Study of collective flow, its disappearance and nuclear dynamics using isospin-dependent quantum molecular dynamics model

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Introduction

With the development of various experimental facilities around the world, the field of nuclear physics has gained a major boost. Various nuclear reactions involving stable or neutron rich nuclei can be studied at these facilities, which, in turn, have provided us a great opportunity to probe the dynamics of the nuclear reactions via collective flow, fragmentation and nuclear stopping. Such studies help us to determine the in-medium nuclear interactions, equation of state of symmetric/asymmetric nuclear matter and also the density dependence of the nuclear symmetry energy. The present work deals with the detailed theoretical study of the collective flow, its disappearance (at energy of vanishing flow) and other related phenomena in heavy-ion collisions at intermediate energies. This study is carried out within the framework of Isospin-dependent Quantum Molecular Dynamics (IQMD) model [1]. The IQMD model is n-body theory which simulates heavy ion reaction on event by event basis, hence preserves correlations and fluctuations of a reaction. The isospin degree of freedom enters into the calculations via symmetry potential, cross-sections, and Coulomb interaction. The several attempts in the literature showed that IQMD model has been successful in explaining several phenomena at low and intermediate energies.

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Results and discussion

As a first part of the study, we investigated the role of structural effects i.e. nuclear radii on the dynamics of heavy-ion reactions at intermediate energy. Our study pointed towards highly sensitive behavior of the lighter systems towards structural effects, whereas heavier systems are found to be insensitive towards the choice of the nuclear radius. Moreover, we also reproduced the energy of the vanishing flow for the reaction of $^{12}C+^{12}C$ using experimental Elton radius which was not possible in the past [2].
Next, we presented the calculations of the mass dependence of energy of vanishing flow for the reactions with masses ranging between 24 and 394 units for which the experimental energies of vanishing flow are available [3]. Our calculations using SMD equation of state along with reduced cross-section confirmed the power law dependence of the energy of vanishing flow, in accordance with earlier studies, and showed a good agreement with the experimentally observed mass dependence of the EVF. We also presented a complete study of the impact parameter dependence of the EVF over the entire mass range (for which experimental data is available) and confronted our calculations with experimental data. Our calculations reproduced the experimental data to a reasonably good extent. We also compared our calculations on the EVF with various other theoretical models calculations and tried to analyze the difference in the calculations if any. Our findings revealed that once the physical parameters are fixed, different numerical realizations as well as various transport models such as BUU, IBUU, RVUU, LV, QMD, IQMD, RQMD, AMD and optical

model yield nearly same energy of vanishing flow in most of the cases [3].
The energy of vanishing flow has been reported to depend on the equation of state, nn cross-section as well as on other model ingredients. Yet, no systematic study is available with regard to these parameters. To have an accurate information about the parameters of interest, we analyzed, in detail, the role of hard and soft equations of state (with and without momentum-dependent interactions), different nn scattering cross-sections, Coulomb potential and symmetry energy and isospin dependence of the cross-section on the directed flow and its disappearance over a wide range of mass (30-394 units) and impact parameters [4, 5]. Our investigations pointed towards the significant sensitivity of the mass dependence of EVF towards above mentioned parameters at central as well as peripheral collisions except to nn scattering cross-section at central collisions except in case of the central collisions, power law factor τ remains unaffected by the choice of the nn scattering cross-section. Our study also projected the mass dependence of the energy of vanishing flow at peripheral collisions as an useful probe to pin down the stiffness of nuclear matter. Moreover, the dominance of Coulomb potential was observed among the three isospin effects at peripheral collisions.
The synthesis of superheavy nuclei has attracted much attention from the nuclear physics community and recent studies have also focused in investigating the ground state properties of the superheavy nuclei such as half-life time period, different decay mode, rotational effects and root mean square radii etc. Therefore, it would be interesting to analyze directed flow and its disappearance to the reactions involving superheavy nuclei. So next, we extended our study on the mass dependence of energy of vanishing flow in the superheavy mass region within the framework of isospin-dependent quantum molecular dynamics model [6]. Our calculations for the mass dependence of the EVF in the superheavy mass region showed significant deviations from the power law mass dependence from the well documented $A^{1/3}$ dependence obtained for the stable nuclei a significant dominance of the repulsive Coulomb force in superheavy mass region. This study enhances our understanding about the dynamics of the flow in the reactions involving superheavy nuclei.
Lastly, we studied the degree of the equilibrium attained in a reaction through the 3D density plots, anisotropy ratio as well as by the rapidity distribution of the nucleons in HIC at intermediate energies. The equilibrium achieved in a reaction is found to be directly related to the number of the binary collisions and found to depend on the incident energy, colliding geometry as well as on the choice of radii. The effect of the radius on the equilibrium attained in heavy systems is found to be negligible compared to that observed in the lighter systems. Also in the reactions involving superheavy nuclei, the role of Coulomb potential was analyzed on the equilibrium attained in a reaction.

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