The study of participant-spectator matter and collision dynamics in heavy-ion collisions

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Abstract

We aim to study the participant-spectator matter over a wide range of energies of vanishing flow and masses. For this, we employed different model parameters at central and semi-central colliding geometries. Remarkably, a nearly mass independent nature of the participant matter was obtained at the energy of vanishing flow. This makes it a very strong alternative candidate to study the energy of vanishing flow. We also show that the participant matter can also act as an indicator to study the degree of thermalization. The degree of thermalization reached in central collisions is nearly the same for different colliding nuclei at the energy of vanishing flow.

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1 Introduction

One of the main goals of heavy-ion collisions at intermediate energy is to study the nuclear properties of hot and dense environment. This is influenced by the nuclear matter equations of state as well as by the in-medium nucleon-nucleon cross sections[1–3]. In addition, the incident energy, the mass of colliding system as well as impact parameter also has a strong influence[4–7]. The nuclear interactions are attractive at low incident energies allowing the scattering of nucleons into backward hemi-sphere. These interactions, however turn repulsive, once incident energy is high enough. In this energy variation, these interactions counterbalance each other, at a particular point. This leads to no net preference to the nuclear transverse in-plane flow, therefore, net nuclear flow disappears[8–28] This energy of vanishing flow (EUF) has always been of great interest. It gives a possibility to extract the nuclear matter equation of state and strength of in-medium nucleon-nucleon cross section[8–11, 13, 14, 22].

Recently, we presented, for the first time, a complete study of the energy of vanishing flow over the entire periodic table[28]. There, a mass power law was obtained and a very close agreement with the experimental observations was also found[28]. In another communication, we also studied the other phenomena of heavy-ion reactions at the energy of vanishing flow. For the first time, we reported that the participant-spectator matter at EVF is quite insensitive to the mass of the colliding system. It, therefore, can act as a barometer for the study of the energy of vanishing flow[29]. Here, we plan to extend the study of vanishing flow for other equations of state as well as for the momentum dependent interactions. We plan to look whether the above participant-spectator matter demonstration still holds good or not. This will also give us a clue whether the participant-spectator matter at the point of vanishing flow is indeed an indicator of the counterbalancing of the attractive and repulsive interactions or is only an accidental coincident. Section 2 describes the model in brief. Section 3 explains the results and discussion and section 4 summarizes the results.

2 The model

The present study is conducted within the framework of quantum molecular dynamics (QMD) model[2–5, 7, 25–29]. In the quantum molecular dynamics model, each nucleon propagates under the influence of mutual two and three-body interactions. The propagation is governed by the classical equations of motion:

\[
\dot{r}_i = \frac{\partial H}{\partial \dot{p}_i}; \quad \dot{p}_i = -\frac{\partial H}{\partial r_i},
\]

where H stands for the Hamiltonian which is given by:

\[
H = \sum_i^A \frac{p_i^2}{2m_i} + \sum_i^A (V_{Skyrme}^i + V_{Yuk}^i + V_{Coul}^i + V_{md}^i).
\]

The $V_{Skyrme}^i$, $V_{Yuk}^i$, $V_{Coul}^i$, and $V_{md}^i$ are, respectively, the Skyrme, Yukawa, Coulomb, and momentum dependent potentials (MDI). The momentum dependent interactions are
obtained by parameterizing the momentum dependence of the real part of the optical potential. The final form of the potential reads as [2]

\[ U_{mdi} \approx t_4 \ln^2[t_5(p_1 - p_2)^2 + 1]\delta(r_1 - r_2). \]  

Here \( t_4 = 1.57 \text{ MeV} \) and \( t_5 = 5 \times 10^{-4} \text{MeV}^{-2} \). A parameterized form of the local plus MDI potential is given by

\[ U = \alpha \left( \rho / \rho_0 \right) + \beta \left( \rho / \rho_0 \right)^\gamma + \delta \ln^2[\epsilon(\rho / \rho_0)^{2/3} + 1] \rho / \rho_0. \]

The parameters \( \alpha, \beta, \gamma, \delta, \) and \( \epsilon \) are listed in Ref [2]. We shall use both the soft and hard equations of state. As explained in Ref [28]. and others,[14, 23, 24, 27] an isotropic and constant nucleon-nucleon cross section between 40 and 55 mb is also employed.

