

Study of Intermediate Energy Heavy-ion Collisions in Asymmetric Colliding Nuclei Using Computational Methods

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Abstract— We study the fragmentation pattern of some of the nearly symmetric and asymmetric reactions within the microscopic framework of isospin-dependent quantum molecular dynamics model and compare our calculated results with available experimental data as well as with the results of other model calculations. We find that though isospin-dependent quantum molecular dynamics model works fine for various nearly symmetric and asymmetric reactions, it fails to handle the dynamics of highly asymmetric reactions at very low incident energies.

Index Terms— Asymmetric reactions, Molecular dynamics model, clusterization algorithm, heavy-ion collisions at intermediate energies.

I. INTRODUCTION

Probing the characteristics of nuclear matter at the extreme conditions of density and temperature is a major challenge in nuclear physics research. Such situation of high density and temperature can be produced in heavy-ion-induced collisions (reactions) at intermediate energies [1], [2], [3], [4], [5], [6], [7], [8], [9]. The main motivation behind studying heavy-ion collisions at intermediate energy range is to determine the nuclear matter equation of state (EOS) and to understand the collision processes which vary over the large range of energies available (due to advancements in the radioactive-ion beam facilities all around the world) today.

It is worth mentioning that heavy-ion collisions at intermediate energies result in the formation of hot nuclei with moderate temperature and these nuclei can be de-excited by different decay modes including multifragmentation [1], [2], [4], [5], [6], [7], [8], [9]. This phenomenon of nuclear matter fragmenting into various pieces is an area of much activity both in experiments and in the theory. It also helps in understanding the processes of phase-transition in nuclear matter and the nuclear matter equation of state.

The experiments carried out for multifragmentation can be divided into symmetric and asymmetric reactions [1], [8], [9]. The asymmetry of a reaction can be defined with the help of parameter $\eta = |(A_T - A_P)/(A_T + A_P)|$; where A_P and A_T are the

masses of the projectile and target, respectively. Various non zero values of η define different asymmetries of a reaction, whereas $\eta = 0$ represents symmetric reactions. Also, it is very much clear now that reaction dynamics of symmetric reactions can be quite different than asymmetric reactions [2], [5], [8], [9]. This difference in the dynamics results due to deposition of incident energy in the form of thermal and compressional energies in asymmetric and symmetric reactions, respectively. This means that for symmetric reactions, the thermodynamical properties of a model may not play significant role. On the other extreme, the asymmetric reactions compress matter gently and hence, much of the share of excitation energy is in the form of thermal energy. This excess thermal energy can be treated only if the model incorporates thermodynamical properties in a correct way [8].

It is worth mentioning that various studies have been reported in the literature regarding the failure of Quantum Molecular Dynamics (QMD) type models to handle the dynamics of asymmetric reactions, though, they work fine for symmetric reactions [5], [10]. In this regard, Donangelo et al. [10] studied the reactions of $^{16}\text{O}/^{40}\text{Ar}/^{84}\text{Kr} + \text{AgBr}$ using different versions of molecular dynamics approach and revealed the failure of these approaches to reproduce the experimental multiplicities in asymmetric reactions. Another study was performed by Souza et al. [11] to investigate the transition from fusion, fission to multifragmentation by simulating the reaction of $^{16}\text{O} + ^{80}\text{Br}$ at different beam energies. Another inadequacy of the QMD approach in reproducing the measured multiplicities of intermediate mass fragments (IMFs) for asymmetric reactions was reported in Ref. [5]. Therefore, one is interested in finding/developing modified versions of Quantum Molecular Dynamical type models that can handle the dynamics of asymmetric reactions. Recently, two of us and collaborators performed a detailed study [8] using Isospin-dependent Quantum Molecular Dynamics (IQMD) model [12] and reported that IQMD model (due to various refine ingredients such as symmetry potential and initial large Fermi-momentum) can handle the dynamics of asymmetric reactions in the Fermi-energy domain. However, extensive experimental measurements are available for asymmetric reactions and therefore for complete picture, we are further interested to check the efficacy and applicability of the IQMD model towards the other asymmetric reactions. Moreover, to investigate the working of different theoretical models towards various symmetric and asymmetric reactions

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is also an important issue. Therefore, in this article, we will apply IQMD approach to check its applicability for some more asymmetric reactions and simultaneously, we will also probe the behavior of other models for the asymmetric reactions. Section II deals with the outlines of the model followed by the calculations in section III. Our results are summarized in section IV.

