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On the scaling of nuclear flow in mass asymmetric heavy ion reactions

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Abstract

Anisotropic flows (directed and elliptic flows) of fragments have been studied in mass asymmetric nuclear reactions $^{122}_{49}In + ^{126}_{50}Sn$, $^{114}_{48}Cs + ^{134}_{54}Xe$, $^{100}_{40}Mo + ^{148}_{64}Gd$, $^{86}_{36}Kr + ^{162}_{67}Ho$, $^{71}_{31}Ga + ^{177}_{71}Lu$, $^{60}_{28}Ni + ^{188}_{76}Os$, $^{50}_{24}Cr + ^{198}_{78}Pt$ and $^{40}_{20}Ca + ^{208}_{82}Pb$ for incident energies between 50 MeV/nucleon and 400 MeV/nucleon at the range of centrality $0.25 < \hat{b} < 0.45$ using isospin-dependent quantum molecular dynamics model. Our findings reveal that strength of flow depends on the fragment mass, rapidity distribution and mass asymmetry of the reaction. The scaling is influenced by the momentum associated with fragments.

Keywords: Intermediate energy heavy ion reactions; Anisotropic nuclear flow; Scaling of flow; Isospin dependent quantum molecular dynamics model

1. Introduction

Main objective of the azimuthally asymmetric emission of nucleons called collective flow in heavy ion collisions at intermediate energies is to provide a deep insight into hot and compressed nuclear matter and nuclear equation of state (EOS) [1–5]. One can produce the nuclear matter having density higher than the normal nuclear matter by colliding two nuclei at intermediate energies. Highly compressed nuclear matter is produced at non-central impact parameters, which

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results in the collective flow associated with the participant nucleons. By studying the flow observable like directed flow, elliptic flow and higher harmonics, one can indirectly estimate the compressibility of nuclear matter.

Among different harmonics of flow, the first harmonic directed flow (v_1) arises due to the pressure gradient in hot nuclear matter and results into preferential sideward deflection of fragments/nucleons. Extraction of EOS can therefore be co-related, because directed flow is considered as an essential signature of compression and expansion of nuclear matter [6,7]. Both hydrodynamics and theoretical transport models [8,9] have revealed that directed flow is a promising observable for exploring a possible phase transition of the nuclear matter. Whereas, the second harmonic, elliptic flow comes into play due to the combined effects of rotation as well as expansion of hot compressed participant matter and shadowing of spectator matter, thus elliptic flow can serve as a probe to investigate the dynamics of heavy ion reaction [10,11].

The number of constituent quark (NCQ) scaling at Relativistic Heavy ion Collider (RHIC) is an important observation in the formation of hadrons through the parton coalescence mechanism [12]. Similarly, nucleon coalescence/number-of-nucleon scaling can also be co-related with NCQ for anisotropic flow of light mass fragments (LMF) in nuclear collisions at low and intermediate energies [13]. Here, the emission of free nucleons or light mass fragments can be obtained. Coalescence or recombination mechanism can be calculated at low transverse momentum values, because Light Mass Fragments (LMFs) ($1 \leq A \leq 4$) have the same anisotropies and momentum spectra, when studied as a function of rapidity distribution and transverse momentum/mass of fragment (p_t/A) [14].

This scaling phenomenon takes place in the light mass fragments/free nucleons, because these fragments have the similar velocities/momentum and originated from the regions where the emitted nuclear matter velocity equals their velocity. However, the recombination mechanism is expected to be poor for heavier mass fragments like Intermediate Mass Fragments (IMFs) ($A_{total}/6$), because the instability of the IMFs leads to further decay through emission of its constituents (free nucleons/LMFs) in different directions. The velocities of these emitted constituents exceeds the maximum value of the nuclear matter's velocity. The nuclear matter velocity or combined velocity in general depend on the rapidity distribution and indicates the unrevealed equation of state of the expanding nuclear matter.

The strength of anisotropic flow is usually calculated with the help of Fourier expansion equation for the azimuthal distribution of emitted fragments w.r.t. the reaction plane. Anisotropic flows are defined as different harmonic coefficients v_n of the Fourier expansion of the particle's non-uniform distribution [15]:

$$\frac{dN}{d\phi} \propto [1 + 2\sum_{n=1}^{\infty} v_n \cos(n\phi)] \tag{1}$$

where ϕ is azimuthal angle of the emitted nucleons/fragments between their transverse momentum and the reaction plane. In the coordinate space, we take the beam axis along the Z-axis and the X-axis is considered as an impact parameter axis. In mass asymmetric nuclear reactions, the distribution of nucleons cannot be symmetric w.r.t. azimuthal angle. Therefore, we also have included the sine term in our calculations of (v_1, v_2, v_3 and v_4) for the asymmetric reactions as:

$$< v_1 > \; = \langle \cos\phi \rangle + \langle \sin\phi \rangle \; = \langle \frac{p_x}{p_t} \rangle + \langle \frac{p_y}{p_t} \rangle \tag{2}$$

$$< v_2 > \; = \langle \cos 2\phi \rangle + \langle \sin 2\phi \rangle \; = \langle \frac{p_x^2 - p_y^2}{p_t^2} \rangle + \langle \frac{2 p_x p_y}{p_t^2} \rangle \tag{3}$$