

Geometry of vanishing flow: A new probe to determine the in-medium nucleon–nucleon cross-section

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Abstract. We studied the transverse flow throughout the mass range from $^{20}\text{Ne}+^{20}\text{Ne}$ to $^{131}\text{Xe}+^{131}\text{Xe}$ as a function of the impact parameter. We found that at smaller impact parameters the flow is negative while going through the impact parameter, transverse flow vanishes at a particular colliding geometry named GVF. We found that the mass dependence of GVF is insensitive to the equation of state and momentum-dependent interactions whereas it is quite sensitive to the cross-section. So it can act as a useful tool to pin down the nucleon–nucleon cross-section.

Keywords. Nuclear flow; quantum molecular dynamics; vanishing of flow.

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The heavy-ion reactions at intermediate energies were used extensively over the last three decades to produce hot and dense nuclear matter leading to the understanding of nuclear matter equation of state (EOS) as well as in-medium nucleon–nucleon (nn) cross-section. Collective transverse in-plane flow [1–3] was found to be one of the most sensitive observables in this direction. A lot of experimental as well as theoretical efforts were made to study the transverse in-plane flow [4,5]. The variation in the flow as a function of beam energy reflects the competition between the attractive and repulsive interactions [6,7]. At a particular incident energy, the strength of these two interactions counter-balance each other and the net transverse in-plane flow vanishes. This energy is often referred to as the energy of vanishing flow (EVF). Krofcheck *et al* [8], for the first time, reported the vanishing of collective flow in $^{139}\text{La} + ^{139}\text{La}$ reaction at around 50 MeV/nucleon. Later, many attempts were made to study the EVF over a wide range of masses and impact parameters. A comparison with experimental data also threw light on the equation of state [9–17]. The EVF has been found to depend also on the combined mass of the system [11]. A power law mass dependence ($\propto A^\tau$) has also been reported in the literature. From earlier measurements, τ

was supposed to be close to $-1/3$ (resulting from the interplay between the attractive mean field and repulsive nn collisions) [11] whereas recent attempts suggested a deviation from the above-mentioned power-law [13–15].

The colliding geometry also plays an important role in determining the flow as well as its disappearance [5,9,12,14,16,17]. As two nuclei collide, the pressure and density increase in the interaction region. At non-zero colliding geometry, due to the anisotropy in the pressure, there is a transverse flow of nuclear matter in the direction of lowest pressure. Therefore, as colliding geometry increases from perfectly central collisions (i.e. $b = 0$), the transverse in-plane flow increases, reaches a maximum and with further increase in the impact parameter, the transverse flow decreases and passes through a zero value and achieves even negative values [12]. For grazing collisions, it must vanish again. Thus, barring the perfectly central and grazing collisions, there should exist a particular colliding geometry at a given incident energy at which the transverse flow must vanish.

In this paper, we propose a new observable, the geometry of vanishing flow (GVF), which can be used to extract information about the EOS as well as about the in-medium nn cross-section. Here, we shall show that the GVF depends on the combined mass of the system and follows a power-law behaviour $\propto A^\tau$.

For this study, we used the quantum molecular dynamics (QMD) model. In QMD model [18–21], each nucleon is represented by a Gaussian distribution whose centroid propagates with classical equations of motion:

$$\frac{d\mathbf{r}_i}{dt} = \frac{dH}{d\mathbf{p}_i}; \quad (1)$$

$$\frac{d\mathbf{p}_i}{dt} = -\frac{dH}{d\mathbf{r}_i}, \quad (2)$$

where the Hamiltonian is given by

$$H = \sum_i \frac{\mathbf{p}_i^2}{2m_i} + V^{\text{tot}}, \quad (3)$$

with total interaction potential

$$V^{\text{tot}} = V^{\text{Loc}} + V^{\text{Yuk}} + V^{\text{Coul}}. \quad (4)$$