II. THE FORMALISM

The Isospin-dependent Quantum Molecular Dynamics (IQMD) model [8], [12] is an improved version of the Quantum Molecular Dynamics (QMD) model [13] and it has been applied successfully for the analysis of various observables from low to relativistic energies. In this model, symmetry potential, isospin-dependent nucleon-nucleon (NN) cross-section and Coulomb interactions come into existence with the incorporation of isospin degree of freedom. In this model, each baryon is represented with the help of Gaussian shaped density distribution given by:

$$f_i(\vec{r}, \vec{p}, t) = \frac{1}{\pi^2 \hbar^2} \exp(-[\vec{r} - \vec{r}_i(t)]^2 \frac{1}{2L}) \times \exp(-[\vec{p} - \vec{p}_i(t)]^2 \frac{2L}{\hbar^2}) \quad (1)$$

The nucleons of the target and projectile interact by two and three-body Skyrme forces, Yukawa potential and Coulomb interactions. In addition, a symmetry potential between protons and neutrons has also been included. The hadrons propagate with the help of Hamilton's equations of motion:

$$\frac{d\vec{r}_i}{dt} = \frac{d\langle H \rangle}{d\vec{p}_i}, \quad \frac{d\vec{p}_i}{dt} = -\frac{d\langle H \rangle}{d\vec{r}_i} \quad (2)$$

With

$$\begin{aligned} \langle H \rangle &= \langle T \rangle + \langle V \rangle \\ &= \sum_i \frac{p_i^2}{2m_i} + \sum_i \sum_{j>i} \int f_i(\vec{r}, \vec{p}, t) V^{ij}(\vec{r}', \vec{r}) \\ &\quad \times f_j(\vec{r}', \vec{p}', t) d\vec{r}' d\vec{r}' d\vec{p}' d\vec{p}' \end{aligned}$$

The baryon potential V^{ij} , in the above relation, reads as:

$$\begin{aligned} V^{ij}(\vec{r}' - \vec{r}) &= V_{Skyrme}^{ij} + V_{Yukawa}^{ij} + V_{Coul}^{ij} + V_{sym}^{ij} \\ &= \left[t_1 \delta(\vec{r}' - \vec{r}) + t_2 \delta(\vec{r}' - \vec{r}) \rho^{\gamma-1} \left(\frac{\vec{r}' + \vec{r}}{2} \right) \right] + \\ &\quad t_3 \frac{\exp(-|\vec{r}' - \vec{r}|/\mu)}{(|\vec{r}' - \vec{r}|/\mu)} + \frac{Z_i Z_j e^2}{|\vec{r}' - \vec{r}|} + \\ &\quad t_4 \ln^2 \left[t_5 \left(\frac{\vec{p}' - \vec{p}}{P} \right)^2 + 1 \right] \delta \left(\frac{\vec{r}' - \vec{r}}{r} \right) + \\ &\quad t_6 \frac{1}{\rho_0} T_{3i} T_{3j} \delta(\vec{r}' - \vec{r}_j). \end{aligned}$$

Here $t_6 = 4C$, $C = 32$ MeV, Z_i and Z_j denote the charges of i^{th} and j^{th} baryon, and T_{3i} and T_{3j} are their respective T_3 components (i.e., $1/2$ for protons and $-1/2$ for neutrons).

The IQMD model stores the phase space of nucleons at different times and therefore, clusters are identified using

various clusterization procedures [14], [15], [16], [17]. In the present study, we will use Minimum Spanning Tree (MST) method [13] to clusterize the phase space of nucleons. This method allows two nucleons to share the same fragment if the distance between their centroids is less than 4 fm. We, however, also acknowledge that various other novel clusterization algorithms are available in the literature [14], [15], [16], [17].