### 3 Results and discussion

As stated in the introduction, the energy of vanishing flow is of great interest. Till now, one has measured and studied theoretically the energy of vanishing flow in \(^{12}\text{C} + ^{12}\text{C}\) \((b/b_{\text{max}} = 0.4), \) \(^{20}\text{Ne} + ^{27}\text{Al}\) \((b/b_{\text{max}} = 0.4), \) \(^{36}\text{Ar} + ^{27}\text{Al}\) \((b = 2 \text{ fm}), \) \(^{40}\text{Ar} + ^{27}\text{Al}\) \((b = 1.6 \text{ fm}), \) \(^{40}\text{Ar} + ^{45}\text{Sc}\) \((b/b_{\text{max}} = 0.4), \) \(^{40}\text{Ar} + ^{51}\text{V}\) \((b/b_{\text{max}} = 0.3), \) \(^{40}\text{Ar} + ^{58}\text{Ni}\) \((b = 0-3 \text{ fm}), \) \(^{64}\text{Zn} + ^{48}\text{Ti}\) \((b = 2 \text{ fm}), \) \(^{58}\text{Ni} + ^{58}\text{Ni}\) \((b/b_{\text{max}} = 0.28), \) \(^{64}\text{Zn} + ^{58}\text{Ni}\) \((b = 2 \text{ fm}), \) \(^{86}\text{Kr} + ^{93}\text{Nb}\) \((b/b_{\text{max}} = 0.4), \) \(^{93}\text{Nb} + ^{93}\text{Nb}\) \((b/b_{\text{max}} = 0.3), \) \(^{129}\text{Xe} + ^{58}\text{Sn}\) \((b = 0-3 \text{ fm}), \) \(^{139}\text{La} + ^{139}\text{La}\) \((b/b_{\text{max}} = 0.3), \) and \(^{197}\text{Au} + ^{197}\text{Au}\) \((b = 2.5 \text{ fm})\)[8–28]. Note that these studies have a couple of limitations in general.

(a) The choice of impact parameter in the above reactions is not fixed. Rather, it varies between 0.1 to 0.4 of the maximum permissible value. It has been reported by many authors[11, 14, 15, 17–19, 26, 27, 30] that the impact parameter variation could have drastic effects on the sensitive quantities like the collective flow. Therefore, this huge variation in the impact parameter should be minimized.

(b) The masses of the colliding nuclei (chosen in the experimental studies) are asymmetric in nature in general. They have large variation in the mass of projectile and target. It is well known that the asymmetric nuclei do not follow the dynamics of the symmetric nuclei at the first place. Secondly, the asymmetry of the reaction has also a significant influence on the collective flow and on the reaction dynamics [31]. In order to have a meaningful and systematic study, we keep both these factors under control. We take symmetric colliding nuclei and keep impact parameter fixed. Therefore, here, we simulated the reactions of \(^{12}\text{C} + ^{12}\text{C}, \) \(^{20}\text{Ne} + ^{20}\text{Ne}, \) \(^{40}\text{Ca} + ^{40}\text{Ca}, \) \(^{58}\text{Ni} + ^{58}\text{Ni}, \) \(^{93}\text{Nb} + ^{93}\text{Nb}, \) \(^{131}\text{Xe} + ^{131}\text{Xe}, \) \(^{197}\text{Au} + ^{197}\text{Au}, \) and \(^{238}\text{U} + ^{238}\text{U}\). This was done to different scaled colliding geometries (i.e., in terms of the combined radius of target and projectile). The static and momentum dependent interactions along with nucleon-nucleon cross sections of 40 and 55 mb are used. The hard (soft) equation of state has been dubbed as Hard (Soft). Whereas hard equation of state with MDI has been labeled as HMD. The magnitude of the cross section appears as a superscript to these abbreviations. The above mentioned simulations were carried out at small energy steps between 30 MeV/nucleon and 250 MeV/nucleon. A straight line interpolation was used to extract the value of the energy of vanishing
Figure 1: Top panel: The participant matter as a function of incident energy for the reaction of $^{40}\text{Ca}+^{40}\text{Ca}$. Parts a, b, c, and d are for Soft$^{55}$, Hard$^{40}$, Hard$^{55}$, and HMD$^{55}$, respectively, using $b/b_{\text{max}} = 0.4$. Parts e and f are for $b/b_{\text{max}} = 0.2$ and $b/b_{\text{max}} = 0.6$, respectively, using a hard equation state with $\sigma = 55$ mb. The solid symbols represent the participant matter defined in terms of nucleon-nucleon collisions. The open symbols are for the participant matter defined in terms of different rapidity distribution cuts (see text for details). Lines are only to guide the eye.