Here V^{Loc} , V^{Yuk} and V^{Coul} represent, respectively, the Skyrme, Yukawa and Coulomb parts of the interaction. Yukawa force is known to be very important for low-energy phenomena like fusion, cluster decay etc. [22]. Using these interactions, the static part of the mean field acting on each nucleon can be written as

$$V^{\text{Loc}} = \frac{\alpha}{2} \left(\frac{\rho}{\rho_0} \right) + \frac{\beta}{\gamma + 1} \left(\frac{\rho}{\rho_0} \right)^\gamma. \quad (5)$$

The parameters α and β ensure right binding energy of the colliding nuclei and γ gives freedom to choose different equations of state. The momentum-dependent interactions can

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be incorporated from the momentum dependence of the real part of the optical potential. The final form of the momentum-dependent potential (V^{MDI}) is given as

$$V^{\text{MDI}} = \delta \cdot \ln^2 [\varepsilon(\rho/\rho_0)^{2/3} + 1] \rho/\rho_0 \quad (6)$$

with δ, ε having values equal to 1.57 MeV and 21.54.

For the present study, we simulated $^{20}\text{Ne} + ^{20}\text{Ne}$, $^{40}\text{Ca} + ^{40}\text{Ca}$, $^{58}\text{Ni} + ^{58}\text{Ni}$, $^{93}\text{Nb} + ^{93}\text{Nb}$ and $^{131}\text{Xe} + ^{131}\text{Xe}$ reactions at full range of colliding geometries ranging from the central to peripheral collisions in small steps of 0.15 at a fixed incident energy of 150 MeV/nucleon. We used hard (dubbed as Hard), hard with momentum-dependent interactions (MDI) (labelled as HMD), and soft equation of state with MDI (SMD) along with constant isotropic constant cross-section of 40 mb as well as Cugnon parametrization of energy-dependent cross-section [23]. The superscripts to the labels represent different nn cross-sections. To calculate the transverse in-plane flow, we use directed transverse momentum ($\langle p_x^{\text{dir}} \rangle$) defined as [15,19]

$$\langle p_x^{\text{dir}} \rangle = \frac{1}{A} \sum_{i=1}^A \text{sign}\{y(i)\} p_x(i), \quad (7)$$

where $y(i)$ and $p_x(i)$ are the rapidity and momentum respectively of the i th particle.

In figure 1, we display $\langle p_x^{\text{dir}} \rangle$ as a function of the reduced impact parameter b/b_{max} (where b_{max} = radius of projectile + radius of target) for different colliding masses between $^{20}\text{Ne} + ^{20}\text{Ne}$ and $^{131}\text{Xe} + ^{131}\text{Xe}$ at an incident energy of 150 MeV/nucleon. All reactions were followed till $\langle p_x^{\text{dir}} \rangle$ saturates. The saturation time is longer for heavier masses compared to lighter ones. As expected, in all cases, $\langle p_x^{\text{dir}} \rangle$ increases with increase in b/b_{max}

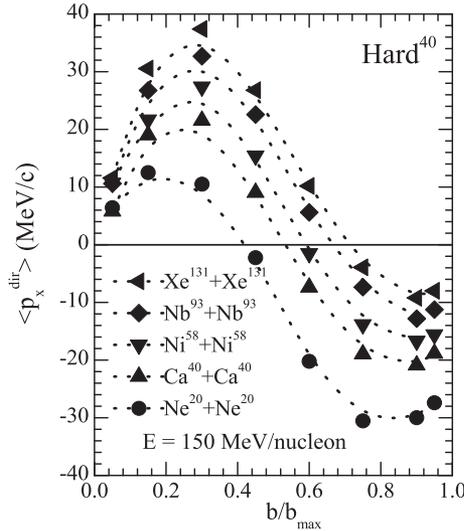


Figure 1. $\langle p_x^{\text{dir}} \rangle$ (MeV/c) as a function of reduced impact parameter b/b_{max} . We display the results of different systems using hard equation of state and a constant cross-section of 40 mb.

from perfectly central collisions and reaches a maximal value. After the maximal value, it decreases with further increase in the colliding geometry and passes through a zero value at some intermediate impact parameter. This colliding geometry at which $\langle p_x^{\text{dir}} \rangle$ passes through a zero value has been dubbed as geometry of vanishing flow (GVF). With further increase in b/b_{max} , $\langle p_x^{\text{dir}} \rangle$ becomes negative and attains the maximal negative value after which it again vanishes at grazing collisions. The trend is uniform throughout the present mass range. The value of the GVF varies with the mass of the combined system. For lighter systems, the value of GVF is smaller compared to the heavier ones.

