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ON THE ENERGY OF MAXIMUM PRODUCTION OF INTERMEDIATE MASS FRAGMENTS IN HEAVY-ION COLLISIONS USING MICROSCOPIC MODEL

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Abstract. The present study is aimed to show the role played by impact parameter on the peak production of intermediate mass fragments (IMFs) in heavy-ion collisions. The study is conducted for both mass symmetric and mass asymmetric colliding nuclei. Here, the reactions are simulated using a Monte-Carlo based computer program developed utilizing the dynamical equations. Our present analysis shows that the impact parameter influences the reaction results on peak IMF production more drastically for mass asymmetric reactions than mass symmetric reactions.

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1. INTRODUCTION

To interpret the underlying physics from the experimental data, event generation methods are the most powerful ones. In most of the methods the event generation is done using Monte-Carlo technique [1, 2]. The Monte-Carlo method reduce the complexities to a set of basic events and interactions. The applications of Monte-Carlo methods are huge in the branch of engineering, finance, statistics, mathematics, computer science, and the physical and life sciences. In experiments, the Monte-Carlo methods are crucial for designing detectors, understanding their behavior and comparing experimental data to theory. At the same time, the quantum Monte-Carlo methods are also available to solve the many-body problems for microscopic systems. In theoretical studies, a large number of event generators are developed in the branch of heavy-ion collisions, such as HIJING (Heavy-Ion Jet Interaction Generator) [3], AMPT (A Multi-Phase Transport Model) [4], QMD (Quantum Molecular Dynamics) [5], IQMD (Isospin-dependent Quantum Molecular Dynamics) [6], UrQMD (Ultra Relativistic Quantum Molecular Dynamics) [7] etc.

In the last few decades, with the help of experimental and theoretical studies, it is well understood now that the heavy ion collisions are one of the most promising tool to provide the nuclear matter properties in the dense and hot atmosphere. The production of fragments and dynamics of fragment formation in the intermediate energy heavy ion collisions is found to provide crucial information of compressed and excited nuclear matter properties. One needs to rely on the theory due to the inability of observables that can directly trace the dynamics of nuclear matter in

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experiments. This is due to the short span for which the excited compressed nucleus is formed. The above mentioned questions i.e., dynamics of formation of fragments etc. have answers in the abundance of fragments which depends on various entrance channels such as incident energy of projectile, collision geometry, mass asymmetry of colliding nuclei and isospin asymmetry of colliding partners [8, 9, 10, 11, 12, 13, 14]. The present study is to explore some of these effects in particular, the dependence of energy of maximum IMFs production on impact parameter for mass symmetric and asymmetric reactions.

In the past, various attempts have been done to investigate the effect of impact parameter in mass symmetric and asymmetric reactions. In case of symmetric reactions, Tsang *et al.*, studied the impact parameter dependence of IMFs for ^{197}Au + ^{197}Au reactions at incident energies of 100, 250 and 400 MeV/nucleon [14]. This experiment, performed by ALADIN group, has shown that at lower incident energies ($\lesssim$ 100 MeV/nucleon) the multiplicity of IMFs as a function of impact parameter shows only a gradual decrease, whereas a rise and fall behavior was seen at higher incident energies. To explain the observations they used QMD + Minimum Spanning Tree (MST), QMD + Statistical Multifragmentation Model (SMM) and Quasi-Particle Dynamics (QPD) + Expanding Evaporating Source (EES) models and reported a failure of the dynamical models at peripheral geometries. Puri *et al.*, removed this misconception via coupling QMD with Simulated Annealing Clusterization Algorithm (SACA) [15, 16]. In another study, Schüttauf *et al.*, studied the fragment distribution as a function of impact parameter for the reactions of Au + Be, C, Al and Au at energies of 400, 600 and 1000 MeV/nucleon using ALADIN forward-spectrometer [17]. They found a universal rise and fall behavior for spectator fragments for various mass asymmetric reactions. Also, the expansion rate of nuclear matter was found to depend on source size. Blaich *et al.*, reproduced some of the experimental data of Au + C, Au + Al and Au + Cu reactions with QMD model at an incident energy of 600 MeV/nucleon [18]. Puri *et al.*, also used QMD model to observe the impact parameter dependence of fragment multiplicities for ^{40}Ca + ^{40}Ca reaction in the incident energy range of 20 to 150 MeV/nucleon [19]. Later, S. Goyal presented a role of impact parameter on collective flow and energy of vanishing flow for various mass asymmetric reactions [20]. The above mentioned studies shows an extensive role of impact parameter on the reaction output but none study exist on the peak IMF production till date. Therefore, the present work will be dedicated to understand the role played by colliding geometry on the peak IMFs production for mass symmetric and mass asymmetric reactions.

