Webology (ISSN: 1735-188X)
Volume 18, Number 6, 2021

A Systematic Review Of Geometry Of Vanishing Flow For Mass Symmetric And Asymmetric Reactions

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Abstract: We present the review of theoretical work done by using Quantum Molecular Dynamics (QMD) and Iso-spin Dependent Quantum Molecular Dynamics (IQMD) models to study the role of various input parameters like incident energy, mass asymmetry, system size, equation of state, impact parameter, momentum dependent interactions, isospin degrees of freedom (via symmetry energy and Coulomb potential) and reaction cross section on the collective transverse flow and geometry of vanishing flow (GVF). From the review, we notice the sensitivity of collective flow, GVF and mass dependence of GVF on colliding geometry, incident energy, mass asymmetry, isospin, total mass of the reaction, cross-section and mass of the projectile keeping target fixed.

Keywords: heavy-ion collisions, impact parameter, geometry of vanishing flow, collective transverse flow, QMD and IQMD model, Review

1. Introduction

In the last three decades, a lot of theoretical and experimental studies has been performed on collective transverse flow in order to study the properties of dense and hot nuclear matter [1-24]. The collective flow is quite sensitive to incident energy [2,3] because at low incident energies, it is negative due to the dominance of attractive mean field, whereas, at high incident energies, it shifts to positive side due to the governance of repulsive n-n collisions. The sensitivity of collective flow on various entrance channels i.e. equation of state (EoS) of nuclear matter [1], impact parameter [4,5], size of the system [6,7], mass asymmetry of system [8,22], and isospin [9-11,23] has been seen in various independent studies. The energy where flow disappears while going from negative to positive (because of the balancing of attractive and repulsive interactions) is termed as “Balance Energy” [12]. Various independent studies are carried out in the literature to find the value of balance energy and its dependence on input parameters of the reaction like mass asymmetry [8,22], colliding nuclei mass [13,14,22], impact parameter [15] and isospin [10,16,23]. In Ref. [17] and [18], work has been done to find the dependence of elliptical flow and multifragmentation on input parameters, respectively. Moreover, a significant effect on the collective flow and its disappearance has been shown by the colliding geometry of the reaction. Collective flow follows a rise and fall trend as on goes from central to peripheral collisions. The value of impact parameter where collective flow disappears is termed as Geometry of Vanishing Flow (GVF) [19-24]. The value of GVF is dependent on various factors which is presented in various independent studies for the symmetric [19-23] and mass asymmetric reactions [20-22] at different incident energies. The nuclear dynamics at GVF is also presented in the literature [24]. Therefore, in this study, we plan to see the behavior of GVF by reviewing all the literature and present the results in a systematic way. The simulations in the literature are done with (n-body) Quantum Molecular Dynamics (QMD) model [19-22] and Iso-spin dependent Quantum Molecular Dynamics (IQMD) model [23,24]. The details of the used models can be found in Ref. [25]. Results and summary are discussed in Sec 2 and 3 along with references in Sec 4.

2. Results and Discussion

In the present study we have reviewed the literature of last 15 years in order to find the variation of geometry of vanishing flow with various entrance channels. The results are presented in the graphical manner.

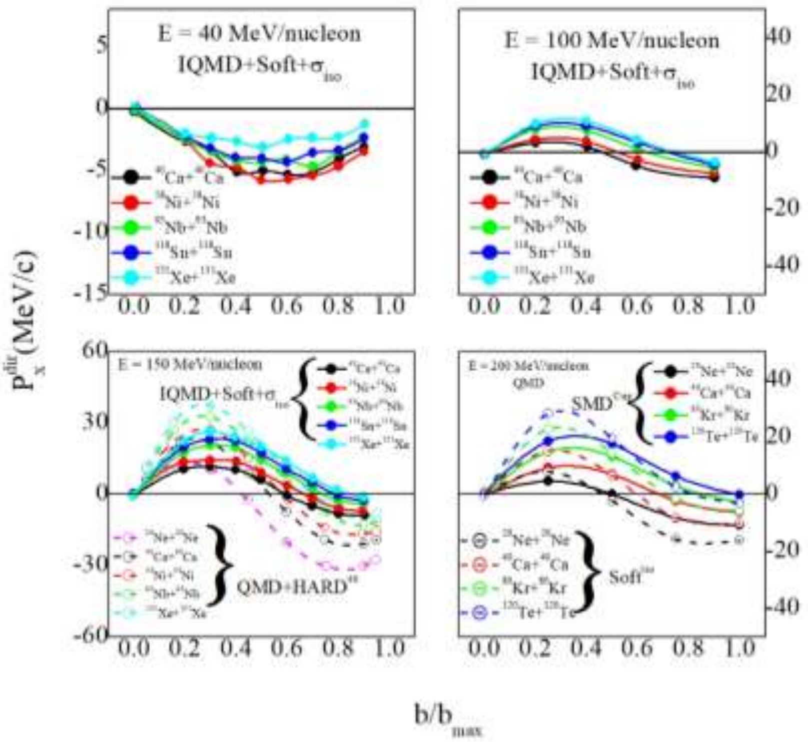

Figure 1. Variation of $<P_x^{dir}>$ with reduced impact parameter (b/b_{max} where $b_{max} = 1.142(A_P^{1/3} + A_T^{1/3})$; $A_{P/T}$ is the mass of projectile/target) at different incident energies for various symmetric systems. The data is taken from Refs. [19-21,23].

