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Role of Incident Energy of Reaction on the Energy and Geometry of Vanishing Flow for Au-Au Collisions.

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Abstract: We study the role of incident energy and impact parameter on the collective transverse flow, energy of vanishing flow (EVF) and the geometry of vanishing flow (GVF) for ^{197}Au+^{197}Au collisions using Quantum Molecular Dynamics Model (QMD). Our results clearly indicate that EVF and GVF are quite sensitive to the colliding geometry and incident energy of the reaction, respectively.

Keywords: *heavy-ion collisions, balance energy, impact parameter, geometry of vanishing flow, directed/collective transverse flow, ^{197}Au+^{197}Au collisions, QMD*

1. Introduction

The properties of nuclear matter that is hot and dense can be studied by considering collective or directed transverse flow of the matter. The flow measurements on symmetric nuclear matter helps to constrain its equation of state (EoS) as collective flow is quite sensitive to EoS [1]. In the last three decades, theoretical and experimental works are extensively carried out on collective flow to study the impact of input parameters like incident beam energy [2,3], impact parameter [4,5], size of the system [6,7], mass and mass asymmetry of system [8], and isospin [9-11] on it. At low energies, the collective flow is negative as attractive mean field governs the system whereas, the flow shifts to positive due to the governance of repulsive n-n collisions at high incident energies. 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 or Energy of Vanishing Flow (EVF) [12]. Extensive study on theoretical and experimental front has been done to find the value of EVF and its dependence on mass asymmetry [8], colliding nuclei mass [13,14], impact parameter [15] and isospin [10,16] of reaction. In Ref. [17] and [18], work has been done to find the dependence of elliptical flow and multifragmentation on input parameters, respectively. Impact parameter, also termed as colliding geometry, has significant effect on the collective flow and its disappearance. It shows a rise and fall behavior as on goes from central to peripheral values. The value at which collective flow crosses zero on the graph with impact parameter is termed as Geometry of Vanishing Flow (GVF) [19]. The value of GVF is dependent on various factors like mass of colliding nuclei, mass asymmetry of the reaction and the reaction cross section [19]. For the symmetric systems it is also seen that the sensitivity of mass dependence of GVF towards n-n cross section makes GVF a good candidate to study n-n cross section, whereas it is insensitive towards

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momentum dependent interactions and matter equation of state [19].

In the literature, the study of EVF and GVF for the symmetric systems is only limited to certain fixed value of energy and impact parameters. Therefore, we plan to see the behavior of collective flow, EVF and GVF for heaviest system i.e. $^{197}Au+^{197}Au$ collisions for a wide range of incident energies and colliding geometries. The simulations are done with (n-body) Quantum Molecular Dynamics (QMD) model which is discussed in brief in Ref [20]. Results and summary are discussed in Sec 2 and 3 along with references in Sec 4.

