On the participant-spectator matter and thermalization of neutron-rich systems in heavy-ion collisions

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We study the participant-spectator matter at the energy of vanishing flow for neutron-rich systems. Our study reveals similar behaviour of participant-spectator for neutron-rich systems as for stable systems and also points towards nearly mass independence behaviour of participant-spectator matter for neutron-rich systems at the energy of vanishing flow. We also study the thermalization reached in the reactions of neutron-rich systems.

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The isospin physics has attracted lot of attention of the present nuclear physics researchers around the world for the past decade. The establishment and upcoming radioactive ion beam (RIB) facilities provide a major boon to this [1, 2]. RIBs provide the possibility to study the nuclear matter under the extreme conditions of isospin asymmetry. Heavy-ion reactions induced by neutron-rich matter provide a unique opportunity to explore the isospin dependence of in-medium nuclear interactions, since isospin degree of freedom plays an important role in heavy-ion collisions through both nuclear equation of state (EOS) and in-medium nucleon-nucleon cross section. Role of isospin degree of freedom has been investigated in collective flow and its disappearance (energy at which flow disappears is called energy of vanishing flow (EVF) or balance energy (E_{bal})) for the past decade. Isospin effects in flow were first predicted by Pak et al. [3] These isospin effects are due to the competition among various reaction mechanisms like Coulomb force, symmetry energy, isospin dependence of cross section, and surface effects. Though many studies are available on the energy of vanishing flow, very few studies exist in the literature that are carried out to study other heavy-ion phenomena at the balance energy [4–7]. Balance energy results due to the counterbalancing of the attractive mean field and repulsive nucleon-nucleon collisions. In terms of theoretical description, it is the relative dominance of real and imaginary parts of G-matrix which decides the fate of a reaction. The dominance of nucleon-nucleon collisions at high incident energies makes the imaginary part very significant. However, both real and imaginary parts of complex G-matrix are equally important at intermediate energies. This picture can also be looked in terms of participant-spectator matter and fireball concept. In Ref. [7], Sood and Puri studied the participant-spectator matter and nuclear dynamics for stable systems. The study revealed that for stable systems (N/Z ≃ 1), participant-spectator matter at E_{bal} is quite insensitive to the mass of the colliding system. It, therefore, can act as a barometer for the study of balance energy. No study exists in literature to demonstrate how these observables behave for neutron-rich systems. Here we plan to extend the above study for the neutron-rich systems and to look whether the above participant-spectator demonstration still holds for systems lie far away from the stability line. The present study is carried out within the framework of isospin-dependent quantum molecular dynamics (IQMD) model [8].

We simulate the reactions of Ca+Ca, Ni+Ni, Zr+Zr, Sn+Sn, and Xe+Xe series having N/Z = 1.0, 1.6 and 2.0. In particular, we simulate the reactions of $^{40}$Ca+$^{40}$Ca
(105), $^{52}$Ca+$^{52}$Ca (85), $^{60}$Ca+$^{60}$Ca (73); $^{58}$Ni+$^{58}$Ni (98), $^{72}$Ni+$^{72}$Ni (82), $^{84}$Ni+$^{84}$Ni (72); $^{81}$Zr+$^{81}$Zr (86), $^{104}$Zr+$^{104}$Zr (74), $^{120}$Zr+$^{120}$Zr (67), $^{100}$Sn+$^{100}$Sn (82), $^{129}$Sn+$^{129}$Sn (72), $^{150}$Sn+$^{150}$Sn (64) and $^{110}$Xe+$^{110}$Xe (76), $^{140}$Xe+$^{140}$Xe (68) and $^{162}$Xe+$^{162}$Xe (61) at an impact parameter of $b/b_{\text{max}} = 0.2-0.4$ at the incident energies equal to balance energy. The values in the brackets represent the balance energies for the systems. We use a soft equation of state along with the standard isospin- and energy-dependent cross section reduced by 20%, i.e. $\sigma = 0.8 \sigma_{\text{free}}$. The reactions are followed till the transverse in-plane flow saturates. It is worth mentioning here that the saturation time varies with the mass of the system. Saturation time is about 100 (150 fm/c) in lighter (heavy) colliding nuclei in the present energy domain. We use the quantity "directed transverse momentum $\langle p_{x}^{\text{dir}} \rangle$" to define the nuclear transverse in-plane flow, which is defined as [7, 8]

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

where $y(i)$ and $p_{x}(i)$ are, respectively, the rapidity (calculated in the center of mass system) and the momentum of the $i^{th}$ particle. The rapidity is defined as

$$Y(i) = \frac{1}{2} \ln \frac{\vec{E}(i) + \vec{p}_{z}(i)}{\vec{E}(i) - \vec{p}_{z}(i)},$$

where $\vec{E}(i)$ and $\vec{p}_{z}(i)$ are, respectively, the energy and longitudinal momentum of the $i^{th}$ particle. In this definition, all the rapidity bins are taken into account. It is worth mentioning that the $E_{\text{bal}}$ has the same value for all fragments types [3]. Further the apparatus corrections and acceptance do not play any role in calculation of the $E_{\text{bal}}$.

Since the balance energy represents the counterbalancing of attractive mean filed potential and repulsive nucleon-nucleon scattering and so this counterbalancing is reflected in participant and spectator matter as predicted in Ref. [7] In the present study, we define the participant-spectator matter in terms of nucleonic concept. All nucleons having experienced at least one collision are counted as participant matter. The remaining matter is labeled as spectator matter. These definitions give us the possibility of analyzing the reaction in terms of the participant-spectator fireball model.

