# Transverse flow and its disappearance: role of mass asymmetry

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## Introduction

Heavy-ion collisions in terrestrial labs serve as best candidates to study the properties of hot and dense nuclear matter. Various phenomena like collective flow, multifragmentation, nuclear stopping and particle production take place at intermediate energies. Out of these, collective transverse in-plane flow enjoys a special status as it is found to be most sensitive towards different signals of excited nuclear matter. It sheds light on equation of state (EOS) and in-medium nucleon-nucleon (nn) cross section. In addition, it has also been reported to be highly sensitive to entrance channel parameters like combined mass of system, colliding geometry as well as incident energy of projectile. The energy dependence of flow led to disappearance of flow at energy of vanishing flow.

Colliding geometry, on the other hand, also plays a significant role in transverse in-plane flow. The impact parameter dependence of transverse in-plane led to its disappearance at impact parameter termed as the geometry of vanishing flow (GVF) [1]. A couple of studies on the GVF have been done in recent past which pointed towards sensitivity of the GVF to in-medium nn cross section and its insensitivity to nuclear EOS.

Reaction dynamics also depend on the asymmetry between projectile and target nuclei [2, 3]. In the present work, we aim to study behavior of GVF for asymmetric reactions, i.e., for different projectile and target nuclei. This is done by keeping target fixed and varying projectile from lighter to heavier masses. On the experimental front also, such studies can be conformed at Super Conducting Cyclotron at VECC, Kolkata, where one have possibility of lighter beams.

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## The model

The present study is carried out using quantum molecular dynamics (QMD) model [4]. In QMD model, nucleons (represented by Gaussian wave packets) interact via mutual two- and three-body interactions. The nucleons propagate according to Hamilton's equations of motion.

$$\dot{\mathbf{p}}_i = -\frac{\partial\langle H\rangle}{\partial \mathbf{r}_i}; \dot{\mathbf{r}}_i = \frac{\partial\langle H\rangle}{\partial \mathbf{p}_i}. \quad (1)$$

The expectation value of the total Hamiltonian reads

$$\langle H\rangle = \langle T\rangle + \langle V\rangle = \sum_i \frac{\mathbf{p}_i^2}{2m_i} + V^{Skm} + V^{Yuk} + V^{Coul} \quad (2)$$

Here $V^{Skm}$, $V^{Yuk}$, and $V^{Coul}$ are, respectively, the local (two and three-body) Skyrme, Yukawa, and Coulomb potentials.

## Results and discussion

We simulated the reactions of $^{4}$He+$^{197}$Au, $^{12}$C+$^{197}$Au, $^{58}$Ni+$^{197}$Au, $^{92}$Zr+$^{197}$Au, and $^{131}$Xe+$^{197}$Au at incident energies of 100 and 400 MeV/nucleon throughout the range of colliding geometry (b/b$_{max}$ = 0, 0.2, 0.4, 0.6 and 0.8). For the present study, we used a soft

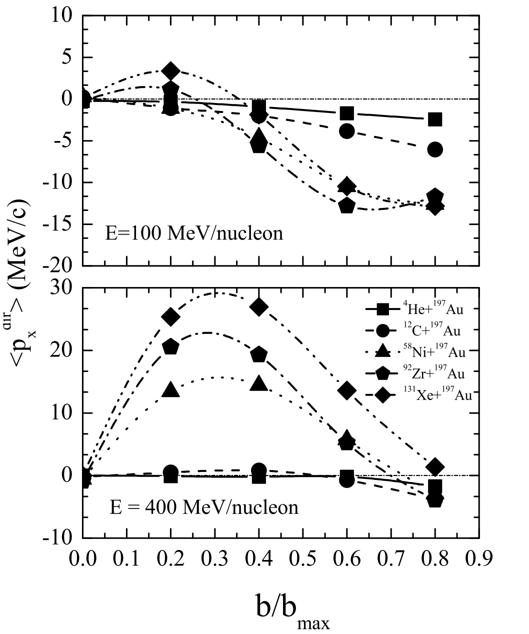


FIG. 1: Impact parameter dependence of transverse in-plane-flow $\langle p_x^{dir} \rangle$ at energies of 100 (upper panel) and 400 MeV/nucleon (lower) for various systems.

equation of state along with energy-dependent Cugnon nucleon-nucleon cross section. The directed transverse flow "*directed transverse momentum* $\langle p_x^{dir} \rangle$" is defined as [5]

$$\langle p_x^{dir} \rangle = \frac{1}{A} \sum_{i=1}^{A} sign\{y(i)\} p_x(i), \qquad (3)$$

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

In Fig. 1, we display the impact parameter dependence of $<\mathrm{p}_x^{dir}>$ for various reactions at 100 MeV/nucleon (upper panel) and 400 MeV/nucleon (bottom panel). Circles, triangles, pentagons and diamonds represent the collisions of $^4$He, $^{12}$C, $^{58}$Ni, $^{92}$Zr, and $^{131}$Xe respectively on $^{197}$Au target. From the figure, we see that at 100 MeV/nucleon (upper panel) $<\mathrm{p}_x^{dir}>$ remains negative for the reactions of lighter projectiles like $^4$He, $^{12}$C and $^{58}$Ni on $^{197}$Au throughout the range of colliding geometry and decreases when we go from central to peripheral collisions. This is because of the fact that projectile has very less energy to cause binary nn collisions. As we move to the reaction of heavier projectiles like $^{92}$Zr and $^{131}$Xe with $^{197}$Au target, we see that $<\mathrm{p}_x^{dir}>$ increases when we move from perfectly central collisions to semicentral collisions, reaches a maximum and finally decreases and become negative for peripheral collisions. This is because of the real absence of nn collisions at peripheral geometry as explained earlier also. Also at 400 MeV/nucleon (bottom panel), we see that the $<\mathrm{p}_x^{dir}>$ is more that that at 100 MeV/nucleon at all the colliding geometries for all the colliding pairs. This is because of the enhancement of the nn collisions with increase in the incident energy. From the figure, we also see that for all the reactions, $<\mathrm{p}_x^{dir}>$ first increase when we go from perfectly central collision to semi central collision, reaches a maximum value at a particular value of impact parameter and then again decrease except for the reaction of very light projectile of $^4$He on $^{197}$Au. For $^4$He+$^{197}$Au collisions , $<\mathrm{p}_x^{dir}>$ is almost zero through the range of colliding geometry because the projectile nucleus is too light and so it cannot affect the heavy target $^{197}$Au and flow remains zero. The value of impact parameter where $<\mathrm{p}_x^{dir}>$ crosses zero is the GVF.

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