Impact parameter dependence of energy of vanishing flow: comparison with experimental data

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Introduction

Heavy-ion collisions at intermediate energies, as for example, provided by FOPI and INDRA collaborations, have been investigated for several decades using different observables such as directed flow, elliptical flow, multifragmentation and nuclear stopping etc. to probe the bulk nuclear matter properties at different thermodynamical conditions. Among these observables, *the directed flow*, a measure of collective momentum transfer in the reaction plane, is one of the most extensively studied variables to constrain the equation of state (EOS) of symmetric nuclear matter. Currently intermediate mass fragments (IMF's) and light charged particles (LCP's) directed flow is also being used to understand the nature of asymmetric nuclear matter [1]. At the same time, isospin dependence of directed flow and its disappearance is also being used to probe the density dependence of nuclear symmetry energy [2]. The beam energy dependence of the directed flow leads to its disappearance at a particular energy known as the energy of vanishing flow (EVF). The EVF represents the balance between attractive mean field (dominant at low energies) and repulsive nucleon-nucleon (nn) scattering (significant at high energies). For the nuclear physics community, the energy of vanishing flow is of great interest as experimentally measured EVF can easily be compared to theoretical predictions. Experimentally, EVF has been measured for more than 15 systems, but most of the measurements are constrained to central collisions, only few are extended for the entire range of colliding geometry [3–5]. Due to extensively available data on the EVF, the corresponding theoretical efforts have also been carried out to reproduce the data in the search of EOS and in-medium nn cross-section. The EVF is found to be sensitive to EOS as well as in-medium nn cross-section depending upon on the mass and colliding geometry of reacting partners. Also, most of the theoretical attempts dedicated to reproduce the mass dependence of the EVF are limited to central collisions only. The mass dependence of the EVF follows a power law $\propto A^{-\tau}$. The value of τ is found to vary with EOS as well as with the mass range being considered [6]. The sensitivity of the collective flow and its disappearance towards the choice of colliding geom-

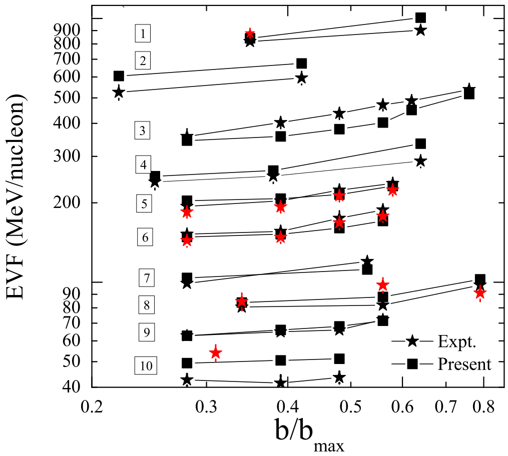

FIG. 1: The energy of vanishing flow as a function of impact parameter. Stars with error bar represent experimental measurements whereas squares correspond to present calculations using SMD EOS with reduced nn cross-section.

*Electronic address: sakshigautam@pu.ac.in etry is well established. The EVF is found to increase approximately linearly with increase in impact parameter depending on the mass of colliding pair. As for the heavier system change in EVF is less compared to lighter systems. Recently Gautam *el al.* [7] reproduced the measured EVF for the reactions of ^{58}Ni+^{58}Ni and ^{58}Fe+^{58}Fe as a function of impact parameter. They used soft momentum-dependent (SMD) EOS and 20% reduced in-medium nn cross-section to perform the calculations using IQMD model. But their study to see the impact parameter dependence of EVF was limited to only two systems. Here, we aim to study the role of impact parameter dependence on the EVF for all the systems for which experimental data is available by using same set of EOS and in-medium nn cross-section. The present study is carried out using Isospin-dependent Quantum Molecular Dynamics (IQMD) model [2, 7, 8].

Results and discussion

For the present study, we simulated the reactions of ^{36}Ar+^{27}Al, ^{40}Ar+^{27}Al, ^{40}Ar+^{45}Sc, ^{64}Zn+^{27}Al, ^{58}Ni+^{58}Ni, ^{58}Fe+^{58}Fe, ^{64}Zn+^{48}Ti, ^{64}Zn+^{58}Ni, ^{86}Kr+^{93}Nb and ^{197}Au+^{197}Au whose experimental energies of vanishing flow at different impact parameters are available. We use a soft EOS with momentum-dependent interactions (MDI) along with 20% reduced cross-section. In Fig. 1, we display the energy of vanishing flow as a function of impact parameter for the above reactions. Stars with error bars represent measured energies of vanishing flow and squares correspond to our theoretical calculations. The EVF for various reactions has been scaled by different factors to maintain the clarity of the figure. The experimental and theoretical EVF for the reactions of ^{36}Ar+^{27}Al, ^{40}Ar+^{27}Al, ^{40}Ar+^{45}Sc, ^{64}Zn+^{27}Al, ^{58}Ni+^{58}Ni, ^{58}Fe+^{58}Fe, ^{64}Zn+^{48}Ti, ^{64}Zn+^{58}Ni, ^{86}Kr+^{93}Nb and ^{197}Au+^{197}Au have been scaled by a factor of 9.5, 7.0, 4.2, 3.2, 2.8, 2.0, 1.5, 1.3, 1.1 and 1.0, respectively. From the figure, we notice that EVF rises as one moves from central to peripheral collisions and impact parameter dependence gets weaker for heavier systems. Our theoretical calculations are able to reproduce the measured EVF reasonably, in most of the cases. Further, general trends of the EVF with mass and impact parameter are also reproduced. Here it is worth mentioning that in many cases there is a huge difference in the value of EVF reported by various experimental groups. So, one can talk of general trends only. For example in Ref. [9], EVF measured for the reaction of ^{197}Au+^{197}Au is around 60 MeV/nucleon in contradiction to earlier observation in Ref. [5], where the value of EVF was estimated to be around 42±4 MeV/nucleon.

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