a), (b), (c), and (d) display the mass of the heaviest fragment (A^{max}), free nucleons (FNs), light charged particles ($2 \leqslant A \leqslant 4$) (LCPs), and intermediate mass fragments ($5 \leqslant A \leqslant A/3$) (IMFs). The symbols have the same meaning as in Fig. 2. From Fig. 3(a), we see that A^{max} (free nucleons) is higher (lower) for the reactions of ^{60}Zn + ^{60}Zn compared to ^{60}Ca + ^{60}Ca with a liquid drop radius. This is because of the repulsive Coulomb interaction that will throw more matter out of the participant zone and thus leading to bigger A^{max} (lesser free nucleons). This effect is dominating at peripheral collisions. The difference vanishes when we neglect all isospin effects (see diamonds). On the other hand, with the Royer and Rousseau radius, the A^{max} is bigger for ^{60}Ca + ^{60}Ca reactions (circles). It is expected that total number of collisions should be higher in the case of a smaller radius which will lead to smaller A^{max}. But due to a less available phase-space, most of the collisions will be Pauli blocked and thus A^{max} would be bigger in the case of a smaller radius. Moreover, in the case of bigger nuclei, the density profile will smoothen out and, therefore, the role of the attractive mean field decreases which will also lead to smaller A^{max}. The difference though is small, because of the counterisospin effect which is operating. When we neglect all isospin effects with the Royer and Rousseau radius initialization (squares), the difference increases, thus pointing towards the significant role of isospin dependence of the radius. The role of an explicit isospin-dependent radius on the fragmentation of ^{60}Ca + ^{60}Ca reactions is also investigated (crossed pentagons) as done earlier. We notice that A^{max} for the reactions of ^{60}Ca + ^{60}Ca decreases compared to that with actual R_{RR} for the ^{60}Ca nucleus and becomes the same as that for ^{60}Zn + ^{60}Zn reactions. Similarly, multiplicities of light charged particles and intermediate mass fragments also show the role of radius, and behave accordingly. The above-mentioned reactions are highly neutron-rich reactions of ^{60}Ca + ^{60}Ca. To see whether the above results persists for experimentally accessible reactions also, we simulate the reactions of ^{48}Ca + ^{40}Ca and ^{48}Cr + ^{40}Ca at the same reaction conditions. Our findings reveal that the role of the isospin-dependent radius is still there, but, as expected, with a lesser magnitude (results not shown).

We investigated the role of the radius and its isospin dependence on reaction dynamics via studying transverse flow and fragmentation of neutron-rich and neutron-deficient isobaric colliding pairs. Our findings revealed that the radius as well as its isospin dependence has a significant effect on isospin physics and, in fact, the role of isospin on flow and fragmentation gets reversed with explicit isospin in radius.

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