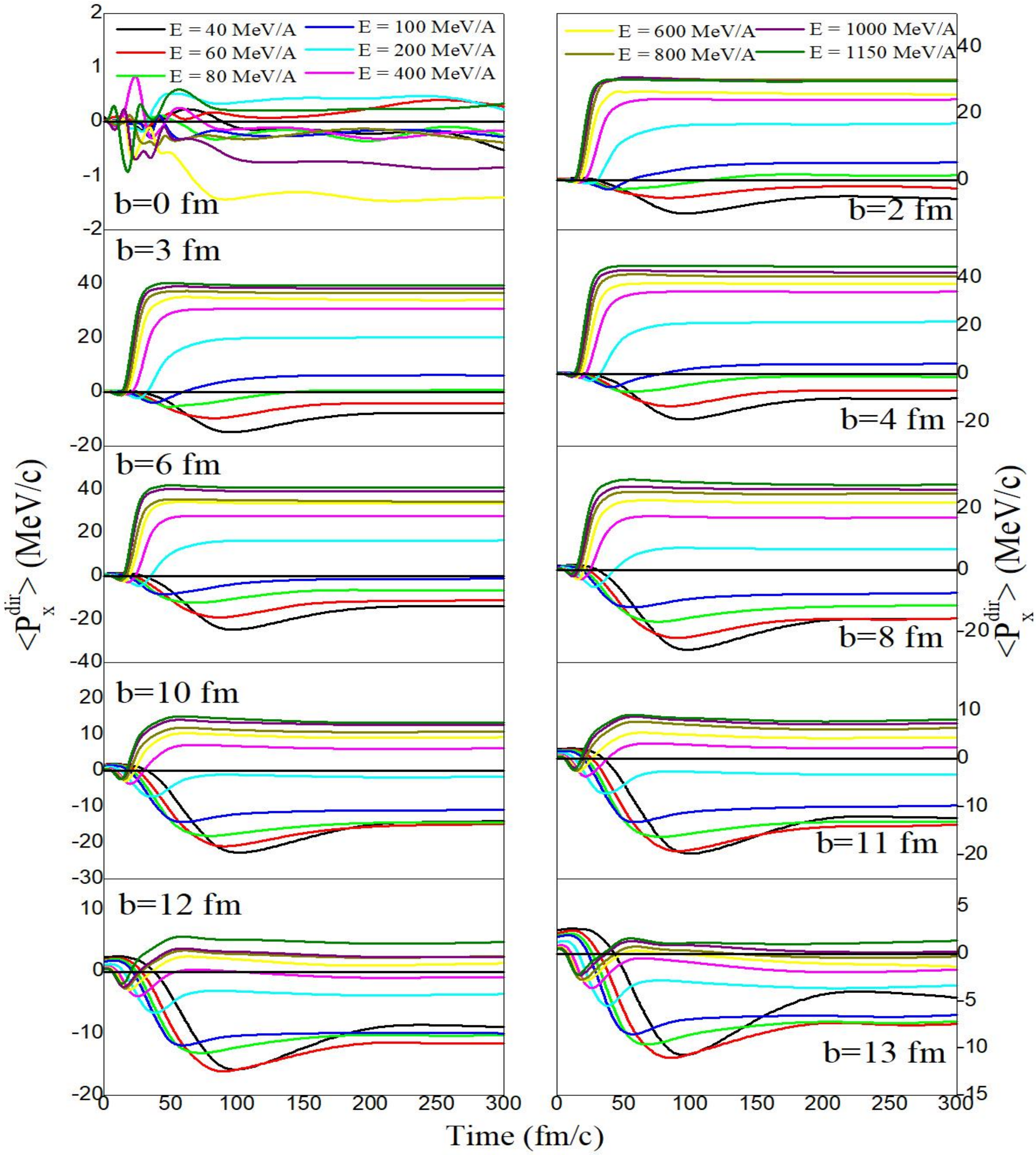

Figure 1. The time evolution of collective flow $<P_x^{dir}>$ for $^{197}Au+^{197}Au$ collisions at different incident energies and for different impact parameters.

2. Results and Discussion

We simulated the reactions of $^{197}Au+^{197}Au$ at various incident energies i.e. E =20, 30, 35, 40, 50, 60, 75, 80, 100, 150, 200, 250, 400, 500, 600, 800, 1000 and 1150 MeV/nucleon and over the entire colliding geometry i.e. for b = 0, 2, 3, 4, 6, 8, 10, 11, 12, and 13 fm. The results are also shown with reduced impact parameter i.e. 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. A soft equation of state along with standard energy dependent n-n cross section [21] is used for the results. The freeze-out time is taken to be 500 fm/c for E = 20 MeV/nucleon and 300 fm/c for remaining values of energy. The transverse collective flow has been calculated by using different variables [14] but in the end yield same results. In the present study the method used in Ref [19,22] is used to calculate transverse/collective flow.

Fig. 1 displays $<P_x^{dir}>$ verses time for $^{197}Au+^{197}Au$ collisions at different incident energies for all colliding geometries. It is clear from the figure that $<P_x^{dir}>$ remains nearly zero for central collisions i.e. b = 0 fm at all energies. As we go from perfectly central collisions i.e. b = 0 towards semi-central one i.e. till b = 4 fm, $<P_x^{dir}>$ increases with increase in energy. This is due to the increase in pressure gradient of reaction which in turn increases the binary n-n collisions with increase in energy. After reaching a maximum value at a particular impact parameter, the values of $<P_x^{dir}>$ starts to decrease with rise in 'b' as n-n collisions starts decreasing with increase of impact parameter. This trend is seen for each incident energy.