In figure 2, we display GVF as a function of combined system mass. In figure 2a, we display the results of Hard^{40} (open diamonds) and HMD^{40} (solid diamonds) EOS. The results of figure 2b are for HMD^{40} and SMD^{40} (open triangles) EOS whereas in figure 2c, we display the results for SMD^{40} and SMD^{Cug} (open circles) EOS. The lines are power-law

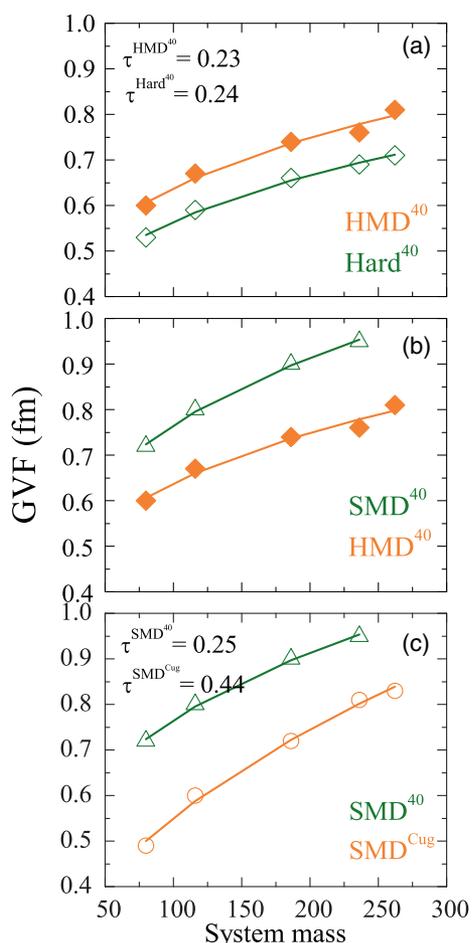


Figure 2. The geometry of vanishing of flow (GVF) as a function of system mass for different equations of state.

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fits ($\propto A^\tau$). In all the cases, GVF follows a power-law behaviour $\propto A^\tau$, where A is the combined mass of the system. The values of $\tau^{\text{Hard}^{40}}$, $\tau^{\text{HMD}^{40}}$, $\tau^{\text{SMD}^{40}}$ and $\tau^{\text{SMD}^{\text{Cug}}}$ are, respectively, 0.24 ± 0.01 , 0.23 ± 0.02 , 0.25 ± 0.01 and 0.44 ± 0.02 . Note that the values of $\tau^{\text{SMD}^{\text{Cug}}}$ are quite different from the values of $\tau^{\text{Hard}^{40}}$, $\tau^{\text{HMD}^{40}}$ and $\tau^{\text{SMD}^{40}}$ which are almost same, indicating that the mass dependence of GVF is insensitive to different equations of state as well as to momentum-dependent interactions. It is, however, very sensitive to in-medium nn cross-section. Note that the average strength of σ^{Cug} in Fermi energy is about 32 mb and with a slight change in the cross-section, the value of τ is almost doubled. Therefore, the mass dependence of GVF can be used to pin down the in-medium nn cross-section. Moreover, it can also be used to explore the isospin effects related to the cross-section because np cross-section is about a factor of three higher than the nn or pp cross-section in the present energy range.

