Collective flow and balance energy in asymmetric heavy-ion collisions

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Introduction

Heavy-ion collisions at intermediate energy provide a useful tool to determine the nuclear matter equation of state as well as in-medium nucleon-nucleon (nn) cross-section. One of the most promising phenomena that can be helpful in this context is the *disappearance of transverse in-plane flow*. At low incident energies, the dominance of attractive interactions results in the emission of particles into backward hemisphere which leads to negative transverse in-plane flow whereas at higher incident energies, the particles are emitted into forward hemisphere resulting in positive flow. As one goes from low incident energy to higher one there exist a particular energy at which the net transverse in-plane flow disappears. This energy is termed as the *energy of vanishing flow* (EVF) [1, 2]. Up to now, one has measured the energy of vanishing flow in the reactions of ^{12}C+^{12}C, ^{20}Ne+^{27}Al, ^{36}Ar+^{27}Al, ^{40}Ar+^{27}Al, ^{40}Ar+^{45}Sc, ^{40}Ar+^{51}V, ^{64}Zn+^{27}Al, ^{40}Ar+^{58}Ni, ^{64}Zn+^{48}Ti, ^{58}Ni+^{58}Ni, ^{58}Fe+^{58}Fe, ^{64}Zn+^{58}Ni, ^{86}Kr+^{93}Nb, ^{93}Nb+^{93}Nb, ^{129}Xe+^{118}Sn, ^{139}La+^{139}La, and ^{197}Au+^{197}Au [3]. However most of the reactions studied are nearly symmetric. Since, the dynamics of heavy-ion reactions also depends on asymmetry of the reaction [4]. We therefore, aim to study the transverse in-plane flow as well as its disappearance for different colliding nuclei with varying asymmetry. We plan to address this question using quantum molecular dynamics (QMD) model [5].

Model

The QMD model is an n-body theory that simulates the heavy-ion reactions on event by event basis. This is based on a molecular dynamics picture where nucleons interact via two and three-body interactions. The nucleons propagate according to the classical equations of motion:

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

where H stands for the Hamiltonian which is given by

$$H = \sum_i \left[T_i + \frac{1}{2}\sum_{ij} V_{ij} \right]. \quad (2)$$

T$_i$ is the kinetic energy term and V_{ij} is the nuclear potential which consists of

$$V_{ij} = V^{Skyrme} + V^{Yuk} + V^{Coul}, \quad (3)$$

where V^{Skyrme}, V^{Yuk} , and V^{Coul} are, respectively, the local Skyrme, Yukawa, and Coulomb potentials. The final transverse in-plane flow is calculated using

$$\left\langle p_x^{dir} \right\rangle = \frac{1}{A}\sum_{i=1}^{A} sign\{y(i)\}\mathbf{p}_\mathbf{x}(i). \quad (4)$$

Here $y(i)$ is the rapidity and $\mathbf{p}_\mathbf{x}(i)$ is the transverse momentum of i^{th} particle. The rapidity is defined as:

$$y(i) = \frac{1}{2}\ln\frac{\mathbf{E}(i)+\mathbf{p}_\mathbf{z}(i)}{\mathbf{E}(i)-\mathbf{p}_\mathbf{z}(i)}, \quad (5)$$

where **E**(i) and $\mathbf{p}_\mathbf{z}$(i) are, respectively, the total energy and longitudinal momentum of ith particle. The EVF was then deduced using a straight line interpolation.

Results and discussion

Here we study the collisions of various projectiles and targets with varying degree of asymmetry parameter (η) keeping the combined mass of the system fixed (100 in our case), where η is defined as

$$\eta = \left| \frac{A_T - A_P}{A_T + A_P} \right|. \tag{6}$$

A_T and A_P are the masses of target and projectile, respectively. For symmetric collisions η=0 and nonzero values of η corresponds to different asymmetries. We simulated the collisions with different η ranging from 0-0.86 at different incident energies varying from 40 to 400 MeV/nucleon in small steps and at reduced impact parameter (b/b_{max}) of 0.2. For the present study, we employed a stiff equation of state (K=380 MeV) along with a constant isotropic cross-section of 40 mb strength. In fig. 1, we show $<p_x^{dir}>$ for collisions with different asymmetry as a function of the incident energy. The lines are to guide the eye. The transverse in-plane flow increases monotonically with increase in incident energy in all the cases, which is due to the increase in number of nucleon-nucleon collisions as well as dominance of repulsive mean field. At fixed incident energy, $<p_x^{dir}>$ decreases as the asymmetry of reaction increases in the high energy region whereas the trend gets reversed at very low incident energies (e.g. 40 MeV/nucleon). The energy of vanishing flow remains nearly same up to η = 0.52 after which it increases sharply which may be due to decrease in the number of collisions as well as Coulomb repulsion.

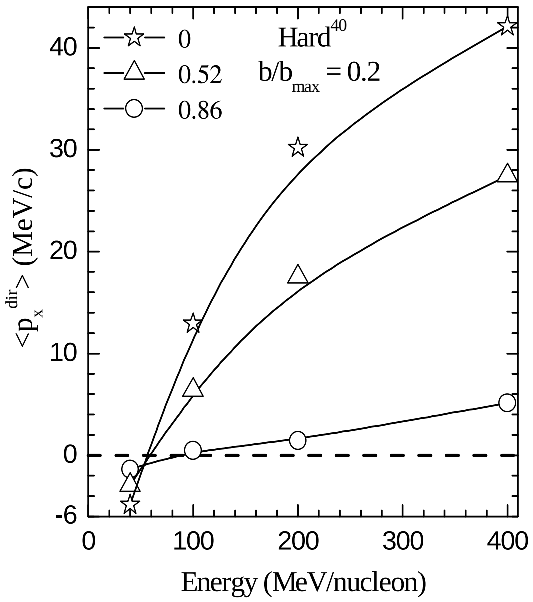

Fig. 1 The transverse in-plane flow $<p_x^{dir}>$ as a function of incident energy for different aymmetric systems having same mass.

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