This paper is organized as following: In section 2, we present brief details of the simulation code i.e., Isospin-dependent Quantum Molecular Dynamics (IQMD) code used in the study. In section 3, we will put forward results and discussions. Lastly, we will summarize our work in section 4.

2. Methodology

In the present work, a computer code dubbed as Isospin-dependent Quantum Molecular Dynamics (IQMD) model, that simulates the reactions on event-by-event basis is used [6]. Here, one calculates the trajectories of each nucleon at a time difference of 0.1 fm/c in time. This model is based on dynamical equations to calculate the trajectories of the baryons at various time steps during a reaction.

During the motion, the baryons follows curved paths due to the following potentials:

$$V_{ij} = V_{ij}^{Sky} + V_{ij}^{Yuk} + V_{ij}^{Coul} + V_{ij}^{Sym} \tag{1}$$

$$= [t_1\delta(\mathbf{r}_i - \mathbf{r}_j) + t_2\delta(\mathbf{r}_i - \mathbf{r}_j)\rho^{\gamma-1}((\mathbf{r}_i + \mathbf{r}_j)/2)] + t_3\frac{e^{-|\mathbf{r}_i-\mathbf{r}_j|/\omega}}{|\mathbf{r}_i - \mathbf{r}_j|/\omega} + \frac{Z_iZ_je^2}{|\mathbf{r}_i - \mathbf{r}_j|} + t_6\left(\frac{1}{\rho_0}\right)T_{3i}T_{3j}\delta(\mathbf{r}_i - \mathbf{r}_j). \tag{2}$$

Here, Z_i and Z_j denote the charges of the 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 parameters $t_1, \ldots, t_6$ are adjusted to the real part of the nucleon optical potential. After the scattering, to take care of Pauli principle in classical ways one incorporates Pauli blocking. In the later stages, the nuclear matter becomes cold and only nucleons which are bound occupy the neighboring sites and are clusterized using the spatial correlations [5, 21, 22].

3. Results and Discussion

For the present study, we have simulated mass symmetric and asymmetric reactions on event-by-event basis. The mass asymmetry is defined with the mass asymmetry parameter, $\eta_A = |\frac{A_T-A_P}{A_T+A_P}|$; where A_P (A_T) is the mass of projectile (target). The value of η_A varies between 0 (symmetric) and 1 (extreme mass asymmetric). The reactions are simulated at different reduced impact parameters of b^{red} = 0.1, 0.3, 0.5, 0.7 and 0.9, where $b^{red} = b/b_{max}$ and $b_{max} = 1.12\ (A_P^{1/3} + A_T^{1/3})$. For the symmetric reactions, we simulated the reactions of ^{80}Se + ^{80}Se ($\eta_A = 0.0$) in the incident energy range of 25-115 MeV/nucleon at different colliding geometries. For the case of asymmetric system, we simulated the reactions of ^{27}Mg + ^{138}Ba (η_A = 0.7) in the energy range of 30-315 MeV/nucleon at different geometries.