In Fig. 1 we display the variation of $<P_x^{dir}>$ (MeV/c) with reduced impact parameter (b/b_{max}) at incident energies of E = 40, 100, 150 and 200 MeV/nucleon [19-21,23]. As it is clear from the figure that the results for various symmetric systems, along with different incident energies, are for different equation of states, system size, cross-sections, and dynamical models. At 40 MeV/nucleon i.e. very low incident energy, the collective flow is negative for each colliding system throughout the colliding geometry range. This is due to the dominance of attractive mean field over the binary n-n repulsive interactions [23]. But as we move from very low incident energy towards higher one, i.e. for 100 MeV/nucleon, 150 MeV/nucleon and 200 MeV/nucleon, due to the dominance of repulsive interactions, the flow rises with impact parameter. At semi-central geometries, it reaches a maximum value and finally becomes negative at higher impact parameters (because of the absence of repulsive interactions at peripheral geometries). Geometry of vanishing flow (GVF) is the impact parameter where <P_x^{dir}> (MeV/c) becomes zero. At 150 MeV/nucleon, comparison of the results is shown with different models (QMD and IQMD) and different equation of states. The difference in GVF is due to the difference in cross-section values in both cases as its mass dependence is not sensitive to momentum dependent interactions (MDI) and EoS [19]. At 200 MeV/nucleon, comparison of results is shown for different EoS's i.e. SMD and Soft with same cross-section value. The GVF is little bit more in case of SMD due to the increase in binary n-n collisions with MDI. The effect is more pronounced for heavier systems.