Fig. 2 displays the time evolution of $<P_x^{dir}>$ for $^{197}Au+^{197}Au$ at different colliding geometries. The effect of impact parameter on $<P_x^{dir}>$ is seen at different incident energies. During the initial times of the reaction, because of the dominance of attractive interactions (mean field), the flow is negative. Depending on energy, these interactions remain attractive or turn repulsive in nature. It is very much evident from the figure that for each colliding geometry, at low incident energies till 60-80 MeV/nucleon, the mean field dominates and the flow is negative. As the energy increases, the repulsive n-n collisions start dominating and the flow is positive for semi-central geometries. For the incident energy greater than 200 MeV/nucleon, only mean field dominates and at all the impact parameters the flow is positive.

Fig. 3 displays the incident energy dependence (from 20 MeV/nucleon to 1150 MeV/nucleon) of $<P_x^{dir}>$ for $^{197}Au+^{197}Au$ at different colliding geometries. Different colored lines in the figure represent different impact parameters. At all impact parameters, flow is negative at low incident energies and with rise in incident energy turns positive. The value of energy where flow is zero, is termed as balance energy or EVF. From the figure, it is clear that for all the colliding geometries, the flow increases with energy but the increase is intense at low energies compared to higher one where flow starts saturating. From central to semi-central collisions, the flow is increasing but starts decreasing as the impact parameter further increases. The value of EVF increases as impact parameter increases, which is clearly shown in Fig. 4. This is because as b increases, n-n collisions decreases and more energy is required to balance the mean field attractive interactions and repulsive n-n in medium interactions.