flow. The extraction and discussion has been reported elsewhere [28]. Once the energy of vanishing flow is known, the participant–spectator matter is extracted with two different procedures as explained in Ref [29]. (a) All nucleons having experienced at least one collision are counted as participant matter (labeled as PM-C). The remaining matter is labeled as spectator matter (labeled as SP-C). The nucleons with more than one collision are labeled as super-participant matter (labeled as SPM-C). These definitions give us a possibility to analyze the reaction in terms of the participant–spectator fireball model.
These definitions, however, are more of a theoretical interest since the matter defined in these zones cannot be measured. (b) Alternately, we define the participant and spectator matter in terms of the rapidity distribution. The rapidity of \(i\)th particle is defined as

\[
Y(i) = \frac{1}{2} \ln \frac{E(i) + p_z(i)}{E(i) - p_z(i)},
\]

where \(E(i)\) and \(p_z(i)\), are, respectively, the total energy and longitudinal momentum of \(i\)th particle. We shall rather use a reduced rapidity \(Y_{\text{red}}(i) = Y_{\text{c.m.}}(i)/Y_{\text{beam}}\). Here different cuts in the rapidity distributions can be imposed to define the different participant matter. This method is often used in literature for experimental analysis [32]. We shall define normalized participant matter by imposing three different cuts: (i) all nucleons with \(-1.0 \leq Y_{\text{red}}(i) \leq +1.0\) (labeled as PM-R1), (ii) \(-0.75 \leq Y_{\text{red}}(i) \leq +0.75\) (marked as PM-R2) and (iii) \(-0.5 \leq Y_{\text{red}}(i) \leq +0.5\) (marked as PM-R3). These three different definitions give us possibility to examine the participant matter at EVF. This can also be verified experimentally.

First of all, we look for the participant-spectator matter in the incident energy plane. In Fig. 1, we display the participant matter as a function of the incident energy for the reaction of \(^{40}\text{Ca}+^{40}\text{Ca}\). The solid symbols represent PM-C whereas open symbols are for different rapidity distribution cuts. The open diamonds, open left triangles, and open pentagons represent, respectively, PM-R1, PM-R2, and PM-R3. The different sub-figures are for the different sets of model parameters.

First of all, PM-C increases linearly with increase in the incident energy in all the cases. The increase in the frequency of nucleon-nucleon collisions is responsible for this linear response. At incident energies below 200 MeV/nucleon, PM-C depends significantly on the momentum dependence of the interactions since at low incident energies, most of the collisions are blocked, resulting in less significant dependence of PM-C on individual collisions. Interestingly, PM-C is insensitive towards the impact parameter at all the incident energies. On the other hand, PM-R1, PM-R2, and PM-R3 are insensitive to the model parameters. However, they depend strongly on the impact parameter. The rapidity is also an indicator of the degree of thermalization reached in a reaction. The thermalization has been known to be insensitive towards the EOS and MDI. Whereas it depends strongly on the impact parameter [7]. Interestingly, the energy dependence of the participant matter (defined in terms of different rapidity distribution cuts) varies with the impact parameters. At central colliding geometries \((b/b_{\text{max}} = 0.2)\), PM-R1, PM-R2, and PM-R3 increase sharply up to mild energies in agreement with Ref [7]. At semi-central geometries \((b/b_{\text{max}} = 0.4)\), PM-R1 increases, whereas PM-R2 remains constant. On the other hand, PM-R3 decreases by small amount with increase in the incident energy. However, at semiperipheral geometries \((b/b_{\text{max}} = 0.6)\), all three participant matters (i.e., PM-R1, PM-R2, and PM-R3) decrease with increase in the incident energy which may be due to the fact that the dominance of mean field at low incident energies and higher impact parameter causes the thermalization in a reaction. It has been reported in Ref [29] that the nature of participant-spectator matter is not altered by the mass of the colliding nuclei. Of course, the incident energy of the projectile has a significant role to play.

Let us now discuss the participant-spectator matter at the energy of vanishing flow.
As reported in Ref.[10, 11, 13, 22, 28] the energy of vanishing flow exhibits \((A^{-\tau})\) power law mass dependence. Naturally, the lighter colliding nuclei have higher balance energy whereas heavier colliding nuclei have smaller balance energy. This is true for every equation of state with or without momentum dependence as well as for different cross sections. It was argued that due to small number of nucleon-nucleon collisions in lighter colliding nuclei, one needs higher incident energies to reach the balance point. In our earlier report,[29] participant-spectator matter has been reported to be almost constant at EVF for entire periodic table in central collisions. This happens because of the fact that at the balance energy, the attractive and repulsive forces counterbalance each other. This leads to the same amount of participant-spectator matter. We here extended this concept for different colliding geometries and also for different model ingredients to see whether the above concept is still valid or not. It is worth mentioning that the variation in EVF for a particular colliding mass using different model ingredients can be as large as 75 MeV/nucleon.