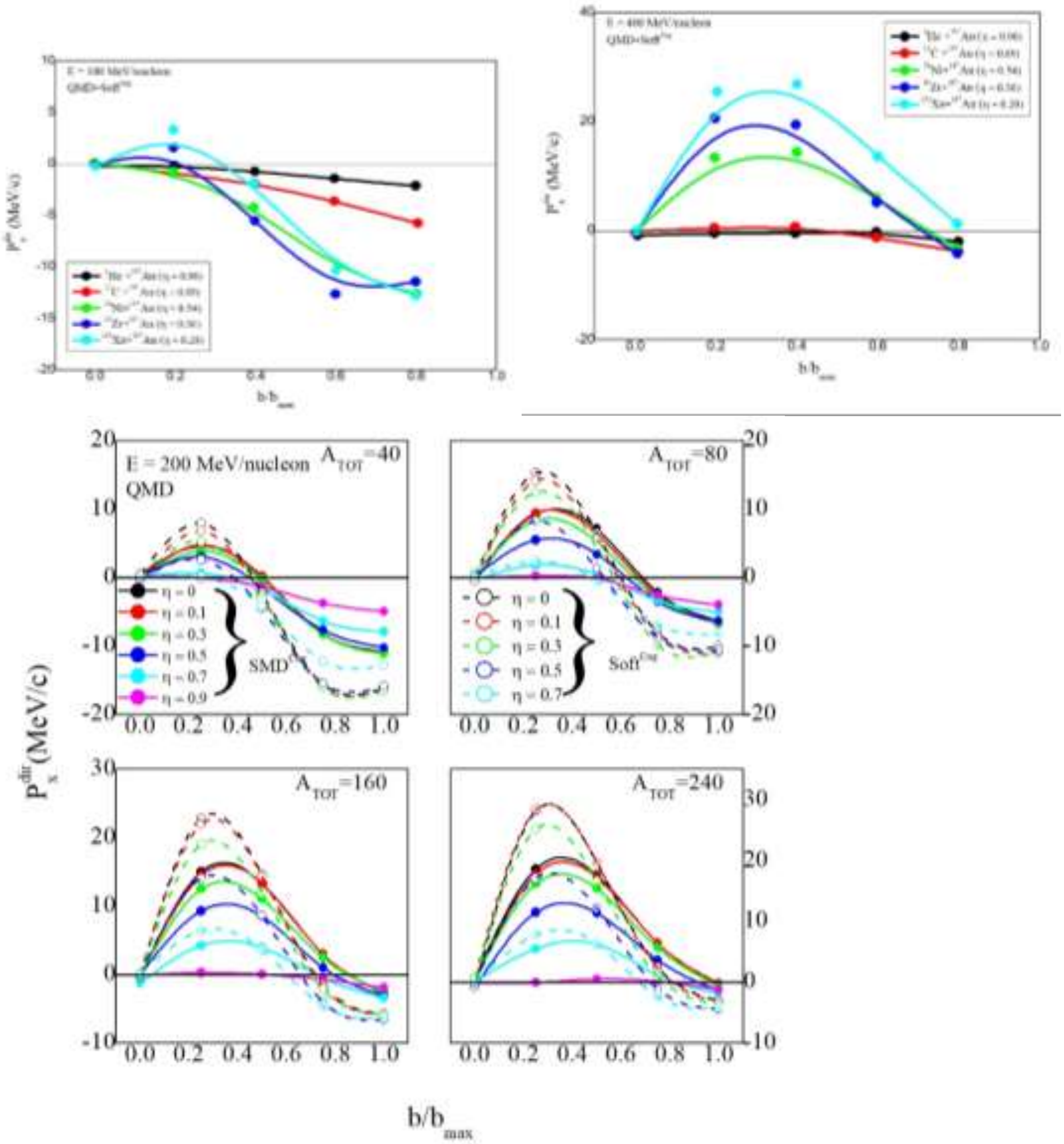

Figure 2. Variation of <P_x^{dir}> with reduced impact parameter at 100, 200 and 400 MeV/nucleon for mass asymmetric systems. The data is taken from Refs. [20-22].

Fig. 2 displays the variation of <P_x^{dir}> (MeV/c) with reduced impact parameter at incident energies of E = 100, 400 and 200 MeV/nucleon [20-22] for different mass asymmetric reactions. For the top and middle panel, the total mass of the system is not constant. The mass of the projectile is varied and the target mass is kept fixed. This is done to see the impact of projectile mass on the flow and GVF. The results clearly depict that at 100MeV/nucleon, for lighter projectiles, the flow remains negative at all colliding geometries (pointing towards emission of particles from target) and for heavier projectile, same trend i.e. rise of $<P_x^{dir}>$ from perfectly central to semi-central collisions, reaching maximum and finally decreasing and becoming negative for peripheral geometries is seen. At 400 MeV/nucleon, at all impact parameters, $<P_x^{dir}>$ is more than at 100 MeV/nucleon. This is due to the increase in binary collisions with energy. At 200 MeV/nucleon, the results are shown for different mass asymmetries and equation of state for different total system mass. Uniform trend of rise and fall with b/b_{max} is seen in all cases. The variation in collective flow and GVF with total mass, equation of state and η is seen. Moreover, the role of equation of state on GVF is more pronounced for heavier systems with high asymmetry ($\eta = |A_T-A_P/A_T+A_P|$; $A_{P/T}$ is the mass of projectile/target).

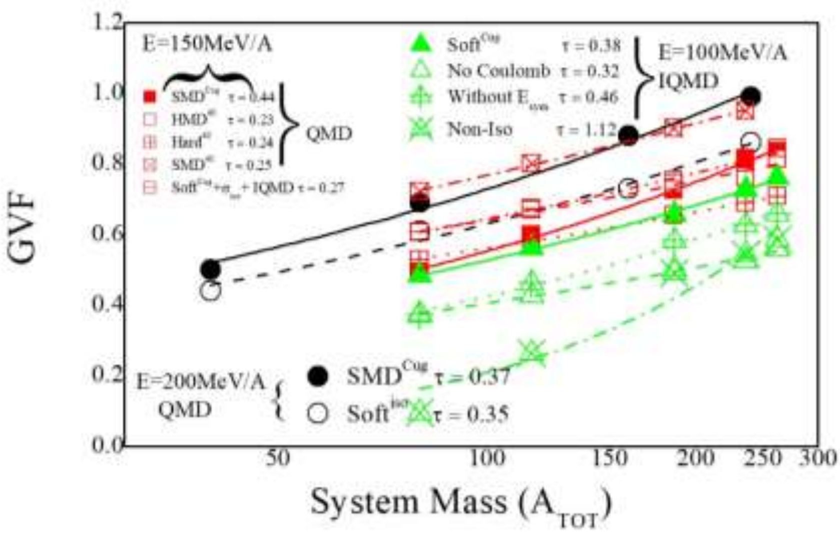

Figure 3. The variation of GVF with total mass of the system. The results are shown for symmetric systems at different incident energies, equation of states, dynamical models and cross-sections. The lines are power law fits ($\propto A^{\tau}_{TOT}$). The data is taken from Refs. [19-21,23].

