Isospin effects in flow, its disappearance and other related phenomena

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Abstract. We study the role of isospin degree of freedom in reaction dynamics via transverse in-plane flow and its disappearance for isobaric as well as isotopic colliding pairs. Our findings reveal that for isobaric pairs, the Coulomb potential is dominant over the symmetry energy throughout the mass range. Next, we shift to isotopic colliding pairs and find that the transverse flow is sensitive to the symmetry energy and its density dependence in Fermi energy region. Motivated by this, we also study the energy of vanishing flow as a function of isospin ratio (N/Z) for various isotopes. We find that N/Z dependence of the energy of vanishing flow is sensitive to the symmetry energy and insensitive to isospin dependence of nucleon-nucleon (nn) cross section. We also study thermalization achieved in reactions at incident energy equal to the corresponding energies of vanishing flow.

1. Introduction
The recent advancements in the radioactive ion beam facilities have generated a lot of interest in the isospin physics. The role of isospin degree of freedom comes into picture through nuclear equation of state and in-medium nucleon-nucleon cross section. Heavy-ion collisions induced by neutron-rich nuclei serve as an excellent tool to study the role of isospin degree of freedom via properties of neutron-rich nuclear matter. A lot of theoretical and experimental efforts have been carried out for the past decade to study the role of isospin degree of freedom in the collective transverse in-plane flow, multifragmentation and nuclear stopping. Isospin effects in the collective flow were first predicted by Li et al [1]. An year later, the isospin effects in the flow and in its disappearance were confirmed experimentally by Pak et al [2] for the reactions of $^{58}$Fe+$^{58}$Fe and $^{58}$Ni+$^{58}$Ni. The study showed that neutron-rich colliding pair has higher energy of vanishing flow (at which transverse in-plane flow disappears). The experimental measurements were also compared with theoretical calculations of BUU model. The calculated results were found to under predict the data throughout the range of colliding geometry. Another attempt to study isospin effects is done by Chen et al [3] using IQMD model and their calculations over predict the data. So, firstly, we shall aim to see isospin effects in the collective flow and its disappearance.

In connection to the isospin physics, the nuclear symmetry energy and its density dependence is another hot topic these days. Though its value at sub-saturation density region has been constrained by extensive efforts on both theoretical and experimental fronts, behavior of the symmetry energy above the saturation density is still unknown. Since the symmetry energy is not a directly measurable quantity, so its value has to be extracted from observables related...
to it. The observables like isospin diffusion, isospin fractionation, n/p ratio, differential flow of neutrons and protons, $t/3\text{He}$ ratio, $\pi^-/\pi^+$ ratio, $\Sigma^-/\Sigma^+$ ratio and K$^0$/K$^+$ ratio etc. have been proposed as sensitive probes of the symmetry energy. For details, reader is referred to Ref. [4]. At sub-saturation density region, the symmetry energy has been constrained and is of the form $32 \left(\frac{E_w}{\rho}\right)^{\gamma}$ with $\gamma = 0.4-1.1$. On the other hand, at supra-saturation density region, its value is largely unconstrained. In this context, we will also discuss the sensitivity of transverse in-plane flow towards the symmetry energy and its density dependence at supra-saturation region.

The concept of nuclear equation of state relies on global or at least local equilibrium. Also, the hydrodynamical concepts relies on the equilibration of the system and such models are applicable for those systems which are not far from equilibrium. Therefore, the question of equilibration is also important and it is a matter of great concern to see whether hot and compressed nuclear matter thermalizes or not. Finally, we will also shed light on the equilibration of systems at incident energies equal to their corresponding energies of vanishing flow. The present study is carried out within the framework of the isospin-dependent quantum molecular dynamics (IQMD) model which is an extension of the QMD model [5]. The details of the model can be found in Ref. [6].