In Fig. 1, we display the multiplicity of IMFs ($5 \leq A_f \leq A_{total}/6$) obtained for symmetric reactions of ^{80}Se + ^{80}Se at various impact parameters. From the figure, we see that the IMFs multiplicity first increases rapidly then decreases gradually for all impact parameters. Interestingly, it is clear from the figure that the rise and fall behavior of IMF's multiplicity is at different incident energies for different impact parameters. The energy of maximum production of IMFs ($< E_{c.m.}^{max} >$) calculated using quadratic fit to the theoretical points and maximum number of IMFs produced ($< N_{IMFs}^{max} >$) are also written for better understanding. We see that the values of $< E_{c.m.}^{max} >$ decreases as one increases the impact parameter, same is observed for $< N_{IMFs}^{max} >$. Now, let us understand the results: for the symmetric reactions, collisions are violent at central geometries compared to peripheral geometries. As a result, the maximum number of IMFs produced in central reactions is more than peripheral geometries. At peripheral geometries, the system does not have sufficient energy to excite the nuclear matter thus, participant part decreases and spectator part increases. As a result of which the $< E_{c.m.}^{max} >$ and $< N_{IMFs}^{max} >$ decreases as one moves towards peripheral geometries.

Now, to understand the effect of impact parameter on $< E_{c.m.}^{max} >$ and $< N_{IMFs}^{max} >$ with increase in mass asymmetry, we simulated the reaction of ^{27}Mg + ^{138}Ba (η_A = 0.7) at reduced impact parameters of 0.1, 0.3, 0.5, 0.7 and 0.9. The results are displayed in Fig. 2. The trends of $< E_{c.m.}^{max} >$ and $< N_{IMFs}^{max} >$ for asymmetric