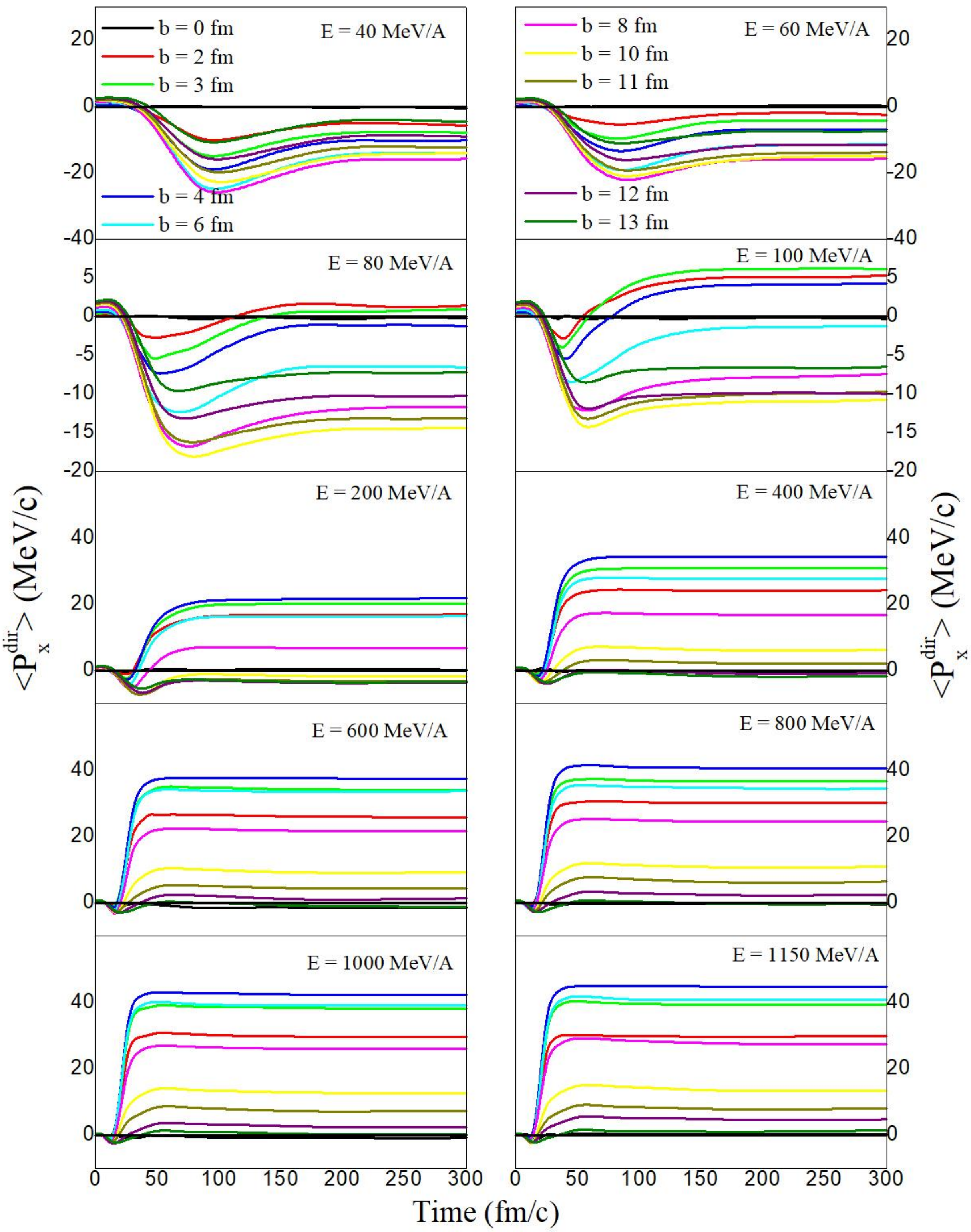

Figure 2. Same as figure 1 but comparison is done with different impact parameters for different energies.

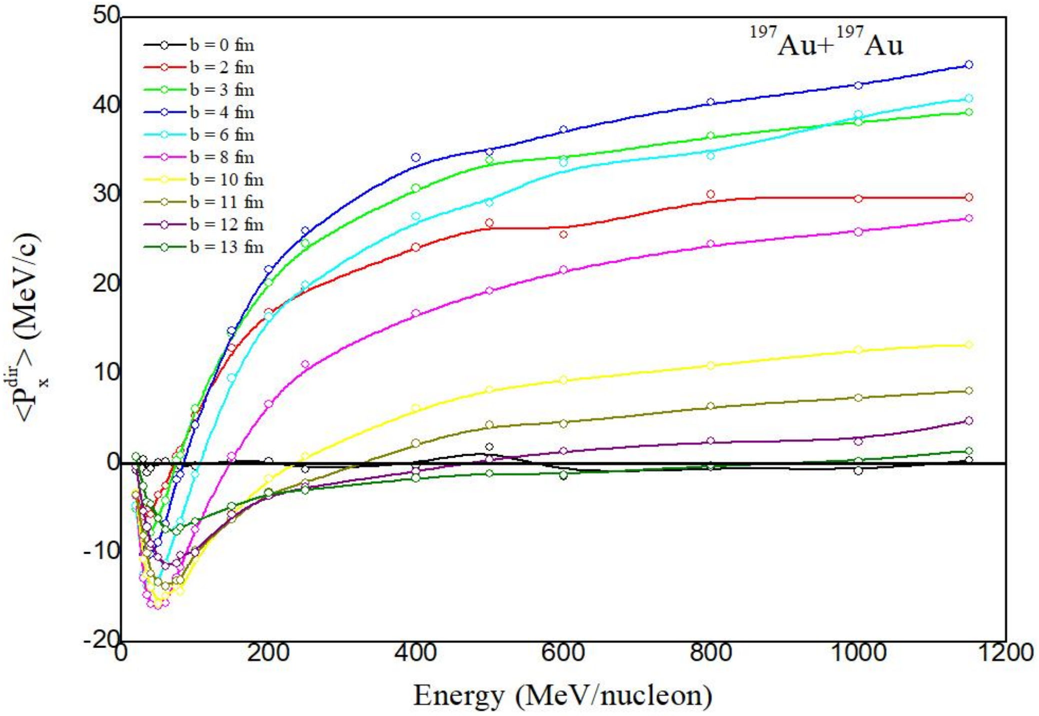

Figure 3. Incident energy dependence of final stage $<P_x^{dir}>$ (transverse/collective flow) at impact parameters of b = 0, 2, 3, 4, 6, 8, 10, 11, 12, and 13 fm for $^{197}Au+^{197}Au$ collision.