III. RESULTS AND DISCUSSION

Here, we simulate central reactions of $^{16}\text{O} + ^{80}\text{Br}$ ($\eta = 0.66$), $^{16}\text{O} + ^{108}\text{Ag}$ ($\eta = 0.74$), $^{197}\text{Au} + ^{12}\text{C}$ ($\eta = 0.89$), $^{36}\text{Ar} + ^{197}\text{Au}$ ($\eta = 0.66$) and $^{129}\text{Xe} + ^{197}\text{Au}$ ($\eta = 0.2$) at incident energies ranging between 27 and 400 MeV/nucleon. The choice of incident energy as well as colliding geometry is as per experimental measurements [18], [19], [20]. All the reactions are simulated using soft equation of state and are followed upto 300 fm/c; which is the saturation time for identifying fragments. In addition, isospin and energy dependent nucleon-nucleon (NN) cross-section reduced by 20%, i.e., $\sigma^{\text{NN}} = 0.8 \sigma^{\text{NN}}_{\text{free}}$ is used. The choice of taking this cross-section is advocated by various earlier studies [8], [9].

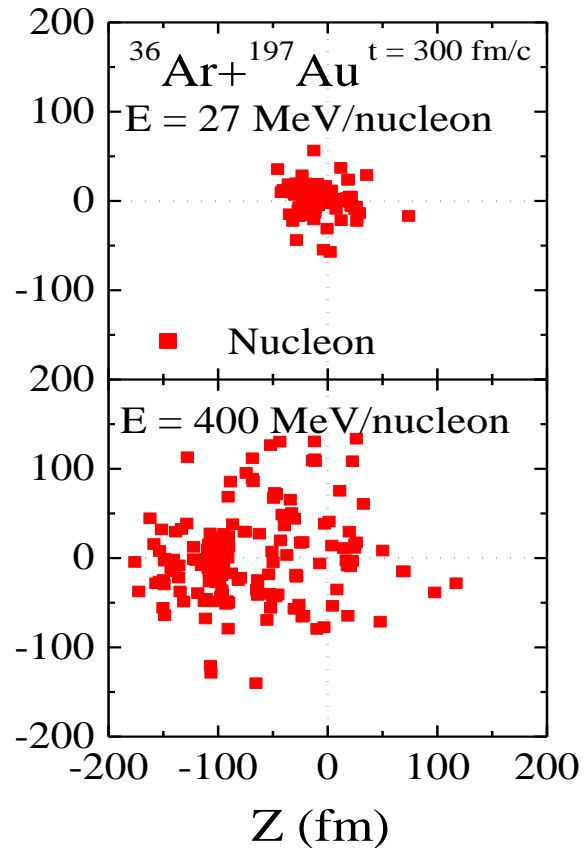


Fig.1. (Color online) The snapshot of the final phase space of a single event for the asymmetric reaction of $^{36}\text{Ar} + ^{197}\text{Au}$ at beam energies of 27 MeV/nucleon (upper panel) and 400 MeV/nucleon (lower panel), respectively.

As stated above, IQMD model is able to study observables from low to relativistic energies, so, let us first see its ability to shatter the asymmetric colliding nuclear matter at low and high incident energies with the help of phase space picture. In

Fig. 1, we display the final state phase space of a single event for the asymmetric reaction of $^{36}\text{Ar}+^{197}\text{Au}$ at two different incident energies of 27 and 400 MeV/nucleon. From the figure, it is very much clear that the breaking of colliding nuclear matter at lower incident energies is small (because at lower incident energies, nuclear matter is compact and almost all the initial correlations are preserved) compared to higher incident energies where violent nature of collisions destroys the nuclei. Now, we will compare our theoretical calculations using IQMD model with the available measurements for the nearly symmetric and asymmetric reactions of $^{129}\text{Xe}+^{197}\text{Au}$ and $^{36}\text{Ar}+^{197}\text{Au}$, respectively.

In Fig. 2, we display the charge distributions for the reactions of $^{129}\text{Xe}+^{197}\text{Au}$ and $^{36}\text{Ar}+^{197}\text{Au}$ at incident energies of 50, 80 and 110 MeV/nucleon using soft equation of state. From the figure, we observe that our calculations using soft EOS are in nice agreement with the experimental measurements [18]. Earlier calculations performed using Percolation model [18] are also displayed in the same figure (see dotted and dash-dotted lines for filtered and unfiltered calculations respectively). The Percolation model calculations require bond breaking probabilities. Here, filtered and unfiltered results are displayed for bond breaking probability equal to 0.7 i.e ($P = 0.7$). This is because in Percolation model, critical point is at $P = 0.7$ which makes a second order phase-transition. For $P < 0.7$, a heavy percolation cluster (fusion - residue) exists but for $P > 0.7$, the system disassemble completely. Also, it is clear from the figure that IQMD gives different results than Percolation model because the later focuses on the bond breaking probabilities.