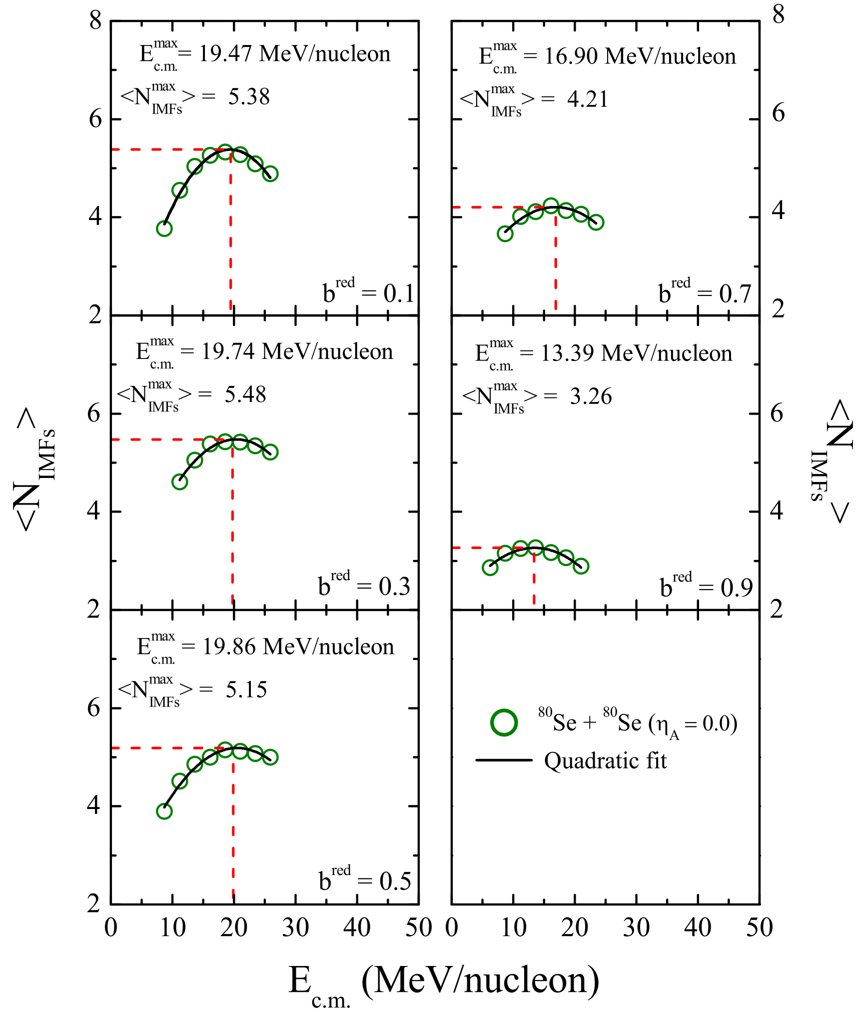

FIGURE 1. The rise and fall of intermediate mass fragments (IMFs) as a function of incident energy for the system of $^{80}Se+^{80}Se$ (open circles) at different impact parameters.

reactions is same as observed for symmetric reactions but the role of impact parameter is enhanced. In asymmetric case, due to large difference in the projectile and target masses the reaction dynamics changes more frequently on varying impact parameters.

For comparison between the results of symmetric and asymmetric reactions, we have displayed the results of $< E^{max}_{c.m.} >$ and $< N^{max}_{IMFs} >$ in Fig. 3. We notice that the $< E^{max}_{c.m.} >$ and $< N^{max}_{IMFs} >$ decreases linearly as one moves from central to

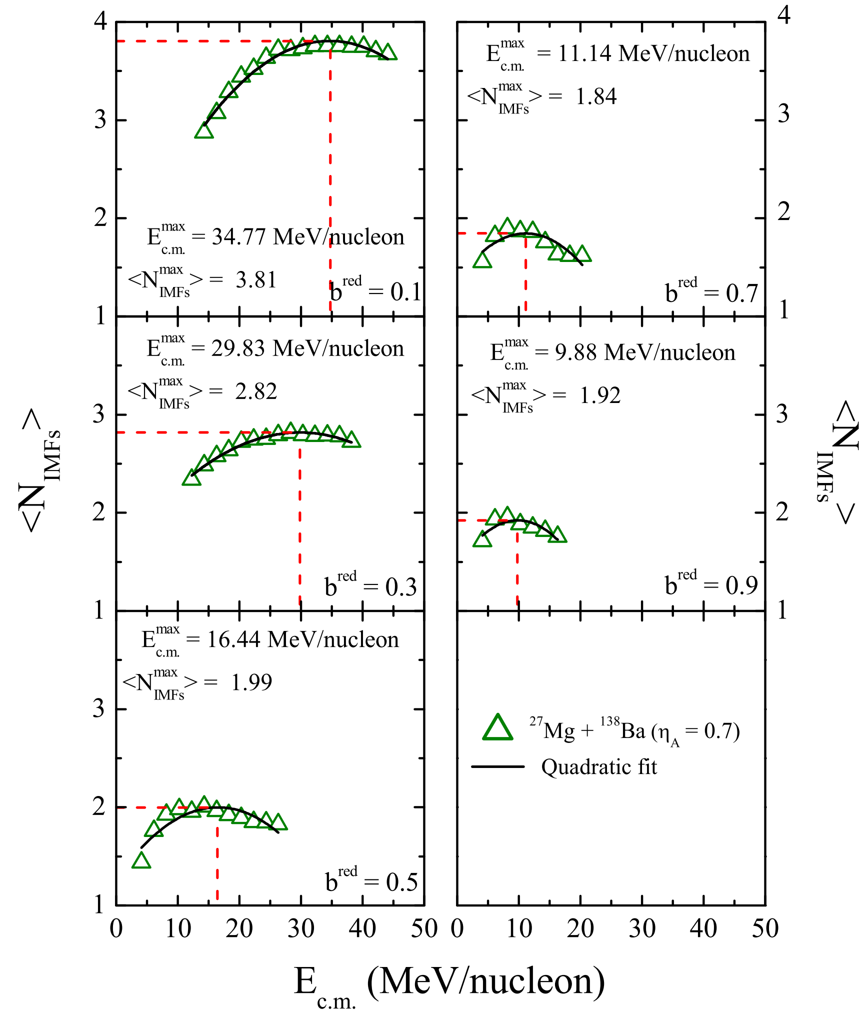

FIGURE 2. The rise and fall of intermediate mass fragments (IMFs) as a function of incident energy for the system of ^{27}Mg+^{138}Ba (open triangles) at different impact parameters.