In fig. 1 we display the time evolution of normalized spectator matter (left panel) and participant matter (right panel). The upper, middle and lower panels represent the results for $N/Z = 1.0$, 1.6, and 2.0, respectively. Lines correspond to different systems. Solid, dashed, dotted, dash-dotted, and short-dotted lines represent the reactions of Ca+Ca,
Figure 1: (Color online) The time evolution of spectator matter (left panels) and participant matter (right panels) for systems having $N/Z = 1.0$, 1.6 and 2.0. Lines are explained in the text.

Ni+Ni, Zr+Zr, Sn+Sn, and Xe+Xe, respectively. From figure, we find that at the start of the reaction, all nucleons constitute the spectator matter. Therefore, no participant matter exists at $t = 0$ fm/c. As the reaction proceeds we have the decrease in spectator matter with corresponding increase in participant matter. We also find that for lighter
systems like Ca+Ca and Ni+Ni, the transition from spectator to participant matter is swift and sudden whereas for the heavier colliding nuclei, the transition is slow and gradual as predicted in Ref. [7]. This is because of the fact that lighter reactions occur at relatively high energies. At the end of the reactions, we have nearly the same participant matter, which indicates the universality in balancing the attractive and repulsive forces. We also see that similar behaviour exists for all N/Z ratios. This indicates that participant-spectator behaviour is similar for neutron-rich systems as for systems lying on the stability line (N/Z = 1).

In fig. 2 we display the N/Z dependence of participant and spectator matter. Upper
Figure 3: (Color online) The system size dependence of participant and spectator matter for different N/Z ratios. Various symbols are explained in the text.

(lower) panel displays the spectator (participant) matter. Squares, circles, triangles, diamonds, and pentagons represent the reactions of Ca+Ca, Ni+Ni, Zr+Zr, Sn+Sn, and Xe+Xe, respectively. We find that for all the system masses participant-spectator matter is almost independent of N/Z. There is a very slight increase (decrease) in spectator (participant) matter with N/Z of the system.

In fig. 3, we display the system size dependence of the participant and spectator matter. Open (solid) symbols represent participant (spectator) matter. Upper, middle and lower panels represent the results for N/Z = 1.0, 1.6 and 2.0, respectively. We see that participant-spectator matter follows a power law behaviour ($\propto A^n$) with the system
mass. The power law factor is $-0.12 \pm 0.04$ ($0.02 \pm 0.01$), $-0.14 \pm 0.06$ ($0.02 \pm 0.01$), and
$-0.03 \pm 0.06$ ($0.01 \pm 0.01$) for spectator (participant) matter having $N/Z = 1.0$, 1.6 and
2.0, respectively. Thus, a nearly mass independent behaviour is obeyed by the participant
and spectator matter for all the $N/Z$ ratios.

In fig. 4 we display the time evolution of anisotropy ratio $< R_a >$ (upper panel) and
relative momentum $< K_{R} >$ (lower panel) for different system masses having $N/Z = 1.0$. The $< R_a >$ is defined as

$$\langle R_a \rangle = \frac{\sqrt{p_x^2} + \sqrt{p_y^2}}{2\sqrt{p_z^2}}.$$  \hspace{2cm} (3)

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 will correspond to $\langle R_a \rangle$
Figure 5: (Color online) The system size dependence of anisotropy ratio for various N/Z ratios.

\[ \tau_i = 0.07 \pm 0.03 \quad \text{N/Z } = 1.0 \]

\[ \tau_{1.6} = 0.04 \pm 0.008 \quad \text{N/Z } = 1.6 \]

\[ \tau_i = 0.07 \pm 0.009 \quad \text{N/Z } = 2.0 \]

System mass (A)

\[ < K_R > = < |\vec{P}_p(\vec{r}, t) - \vec{P}_T(\vec{r}, t)|/h >, \]  \hspace{1cm} (4)

where

\[ \vec{P}_i(\vec{r}, t) = \sum_{j=1}^{A} \frac{\vec{P}_j(t)\rho_j(\vec{r}, t)}{\rho_j(\vec{r}, t)} \quad i = 1, 2. \]  \hspace{1cm} (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. The \( < K_R > \) is an indicator of the local equilibrium because it depends also on the local position \( r \).
From figure 4(a) (upper panel), we see that anisotropy ratio increases as the reaction proceeds and finally saturates after the high density phase is over. We also see that the influence of system size is very less on anisotropy ratio and hence indicates towards the equilibrium of the system. From fig. 4(b) (lower panel) we see that relative momentum decreases as the reaction proceeds and the smaller value of $<K_R>$ at the end of the reaction indicates toward the better thermalization of the matter. We also see from the figure that $<R_a>$ ratio saturates as soon as high density phase is over which signifies that the nucleon-nucleon collisions happening after high density phase do not change the momentum space significantly.

In fig. 5 we display the system size dependence of anisotropy ratio for systems having N/Z ratios 1.0, 1.6 and 2.0. From figure we see that anisotropy ratio follows a power law behaviour ($\propto A^\tau$) with system size. The power law factor is $0.07 \pm 0.03$, $0.04 \pm 0.008$, and $0.07 \pm 0.009$ for N/Z ratios 1.0, 1.6 and 2.0, respectively.

In summary, we studied the participant-spectator matter at the energy of vanishing flow for neutron-rich systems. The study revealed a similar behaviour of participant-spectator for neutron-rich systems as for stable systems and also pointed towards a nearly mass dependence behaviour of participant-spectator matter of neutron-rich systems at the energy of vanishing flow. Similar mass independent behaviour is also found for the anisotropy ratio.

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