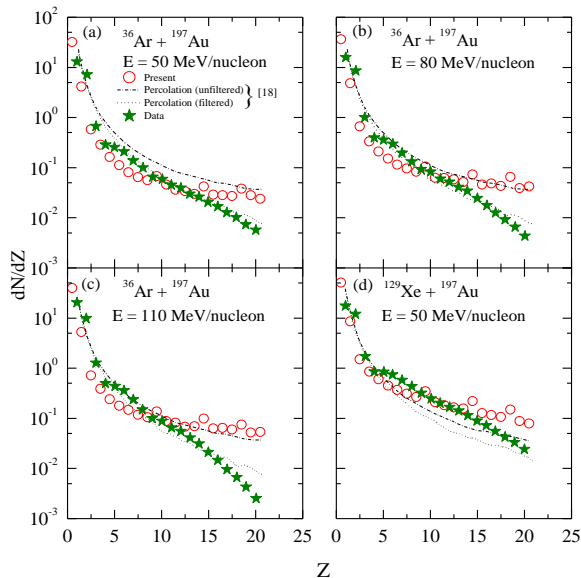


Fig. 2. (Color online) The charge distributions for the reactions of $^{36}\text{Ar}+^{197}\text{Au}$ and $^{129}\text{Xe}+^{197}\text{Au}$ at incident energies of 50, 80 and 110 MeV/nucleon. Open circles and stars correspond to present calculations and experimental measurements, respectively. Experimental data is taken from Ref. [18]. The lines correspond to the results of previous attempts (Ref. [18]).

Next, we confront IQMD model calculations with the

available experimental data of emulsion experiments for asymmetric reactions [11], [19]. The measurements of emulsion experiments are of particular interest because these measurements (which contain fusion as well as multifragmentation and vaporization phenomena) validate any theoretical model designed for studying multifragmentation. We here simulated reaction of $^{16}\text{O}+^{80}\text{Br}$ at several bombarding energies. Stars and solid lines represent the unnormalized experimental data and present calculations, respectively. We observe that the present combination of model ingredients is able to reproduce the experimental charge distributions. For comparison, the calculations of previous attempts [11], [21] are also displayed (see dashed, dotted, dash-dotted lines). Note that molecular dynamics approach using static (soft) equation of state was reported to fail to reproduce the measured charge yield for the reaction of $^{16}\text{O}+^{80}\text{Br}$ [21]. The failure was attributed to the low excitation energy available in case of soft equation of state and therefore, the inclusion of repulsive momentum-dependent interactions was advocated. The inclusion of these interactions leads to extra repulsion and thus, breaking heavier nuclei into lighter ones, giving better agreement with measurements [22].