peripheral reactions for both symmetric and asymmetric reactions. For $< E^{max}_{c.m.} >$, the slopes for $\eta_A = 0.0$ and 0.7 are 7.5 and 34.2, respectively. On the other hand, the slopes of $< N^{max}_{IMFs} >$ are 2.7 and 2.4 for $\eta_A = 0.0$ and 0.7, respectively. The reason for the rise in the $< E^{max}_{c.m.} >$ at central geometries for asymmetric reactions is the share of energy that produces compression in the nuclear system decreases as one moves from symmetric to asymmetric colliding reactions. Therefore, large energy is required to reach the peak production in later compared to former one.

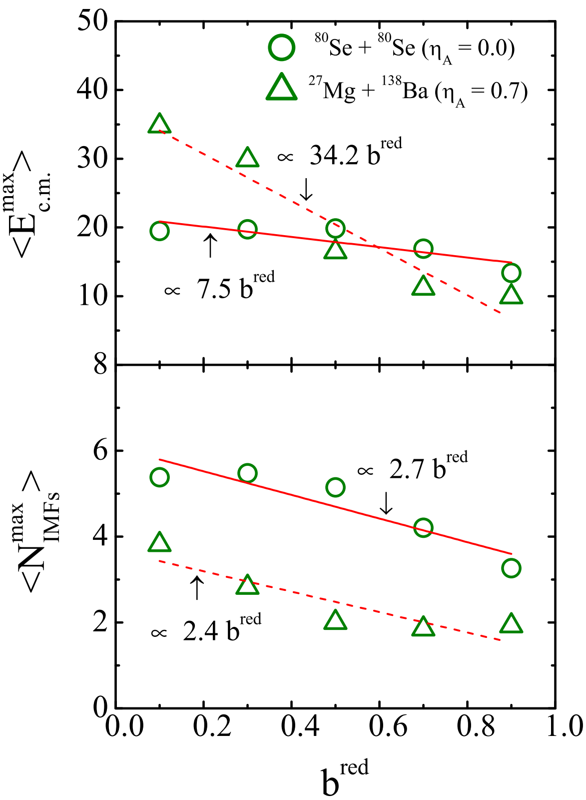

FIGURE 3. The impact parameter dependence of $< E^{max}_{c.m.} >$ and $< N^{max}_{IMFs} >$ for the system of ^{80}Se+^{80}Se (open circles) and ^{27}Mg+^{138}Ba (open triangles).

We also noticed that at peripheral geometries, the $< E^{max}_{c.m.} >$ as well $< N^{max}_{IMFs} >$ of asymmetric reaction is less than that of symmetric reactions. It is because at peripheral geometries the participant zone is largely reduced and hence the number of collisions also decreases. Thus the IMFs production declines and $< E^{max}_{c.m.} >$ is achieved at very low energies and $< N^{max}_{IMFs} >$ produced is very less.

4. Summary

In the present paper, we have studied the role of impact parameter on the $< E^{max}_{c.m.} >$ and $< N^{max}_{IMFs} >$ for symmetric and asymmetric reactions. The $< E^{max}_{c.m.} >$ as well as $< N^{max}_{IMFs} >$ decreases with increase in impact parameters for both symmetric and asymmetric reactions but with different slopes. In case of asymmetric reactions, the slope of decrement of $< E_{c.m.}^{max} >$ is more steeper compared to symmetric one. Hence, the dynamics of asymmetric reactions are more affected with rise in impact parameter of a reaction as compared to symmetric reactions for peak IMFs production.

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