2. Results and discussions

Firstly, we will study the role of isospin degree of freedom on the transverse in-plane flow for isobaric colliding pairs. For the respective study, we simulate the reactions of $^{58}\text{Ni}+^{58}\text{Ni}$ using a soft equation of state along with momentum-dependent mean field. We also use the standard energy-dependent free nn cross section $\sigma_{\text{nn}}^{\text{free}}$ as well as the cross section reduced by 20%, i.e. $\sigma = 0.8 \sigma_{\text{nn}}^{\text{free}}$. It is worth mentioning that the choice of reduced cross section has been motivated by many previous studies [7]. The details about the elastic and inelastic cross sections for proton-proton and proton-neutron collisions can be found in [6]. The transverse in-plane flow is calculated using “directed transverse momentum $\langle p_{x,\text{dir}}^{\text{dir}} \rangle$” which is defined as [8, 9]

$$\langle p_{x,\text{dir}}^{\text{dir}} \rangle = \frac{1}{A} \sum_{i=1}^{A} \text{sign}\{Y(i)\}p_{x}(i),$$  \hspace{1cm} (1)

where $Y(i)$ and $p_{x}(i)$ are, respectively, the rapidity and the momentum of the $i^{th}$ particle. The rapidity is defined as

$$Y(i) = \frac{1}{2} \ln \frac{E(i) + p_{z}(i)}{E(i) - p_{z}(i)},$$  \hspace{1cm} (2)

where $E(i)$ and $p_{z}(i)$ are, respectively, the energy and longitudinal momentum of the $i^{th}$ particle. In this definition, all the rapidity bins are taken into account. The reactions are simulated till transverse in-plane flow saturates. It is worth mentioning that though earlier studies show independence of the balance energy on particle type [2, 10, 11], due to recent improvements in experiments, the balance energy is found to be dependent on emitted particle type [12].

In Fig. 1, we display the time evolution of $\langle p_{x,\text{dir}}^{\text{dir}} \rangle$ for the reactions of $^{58}\text{Ni}+^{58}\text{Ni}$ (left panels) and $^{58}\text{Fe}+^{58}\text{Fe}$ (right) at incident energies around the energy of vanishing flow at all colliding geometries using $\sigma = 0.8 \sigma_{\text{nn}}^{\text{free}}$ and SMD (soft+MDI) equation of state. The choice of impact parameters is guided by experimental results of Ref. [2]. The solid and dashed lines represent the flow at higher and lower value of incident energy. From the figure, we see that at the start of the reaction, $\langle p_{x,\text{dir}}^{\text{dir}} \rangle$ is negative due to dominance of the mean field, reaches a minimum and then increases because of the dominance of binary nn collisions. The energy of vanishing flow is calculated using linear fit between the two incident energies.

In Fig. 2(a), we display the energy of vanishing flow (EVF) as a function of impact parameter. Solid (open) symbols represent the results for $^{58}\text{Ni}+^{58}\text{Ni}$ ($^{58}\text{Fe}+^{58}\text{Fe}$). The stars represent the
experimental data whereas diamonds correspond to our theoretical calculations. The squares (circles) represent the IQMD (IBUU) calculations of [3] ([2]). The lines are only to guide the eye. Our results of the EVF and experimental data for the reaction $^{58}\text{Fe}+^{58}\text{Fe}$ have been slightly offset in the horizontal direction for clarity. The vertical lines on the data points represent statistical errors. From the figure, we notice that neutron-rich colliding pair of $^{58}\text{Fe}+^{58}\text{Fe}$ has higher EVF compared to $^{58}\text{Ni}+^{58}\text{Ni}$. This is attributed to that fact that the scattering cross section for neutron-proton collisions is three times as that for neutron-neutron or proton-proton...
collisions. Since, in neutron-rich system, neutron-neutron collision pairs are more, this in turn, will reduce the collision flow, and thus leads to higher EVF [13]. We also find that the results of IBUU calculations [2] under-predict the data whereas the IQMD calculations of [3] over-predict the data consistently. We find that our theoretical calculations are much closer to the experimental data. To see the effect of reduced nn cross section, we also calculate the EVF by taking full cross section, i.e., $\sigma = \sigma_{nn}^{\text{free}}$. The results are displayed in Fig. 2(b). We find that the EVF decreases by huge amount for both the colliding pairs. This is due to fact that with full cross section, flow due to binary nn collisions increases, thus reducing the EVF.