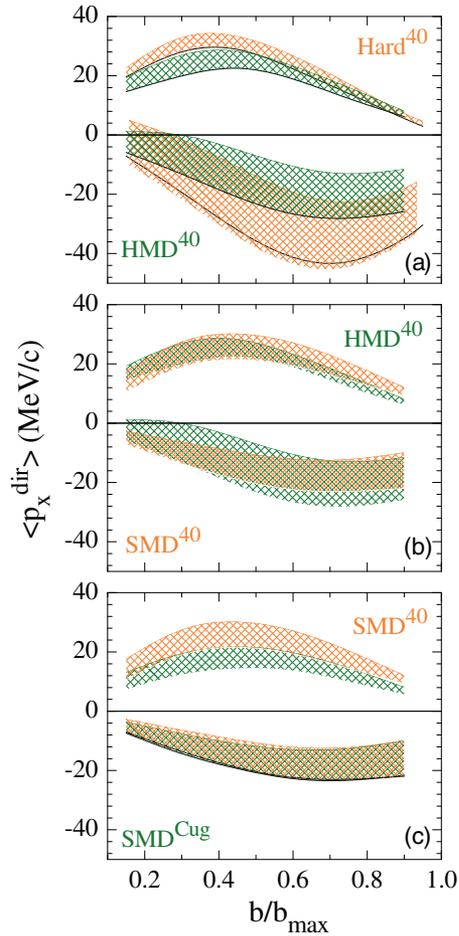


Figure 3. The decomposition of $\langle p_x^{\text{dir}} \rangle$ into mean field and binary collision parts as a function of the reduced impact parameters for different equations of state.

As reported in refs [5,15], the variation in the strength of nucleon–nucleon cross-section by keeping the form of all cross-sections the same, yields a linear variation in the collective flow. In refs [5,15], different strengths of cross-sections (e.g. $\sigma = 20, 35, 40$ and 55 mb) were used and collective flow was found to vary linearly in agreement with other calculations [24].

To understand this behaviour, we can divide the total $\langle p_x^{\text{dir}} \rangle$ into the contribution from the mean field and binary nn collision flow. The decomposition of $\langle p_x^{\text{dir}} \rangle$ is explained at energy of vanishing flow in ref. [15]. In figure 3, we display $\langle p_x^{\text{dir}} \rangle$ due to mean field (labelled as $\langle p_x^{\text{dir}} \rangle_{\text{mf}}$ and collisions ($\langle p_x^{\text{dir}} \rangle_{\text{coll}}$) as a function of the colliding geometry. In the present study, $\langle p_x^{\text{dir}} \rangle_{\text{coll}}$ is always positive whereas $\langle p_x^{\text{dir}} \rangle_{\text{mf}}$ is always negative except at very small colliding geometry (which is not relevant in the context of the present study). The shaded areas cover the full range of mass in the present study. The values of both $\langle p_x^{\text{dir}} \rangle_{\text{mf}}$ and $\langle p_x^{\text{dir}} \rangle_{\text{coll}}$ are larger for heavier mass than for the lighter ones, i.e. upper (lower) boundary of each shaded area represents heavier (lighter) mass. The top panel is for Hard⁴⁰ and HMD⁴⁰, bottom panel is for SMD⁴⁰ and SMD^{Cug} and middle panel is for SMD⁴⁰ and HMD⁴⁰. From figures 2a and 3a, we see that the range of GVF (from lighter to heavy masses) is around 0.5 to 0.8 and in this range, the inclusion of MDI has the same effect on GVF throughout the mass range keeping the value of τ unchanged. Similar effects can also be seen for the equation of state from figures 2b and 3b. From figures 2c and 3c, we see that flow due to the mean field is exactly the same for all the systems at all colliding geometries, whereas the effect of binary collisions is different for different masses at and around the respective GVF, thus making the mass dependence of GVF quite sensitive to the nucleon–nucleon cross-section.

In summary, we have studied the transverse flow throughout the mass range from $^{20}\text{Ne} + ^{20}\text{Ne}$ to $^{131}\text{Xe} + ^{131}\text{Xe}$ as a function of impact parameter. We found that at smaller impact parameters, the flow is negative while going through the impact parameter, transverse flow vanishes at a particular colliding geometry dubbed as the GVF. We found that the mass dependence of GVF is insensitive to the equation of state and momentum-dependent interactions whereas it is quite sensitive to the binary nn cross-section presenting it as a new probe to constrain the strength of binary cross-section.

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