In Fig. 2, we display the participant matter as a function of combined mass of the
system at their corresponding EVF. In Fig. 2a and 2b, we display, respectively, the PM-C and SPM-C. In Fig. 2c, 2d, and 2e, we display (the participant matter defined in terms of different rapidity distribution cuts) PM-R1, PM-R2, and PM-R3, respectively. The solid (open) squares are for Hard\textsuperscript{40} (HMD\textsuperscript{40}). The solid (open) right triangles are for Hard\textsuperscript{55} (HMD\textsuperscript{55}). The lines are the power law fit of the form $cA^\tau$. The solid (dotted) lines are for the hard (HMD) equation of state. All the reactions are at the semi-central geometry of $b/b_{max} = 0.4$. From Fig. 2a and 2b, it is clear that both the PM-C and SPM-C are nearly mass independent for a particular set of the parameters. Interestingly, we see that for PM-R1, no effect appears for different equations of state and cross sections.

In Fig. 3, we display the participant matter as a function of mass of the system for Hard\textsuperscript{55} (solid right triangles) and Soft\textsuperscript{55} (open circles) equations of state. Again, lines are the power law fits ($cA^\tau$). The solid (dotted) lines are for Hard\textsuperscript{55} (Soft\textsuperscript{55}). All types of participant matter are nearly independent of the equation of state as well as of the mass of system. Very small dependence on equation of state is visible for the medium mass systems. This indicates that at EVF, the sensitivity of participant matter is insignificant towards the nuclear matter equation of state.
Figure 4: Top panel: The participant matter as a function of system size at their corresponding energy of vanishing flow. Here we use a hard equation of state along with $\sigma = 55$ mb. The open diamonds (solid right triangles) represent the reactions at $b/b_{\text{max}} = 0.2$ ($b/b_{\text{max}} = 0.4$).

In Fig. 4, we again show the quantities reported in Fig. 1, for central and semicentral colliding geometries. The open diamonds are for $b/b_{\text{max}} = 0.2$ whereas solid left triangles are for $b/b_{\text{max}} = 0.4$. Again, almost model and mass independent behaviour can be seen. This is a very important result since collective flow is very sensitive to the impact parameter. This study can be useful in all experimental measurements where impact parameter variation is not controlled.

From the above discussion, following conclusions are visible.

The participant matter shows almost mass independent behaviour irrespective of the model parameters for central and semicentral reactions. For a given set of the model parameters, EVF is higher for lighter colliding nuclei leading to higher density. This results in frequent nucleon-nucleon collisions resulting in the mass independent behaviour of participant matter. Note that the mass independent nature of participant matter is a very important observation. Especially since participant and spectator matter serve as an indicator of the role of repulsive and attractive forces. The contribution of the mean field towards transverse flow is independent of mass of the system [30]. Therefore, one needs same amount of participant matter to counterbalance attractive forces.
To understand this further, we display in Fig. 5, the final state normalized rapidity distribution. Here we display the reactions of $^{40}$Ca+$^{40}$Ca (dashed line), $^{93}$Nb+$^{93}$Nb (solid line), and $^{197}$Au+$^{197}$Au (dash-double-dotted line). The different sub-figures represent the rapidity distributions for different model parameters.

Figure 5: Top panel: The rapidity distributions for the reactions of $^{40}$Ca+$^{40}$Ca (dashed line), $^{93}$Nb+$^{93}$Nb (solid line), and $^{197}$Au+$^{197}$Au (dash-double-dotted line). The different sub-figures represent the rapidity distributions for different model parameters.

We see that the degree of thermalization reached is nearly the same irrespective of the mass of system. This points towards the mass independent nature of participant matter defined in terms of rapidity distribution cuts. We also see that the thermalization reached at balance point is also independent of different cross sections, momentum dependent interactions, and equation of state. This suggests an insignificant role of the model ingredients. We have also carried out similar calculations for the global anisotropy ratio and local relative momentum. The above mass and model ingredient picture is also valid in these cases.
4 Summary

Our present aim was to study the participant-spectator matter over a wide range of energies of vanishing flow and masses. For this, we employed different model parameters at central and semi-central colliding geometries. Remarkably, a nearly mass independent nature of participant matter was observed at the energy of vanishing flow. This makes it a very strong alternative candidate to study the energy of vanishing flow. We have also shown that the participant matter can act as an indicator to study the degree of thermalization. The degree of thermalization reached in central collisions is nearly same for different colliding nuclei at the energy of vanishing flow.

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