In literature, the isospin effects in flow have been explained as the competition between the Coulomb force, symmetry energy, nn cross section and surface properties. But the relative importance among them was not clear. Motivated by the above good agreement of the data, next, we calculate the EVF throughout the mass range by taking two isobaric pairs having isospin ratio (N/Z) to be 1.0 and 1.4. In particular, we simulate the reactions $^{24}\text{Mg} + ^{24}\text{Mg}$, $^{58}\text{Cu} + ^{58}\text{Cu}$, $^{72}\text{Kr} + ^{72}\text{Kr}$, $^{96}\text{Cd} + ^{96}\text{Cd}$, $^{120}\text{Nd} + ^{120}\text{Nd}$, $^{135}\text{Ho} + ^{135}\text{Ho}$, having N/Z = 1.0 and reactions $^{24}\text{Ne} + ^{24}\text{Ne}$, $^{58}\text{Cr} + ^{58}\text{Cr}$, $^{72}\text{Zn} + ^{72}\text{Zn}$, $^{96}\text{Zr} + ^{96}\text{Zr}$, $^{120}\text{Sn} + ^{120}\text{Sn}$, and $^{135}\text{Ba} + ^{135}\text{Ba}$, having N/Z = 1.4, respectively at $b = 0.35-0.45$. In Fig. 3, we display the system size

![Figure 2](image_url)
dependence of the EVF for N/Z = 1.0 (solid symbols) and 1.4 (open). From the figure, we see that the EVF follows a power law behavior \( \propto A^\tau \) with the system size. The power law parameter \( \tau = -0.45 \pm 0.01 \) and \( -0.50 \pm 0.01 \) for N/Z = 1.4 and 1.0, respectively. The larger value of \( \tau \) in systems with lower isospin ratio is due to dominance of the Coulomb potential in case of systems with more protons. To demonstrate the dominance of the Coulomb potential, we reduce the Coulomb potential by a factor of 100 and calculate the EVF again. The results are represented by diamonds. Now we see that neutron-rich systems have lower EVF throughout the mass range. Also, the values of \( \tau \) are now \(-0.28 \pm 0.02\) and \(-0.25 \pm 0.02\) for isospin ratios of 1.4 and 1.0, respectively. The decrease in the EVF for neutron-rich systems is because of the fact that the reduced Coulomb repulsion leads to higher EVF. As a result, the density achieved during the course of the reaction will be more due to which the impact of the repulsive symmetry energy will be more in neutron-rich systems, leading in less EVF for neutron-rich systems and hence to the opposite trend for \( \tau \) values for two different cases (Coulomb full and reduced). To check this point we have also calculated the EVF by reducing the strength of both symmetry energy as well as Coulomb potential for isobaric pairs with combined mass of the system = 116 and 270 (shown by blue triangles in Fig. 3(a)). We find that both the systems of a given isobaric pair have same EVF. The above discussion clearly points towards the dominance of Coulomb repulsion over symmetry energy for medium as well as heavy mass systems whereas their impact is small in lighter masses. In Fig. 3(b), we display the percentage difference \( \Delta EVF(\%) \) between the systems of isobaric pairs as a function of total reacting mass of system.