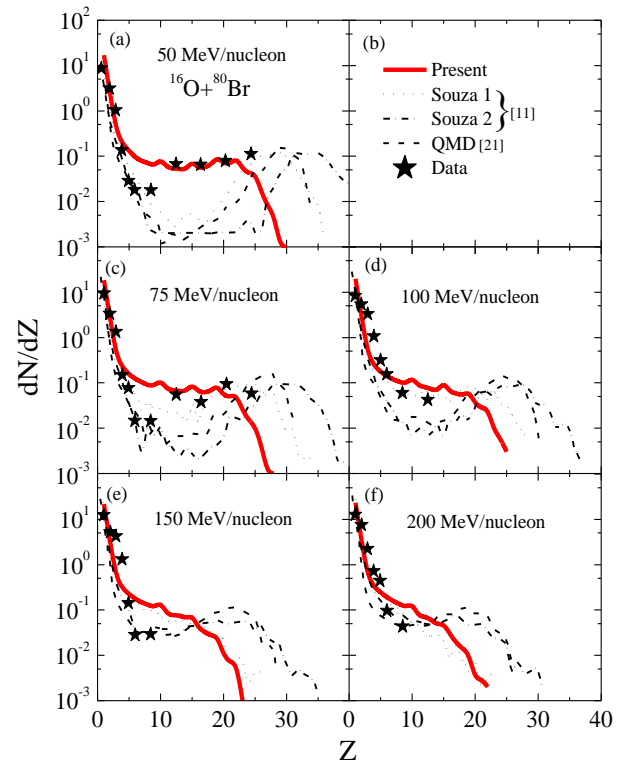


Fig. 3. (Color online) The charge distributions for the reaction of $^{16}\text{O}+^{80}\text{Br}$ at incident energies between 50 and 200 MeV/nucleon. Solid lines represent our present calculations using IQMD model and stars have same meaning as in Fig. 2. The results of previous attempts [11], [22] are also displayed for comparison.

IV. SUMMARY

We presented here an analysis to confront the calculated results of the IQMD model with the various experimental measurements in nearly symmetric and asymmetric reactions. Our study revealed that IQMD model with various refine ingredients is able to handle the dynamics of most of the asymmetric reactions, but it fails to reproduce the measurements for highly asymmetric reactions at lower incident energies. Therefore, further modifications/improvements are required in quantum molecular dynamical type models to handle the dynamics of such reactions.

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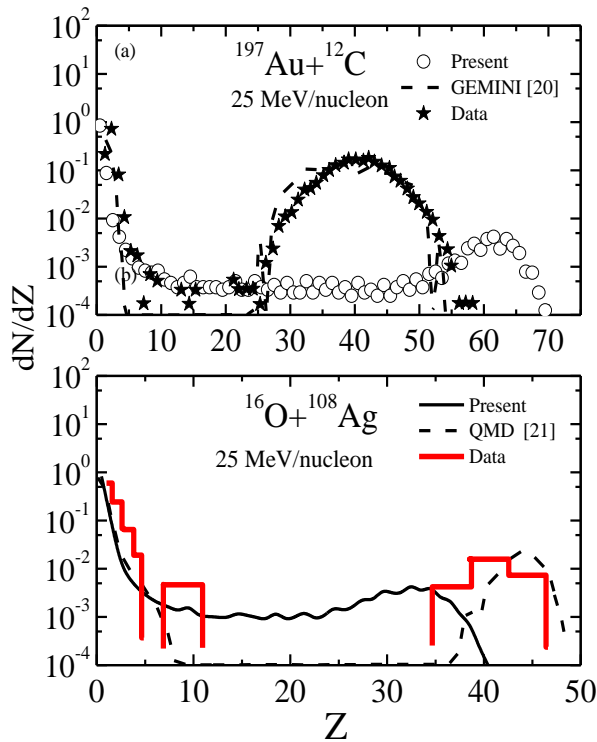


Fig. 4. (Color online) The charge distributions for the reaction of $^{197}\text{Au}+^{12}\text{C}$ (upper panel) and $^{16}\text{O}+^{108}\text{Ag}$ (lower panel) at $E = 25$ MeV/nucleon. Experimental data and previous results are taken from Refs. [19, 20, 22]. "Reprinted from Nuclear Physics A, 945, A. Sharma, A. Bharti, S. Gautam and R. K. Puri, Multifragmentation of nearly symmetric and asymmetric reactions within a dynamical model, 95-111, Copyright (2016), with permission from Elsevier."

But in the present case, IQMD model due to various refine ingredients [8] is able to create an extra repulsion and thus, reproduces the measurements for asymmetric reactions.

Further, we will focus on the highly asymmetric reactions at lower incident energies. This is because at very small incident energies, limited excitation energy may prevent the phenomenon of multifragmentation. In Fig. 4, we display the calculated charge yields along with measurements for the highly asymmetric reactions of $^{197}\text{Au}+^{12}\text{C}$ (upper panel) [20] and $^{16}\text{O}+^{80}\text{Br}$ (lower panel) [19] at incident energy of 25MeV/nucleon. From the figure, we find that calculated results deviate from measured ones. This may be due to the use of simple secondary clusterization algorithm in the present study. On the other hand, further, modifications/improvements are required in the quantum molecular dynamical type models to handle the dynamics of highly asymmetric reactions at very small incident energies.

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