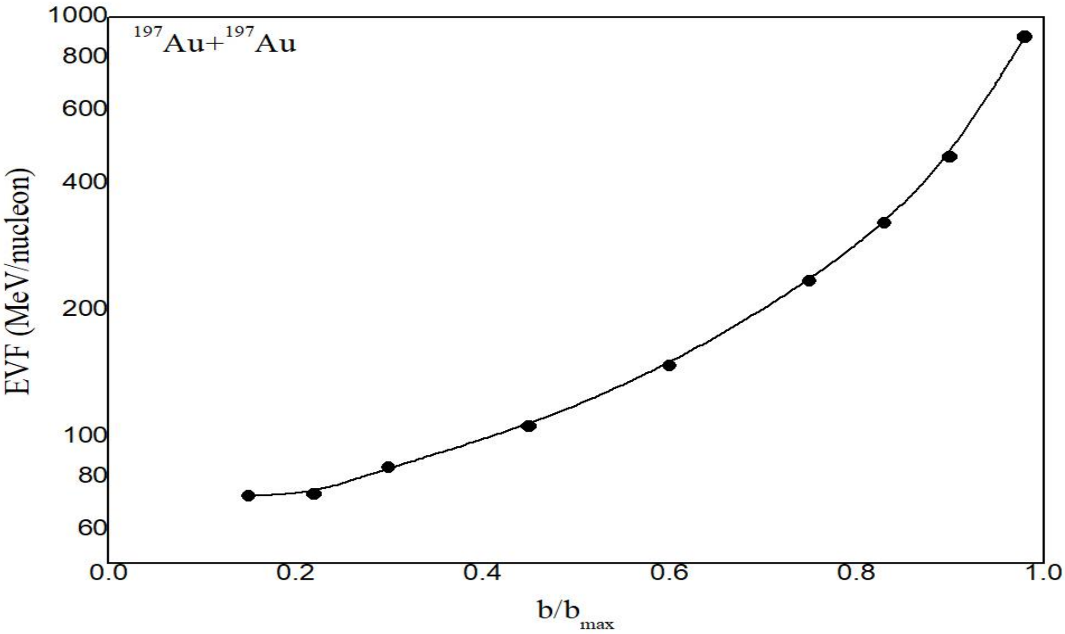

Figure 4. The EVF as a function of reduced impact parameter (b/b_{max}) for $^{197}Au+^{197}Au$ collisions. Log scale is used along y-axis.

