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ROLE OF SPATIAL CORRELATIONS ON THE ONSET OF NUCLEAR VAPORIZATION IN $^{16}O+^{80}Br$ REACTION

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Abstract. We study the onset of nuclear vaporization in the reactions of $^{16}O+^{80}Br$ within the framework of Quantum Molecular Dynamics (QMD) model. The clusterization algorithm Minimum Spanning Tree (MST) is used to identify the fragment structures. The mean charge in each event is correlated and plotted against incident energy of the projectile to find out the energy of the onset of vaporization. We find QMD+MST is able to reproduce the experimental results of the average charge per event qualitatively at all incident energies, whereas quantitative behavior can be reproduced only above 50 MeV/nucleon energy. We also varied the spatial distance constraint in MST method to see its effect on the onset of vaporization.

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1. INTRODUCTION

It is well known that the collision of two nuclei leads to the decay of hot and dense composite system into large number of small chunks of different sizes. The number and size of the fragments depends on the excitation energy of the system. This phenomenon has been termed as "multi-fragmentation" in the literature and can provide vital information about the hot and dense phase of nuclear matter [1, 2, 3, 4].

Due to the fact that the number of particles involved in these collisions is neither large enough to handle statistically nor is too small to handle dynamics using simple dynamic equations, therefore, numerical methods with certain assumptions are developed and used [5, 6, 7, 8, 9, 10, 11, 12]. These methods, with the help of computer modelling can be used to investigate physics leading to fragmentation of colliding system. These numerical models are generally divided into two main categories: Statistical and/or Dynamical models [2, 3, 4]. Both these categories explain different sets of experimental data thus, are considered equally reliable. Here we plan to discuss fragmentation within dynamical channel.

The main problem with dynamical models lies in the conversion of many-body information to a set of fragment information. In this category of conversion models, namely "clusterization algorithms", large number of entries has been reported in the literature [9, 13, 14, 15]. These entries are based on various assumptions [9, 13, 14, 15]. Some of the widely used algorithms are Minimum Spanning Tree (MST) method [9], Restructured Aggregation Model (RAM) [13], Early Clusterization Recognition Algorithm (ECRA) [14], Simulated Annealing Clusterization Algorithm (SACA)

[15] etc. Among these methods, the MST method overshadows others due to its simple structure [11, 17].

According to MST method, if nucleons lie close to each other in coordinate space they must be counted as a single entity or fragment [9]. It is worth mentioning that due to its simple definition, MST method is widely used with various dynamical models not only at intermediate energies but, also at ultra relativistic energies [18]. Interestingly at the same time, many modifications over conventional MST method are also proposed in the literature suspecting that the simple definition of the fragment in MST method may not address the complex physics involved in a heavy-ion collision [15, 16, 17]. The spatial distance between nucleons (in MST method) to qualify as a fragment has been chosen arbitrarily and its range lies between 2 and 6 fm [19]. Generally this spatial cut in MST method is decided according to the problem in hand. Puri *et al* were among the first to pay attention towards the role of MST range on fragment pattern [20]. On the same line, very recently, Tsang *et al* [21] varied the range of the spatial cut based on the isospin content. These studies indicated substantial influence of spatial cut on fragment pattern.

The fragment pattern of course depends on the incident energy if impact parameter/geometry of the reaction is fixed. The production of intermediate mass fragments increases with incident energy but after certain incident energy, the free nucleons and lighter charged particles dominate the reaction outcome. This phase has also been termed as vaporization in the literature [22]. In this direction, Souza *et al* had performed calculations using Quantum Molecular Dynamics (QMD) + Restructured Aggregation Model (RAM) model for the reaction of $^{16}O+^{80}Br$. Their findings revealed the onset of vaporization is around 200

MeV/nucleon [23]. We plan to attempt here the same reaction with QMD + MST method to access the role of different spatial limits (cuts) on the onset of vaporization. It is worth mentioning that the QMD used by Souza *et al* [23] differs in many aspects compared to the one we are using.

This paper is organized as follows: In Section 2, we will describe methodology. Results and calculations are presented in Section 3 which is followed by Section 4 where summary is presented.