**Figure 3.** (a) EVF as a function of combined mass of system. (b) The percentage difference \( \Delta EVF(\%) \) as a function of combined mass of system. Solid (open) symbols are for systems having isospin ratio of 1.0 (1.4). Various symbols and lines are explained in the text. Figure is taken from Ref. [14].
Figure 4. (a) The time evolution of transverse in-plane flow $<p_{x}^{\text{dir}}>$ for $^{60}\text{Ca}+^{60}\text{Ca}$ reactions at 100 MeV/nucleon for various forms of the symmetry energy. (b) The decomposition of $<p_{x}^{\text{dir}}>$ into mean field ($<p_{x}^{\text{dir}}>_\text{mf}$) and collision contribution ($<p_{x}^{\text{dir}}>_\text{coll}$). Various symbols are explained in the text.

where $\Delta EV F(\%) = \frac{EV F_{1}^{4.0} - EV F_{1}^{0.0}}{EV F_{1}^{0.0}} \times 100$. Superscripts to the EVF represent different isospin ratio. The half filled (green) circles are for full Coulomb and half filled (orange) diamonds are for reduced Coulomb. Negative (positive) values of $\Delta EV F(\%)$ shows that the EVF$^{1.0}$ is more (less) than EVF$^{1.4}$. From the figure (circles), we see that the percentage difference between the two masses of a given pair is larger for heavier masses compared to the lighter ones. However, this trend is not visible when we reduce the Coulomb (diamonds). The values of $\Delta EV F(\%)$ is almost constant for medium and heavy masses. Thus, we find that the Coulomb potential is dominant in isospin effect in flow over the symmetry energy for isobaric pairs [14].

In order to keep the Coulomb force same, and to look for observables sensitive to the symmetry energy, next, we have carried out the reactions of isotopic pairs. Firstly, we will discuss the sensitivity of the transverse flow towards density dependence of the symmetry energy for the reactions of neutron-rich colliding pair of $^{60}\text{Ca}+^{60}\text{Ca}$ at incident energy of 100 MeV/nucleon at $b = 0.2-0.4$. The various forms of symmetry energy used for present study are: $E_{\text{sym}} \propto F_1(u)$, $F_2(u)$, and $F_3(u)$, where $u = \frac{\rho}{\rho_0}$, $F_1(u) \propto u$, $F_2(u) \propto u^{0.4}$, $F_3(u) \propto u^2$, and $F_4$ represents
Figure 5. The EVF as a function of isospin ratio for various systems having symmetry energy of the form $F_1(u)$. Various symbols are explained in the text. Lines represent linear fit.

calculations without symmetry energy. In Fig. 4(a), we display the time evolution of transverse flow for different forms of the symmetry energy. The solid, dash-dotted, dash-double dotted lines represent the calculations for $F_1(u)$, $F_2(u)$ and $F_3(u)$. The dashed lines represent lines represent calculations without symmetry energy. From the figure, we see that the transverse flow is sensitive to the symmetry energy in Fermi energy region. We notice that the flow decreases when we have not included the symmetry energy in calculations because of the weakening of repulsive forces. We also see that the flow is same for the symmetry energy of the form $F_3(u)$ as that without symmetry energy. This is due to the fact that behavior of low density particles during initial stage of the reaction (when density is greater than normal nuclear matter density, i.e., supra-saturation density region) decides the final value of flow and strength of symmetry potential for low density particles will be less for $F_3(u)$. The detailed mechanism has been explained in Ref. [15]. It is worth mentioning that the behavior of flow with the stiffness of the symmetry energy is different to what has been predicted in Ref. [16] because of different choice of equation of state (Soft + MDI in Ref. [16]). The above calculations with SMD EOS are in progress and preliminary results show that the behavior of flow is similar as that in Ref. [16]. In Fig. 4(b), we decompose the total $<p_{dir}^x>$ into mean field ($<p_{dir}^x>_{mf}$) and collision contribution ($<p_{dir}^x>_{coll}$). From the figure, we see that the flow due to mean field changes with different density dependence of the symmetry energy, whereas, collisions contribution to the flow does not alter much. Thus, we can say that the transverse in-plane flow can serve a
good probe of the symmetry energy at supra-saturation densities.