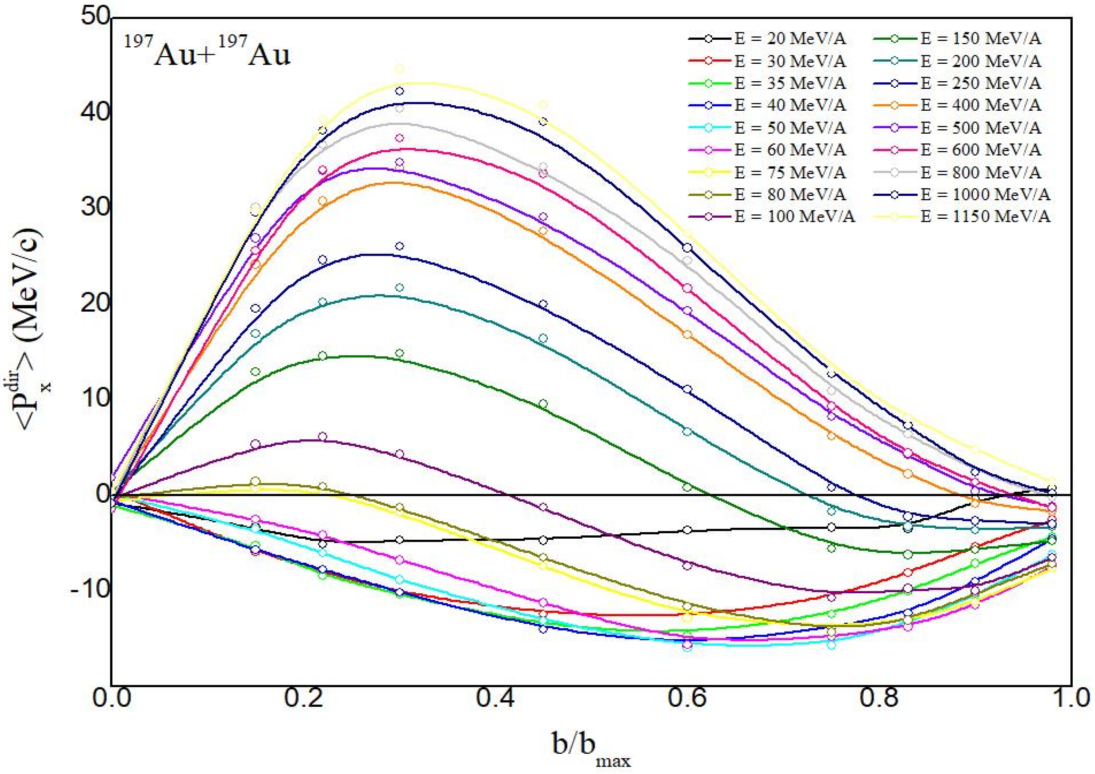

Figure 5. Reduced impact parameter dependence of final stage $<P_x^{dir}>$ (transverse/collective flow) at different incident energies (as shown in figure with different colored lines) for ^{197}Au+^{197}Au collision.

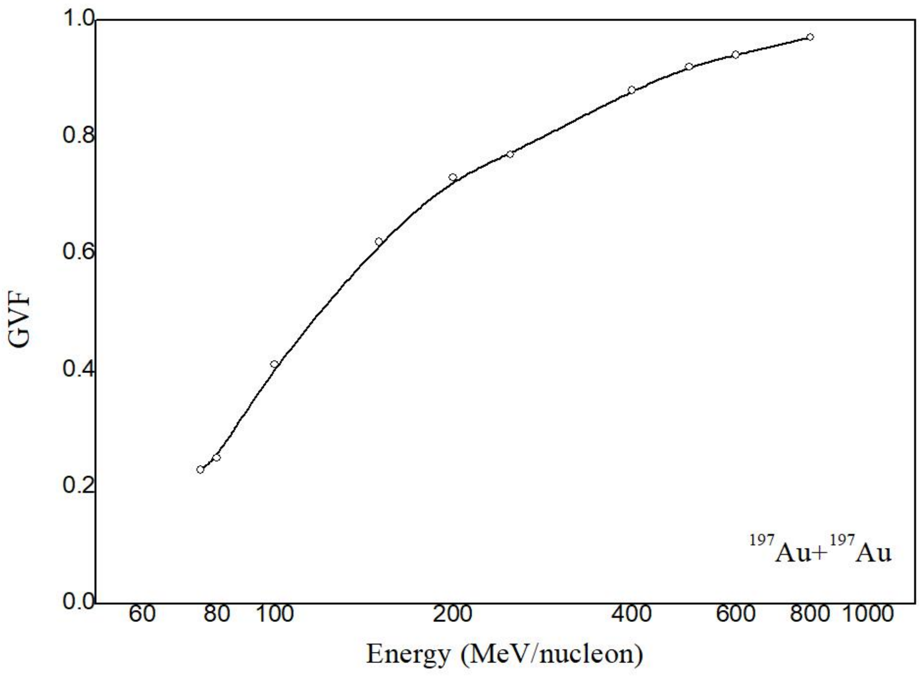

Figure 4. The GVF as a function of incident energy. Log scale is used along x-axis.

Similar to Fig. 3, the reduced impact parameter dependence of flow is shown in Fig. 5. The results are shown at different incident energies. It is clear from the figure that for 20-60 MeV/nucleon i.e. low incident energies, the flow remains negative at all impact parameters, indicating the dominance of attractive interactions. As the incident energy increase to 75 MeV/nucleon till 800 MeV/nucleon, the flow shows a rise and fall trend. The value of reduced impact parameter where flow touches zero point is termed as Geometry of Vanishing Flow i.e. GVF. The value of GVF increases with increase in incident energy (as shown in Fig 6.). The increase is sharp at intermediate energies as compared to higher one. But for very high energies i.e. more than 800 MeV/nucleon, due to the dominance of high n-n repulsive collisions, the value of GVF is not found with the present soft equation of state and standard Cugnon energy dependent cross section of nuclear matter. The results are insensitive to equation of state and momentum dependent interactions but may vary with change in the cross section of the reaction [19].

3. Conclusion

Here a comparative study of collective flow, energy of vanishing flow (EVF) and geometry of vanishing flow (GVF) is done for the reaction of ^{197}Au+^{197}Au at different incident energies ranging from 20 MeV/nucleon to 1150 MeV/nucleon and over entire colliding geometry. Our results using QMD model clearly display that EVF increases with increase in impact parameter and GVF increases with increase in incident energy. Below 75 MeV/nucleon and above 800 MeV/nucleon, GVF is not traceable for the present case.

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