In Fig. 3, we display the system size variation of GVF for symmetric reactions. The data is extracted from Ref. [19-21,23]. Power law fitting is shown by lines. At 150 and 200 MeV/nucleon, we see that EoS and MDI has no effect on the mass dependence of GVF. It is clear from the values of τ. But the cross-section (in case of QMD calculations [19,20]) and isospin (through nn cross section in IQMD calculations [23]) has significant effect on mass dependence of GVF making it a suitable candidate to find nn cross section.

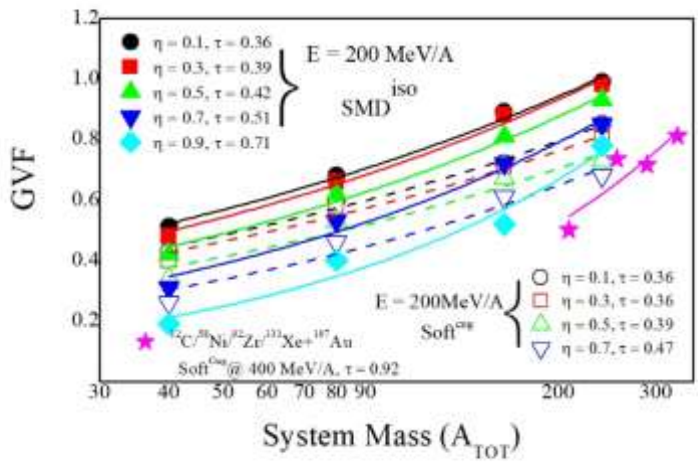

Figure 4. Same as Fig. 3 but for mass asymmetric systems. The lines are power law fits ($\propto A^{\tau}_{TOT}$). The data is taken from Refs. [20-22].

Similar to figure 3, the system size dependence for different mass asymmetric reactions at 200 MeV/nucleon [20,21] and 400 MeV/nucleon [22] is shown in Fig. 4. All the results are calculated using QMD model. It is clear form the figure that with rise in η, the mass dependence of GVF also increases. The role of equation of state is little prominent at higher asymmetries only. The results at 400 MeV/nucleon are show an increase in GVF with total mass of the system. The power factor is different from the other cases as the mass asymmetry is not kept fixed.

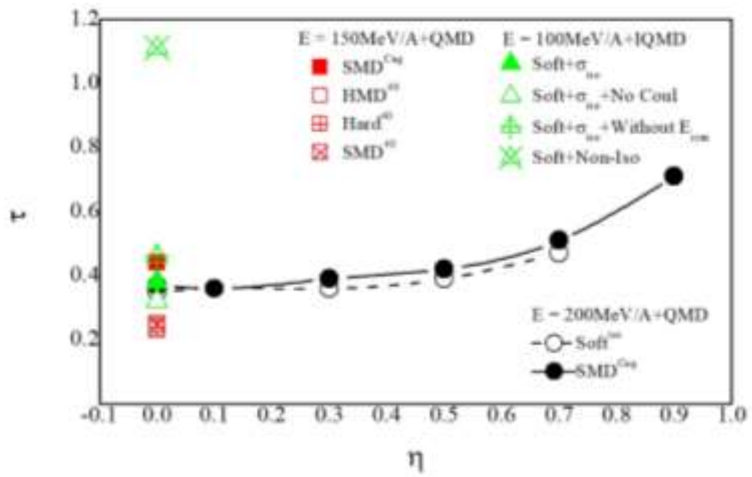

Figure 5. The variation of power factor 'τ' with mass asymmetry 'η' of the reaction. The results are shown at different incident energies. The lines are just to guide the eye. The data is taken from Refs. [19,20,21,23].

In Fig. 5, we present the variation of power factor 'τ' with mass asymmetry 'η' of the reaction. Explanation of the symbols is given in the figure. It is clear for the figure that at 200 MeV/nucleon [20,21], there is an increase in the value of power factor with mass asymmetry of the reaction for both Soft and SMD equations of states. Moreover, the values do not differ from each other representing that GVF is insensitive to equation of state. For symmetric systems i.e. $\eta = 0$, the results at 150 MeV/nucleon [19] and 100 MeV/nucleon [23] are also displayed. The variation in the results is due to the difference in incident energy, mass range, dynamic model and cross section of the reaction.

3. Conclusion

Here a review of geometry of vanishing flow (GVF i.e. the impact parameter at which flow vanishes) is presented in a systematic way to see the impact of entrance channel parameters on mass dependence of GVF. It is clear from the results that (i) collective flow is sensitive to incident energy, impact parameter, mass asymmetry of the reaction, equation of state and cross section of the reaction (ii) for both symmetric and mass asymmetric reactions, EoS and MDI has no effect on the mass dependence of GVF but cross section has significant effect on it.

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