As a next step, we studied the energy of vanishing flow as a function of N/Z for various systems having isospin ratio varying from 1.0 to 2.0. We simulate the reactions of isotopic colliding pairs of $^{40-60}$Ca+$^{40-60}$Ca; $^{56-84}$Ni+$^{56-84}$Ni; $^{81-120}$Zr+$^{81-120}$Zr; $^{100-150}$Sn+$^{100-150}$Sn; and $^{110-162}$Xe+$^{110-162}$Xe, having symmetry energy of the form $F_{sym}$. In Fig. 5, we display N/Z dependence of the EVF for isotopes of Ca+Ca (squares), Ni+Ni (circles), Zr+Zr (triangles), Sn+Sn (diamonds), and Xe+Xe (pentagons). From the figure, we see that the EVF decreases with increasing isospin ratio and follows a linear behavior ($\propto m^* N/Z$) with N/Z. The magnitude of slopes are 33, 25, 21, 18, and 15 for the series of Ca, Ni, Zr, Xe and Sn, respectively. Since we are having isotopes of elements so Coulomb potential will be same throughout the given isotopic series. For a given series, as the isospin ratio increases, the mass and neutron content also increases. The increase in neutron content will lead to dominant role of the repulsive symmetry energy and thus will lead to decrease in the EVF value. Similarly, increase in mass will also decrease the EVF along isotopic series. The relative importance among them is not clear.

Therefore, as a next step, we see the effect of symmetry energy on the N/Z dependence of the EVF throughout the mass range. For this, we perform calculations without the symmetry energy (labeled as $E_{sym}^{off}$ or $F_{sym}^{off}$) and calculate the EVF for two extreme mass systems Ca+Ca and Xe+Xe throughout the N/Z range. The results are displayed in Fig. 6. The solid symbols represent calculations with the symmetry energy. From the figure, we see that the EVF increases for both the masses on reducing the strength of symmetry potential. This happens because of the repulsive nature of the symmetry energy and in its absence, the repulsive forces are weakened and this, in turn, reduces the flow. The change in the EVF also increases with increasing neutron content indicating greater role of the symmetry energy in more neutron-rich systems. Moreover, the slope of N/Z dependence of the EVF decreases drastically for both the systems, thus signifying that symmetry energy effects dominate over mass effects in isospin dependence of the EVF. The magnitude of slope now becomes 11 and 1 for Ca and Xe, series respectively. From the figure, we also see that percentage change ($\Delta m(\%) = \frac{m - m_{sym}}{m} \times 100$) in the slope for Ca (Xe) series is 67% (93%). Interestingly, we find that the EVF is same throughout the N/Z range for Xe series when we switch off the symmetry energy, whereas for Ca series there is a small decrease in the EVF with N/Z. To further explore this point, we make the cross section isospin independent ($\sigma_{np} = \sigma_{nn}$ or $\sigma_{pp}$) and calculate the EVF for three isotopes having isospin ratio 1.0, 1.6 and 2.0 for both Ca+Ca (half filled squares) and Xe+Xe (half filled pentagons) reactions (labeled as $E_{sym}^{off}+\sigma_{non-isosp}$). We find that the EVF increases further (for both colliding systems) on making the cross section isospin independent as the net magnitude of nn cross section decreases, which in turn, will decrease the collision flow. We also see that the slope of N/Z dependence of EVF increases when we do calculations without symmetry energy with isospin independent cross section as compared to calculations without symmetry energy but with isospin-dependent cross section. The magnitude of slope is 22 (6) for Ca (Xe) series. This is because the EVF increases by large amount for systems having less isospin content (for both Ca+Ca and Xe+Xe reactions). This is due to the fact that the neutron-proton collision pairs are greater than neutron-neutron collision pairs in systems having isospin ratio of 1.0. On the other hand, in neutron-rich reactions having isospin ratio of 2.0, the neutron-proton collision pairs are approximately same as that for neutron-neutron collision pairs. Also, the neutron-proton cross section is three time as that of neutron-neutron of proton-proton cross section. Therefore, when we make the cross section isospin independent, change in collisions probability is more in systems having less isospin content compared to neutron-rich systems. Thus, in addition to transverse flow, N/Z dependence of the EVF can also act as a sensitive probe of the symmetry energy.

Lastly, we also shed light on the equilibrium aspects achieved during these reactions. From different studies of heavy-ion collisions at intermediate energies, it has become clear now
that there is no complete equilibration reached in heavy-ion systems even at large reaction times. Therefore, it also becomes important to study the equilibration process. The degree of equilibration is related to the anisotropy ratio \(< R_a >\) and relative momentum \(< K_R >\). The \(< R_a >\) is defined as \[17, 18\]

\[
< R_a > = \frac{\sqrt{p_x^2} + \sqrt{p_y^2}}{2\sqrt{p_z^2}}.
\]

This anisotropy ratio is an indicator of the global equilibrium of the system. This represents the equilibrium of the whole system and does not depend on the local positions. The full global equilibrium averaged over large number of events would correspond to \(< R_a >\) values close to 1. The second quantity, the relative momentum \(< K_R >\) of two colliding Fermi spheres, is defined as \[17\]
Figure 7. The time evolution of the anisotropy ratio \(< R_a >\) (upper panel) and relative momentum \(< K_R >\) (lower panel) for various systems having \(N/Z = 1.0\). Analysis is made at corresponding EVF. Shaded portion represents the high dense phase of the reaction (corresponding to \(\rho/\rho_0 > 1.0\)). Figure is taken from Ref. [18].

\[< K_R > = < |\vec{P}_P(\vec{r}, t) - \vec{P}_T(\vec{r}, t)| >, \] (4)

where

\[\vec{P}_i(\vec{r}, t) = \sum_{j=1}^{A} \frac{\vec{P}_j(t)\rho_j(\vec{r}, t)}{\rho_j(\vec{r}, t)} \quad i = 1, 2. \] (5)

Here \(\vec{P}_j\) and \(\rho_j\) are the momentum and density of the \(j\)th particle and \(i\) stands for either projectile or target.

In Fig. 7, we display the time evolution of the anisotropy ratio \(< R_a >\) (upper panel) and relative momentum \(< K_R >\) (lower panel) for different system masses having isospin ratio of 1.0 at their corresponding energies of vanishing flow (calculated from Fig. 4). From the figure 7(a) (upper panel), we see that the anisotropy ratio increases as the reaction proceeds and finally saturates after the high density phase (see shaded region) is over. It signifies that the nucleon-nucleon binary collisions happening after the high density phase do not change the momentum space significantly. We also notice an insignificant influence of the system size on the anisotropy ratio. From the figure 7(b) (lower panel), we see that the relative momentum decreases as the reaction proceeds. Smaller value of \(< K_R >\) at the end of the reaction indicates better local thermalization of the matter. From the figure, we also notice that even at the expansion stage...
(after say 30 fm/c), $< R_a >$ values are still less than 1 as well as $< K_R >$ values are greater than zero. This means that for the heavy-ion systems, even at the expansion stage of the collision, the full equilibrium is not reached \[18\].

3. Summary

In summary, we have studied the isospin effects in transverse flow for isobaric and isotopic colliding pairs throughout the mass range for semiperipheral collisions. Our findings revealed that in isobaric pairs, neutron-rich systems have higher energy of vanishing flow, due to the dominance of Coulomb potential. The transverse flow in neutron-rich systems is found to be sensitive to the symmetry energy and its density dependence. We have also studied N/Z dependence of the energy of vanishing flow for isotopic pairs and found it to be sensitive to the symmetry energy and insensitive to isospin dependence of nn cross section. Finally, we have investigated equilibration aspects.

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