2. Methodology

2.1. **Quantum Molecular Dynamics (QMD) Model.**

The Quantum Molecular Dynamics [9, 10] model is a many-body dynamical model. In this model, each nucleon is represented by a Gaussian in coordinate and momentum space. The propagation of each nucleon is followed in the mean field of the other nucleons using Hamilton's classical equations of motion:

$$\dot{\mathbf{r}_i} = \frac{\partial H}{\partial \mathbf{p}_i} \quad ; \quad \dot{\mathbf{p}}_i = -\frac{\partial H}{\partial \mathbf{r}_i}. \tag{1}$$

Here Hamiltonian H is the sum of the kinetic and potential energies (Skyrme, Coulomb and Yukawa). If two nucleons come too close, they suffer hard scatterings. The dynamics of phase space of all nucleons is stored at several times from the start till end of the reaction where matter is cold and fragmented.

2.2. **Minimum Spanning Tree (MST) Method.**

The stored phase space of nucleons is then used in secondary clusterization algorithm to identify fragments. In this method, nucleon 'i' is said to be the part of a fragment,

if there exists at least another nucleon 'j' that fulfills the following condition;

$$| \mathbf{r}_i - \mathbf{r}_j | \leq R_{cut}. \quad (2)$$

Here $\mathbf{r}_i$, $\mathbf{r}_j$ is the centroid of nucleons 'i' and 'j', respectively. R_{cut} is a free parameter and its value is fixed by comparing calculations with experimental results. Generally one takes $R_{clus} = 4 \pm 2$ fm. In the present study, we vary this cut by 25% of the mean value to see how it affects the onset of vaporization in highly asymmetric reactions.

3. Results and Discussion

Here we have simulated the reaction of ^{16}O+^{80}Br at incident energies between 15 and 200 MeV/ nucleon. We have used a soft equation of state along with energy-dependent cross-section.

In Fig. 1, we have plotted the normalized average charge in each event with ($< Z >$) and without largest fragment ($< Z_1 >$) as a function of incident energy. The method of calculating normalized mean charge is same as reported in Ref. [23]. The Open (filled) stars represent the experimental data of $< Z_1 >$ ($< Z >$) and open (crossed) triangles represent the corresponding calculations using QMD with default MST method (R_{clus} =4 fm) (labelled as 'MST'). From the figure, we see that the normalized mean charge ($< Z >$) decreases with increase in the incident energy as more amount of energy is stored inside the system that leads to extra breaking and cracking, thus, lesser number of larger fragments. Here the energy of vaporization is taken to be the one where $< Z >$ reaches asymptotic value. The $< Z > \simeq 1$ signifies that the correlations among nucleons are completely broken and matter is in the form of single nucleons only. One can figure out immediately that the QMD + MST model with default values

(3)

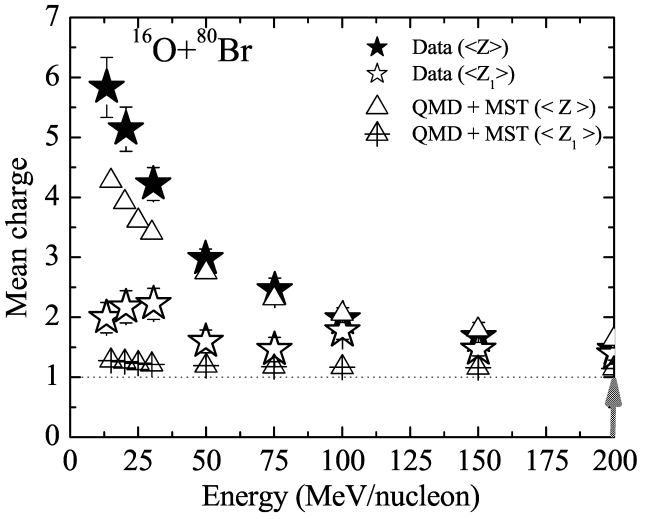

FIGURE 1. The mean charge with ($< Z >$) and without ($< Z_1 >$) largest fragment as a function of incident energy for the system of ^{16}O+^{80}Br. The symbols are explained in the text.

is able to reproduce experimental data at all incident energies reasonably well. The exact reproduction happens above 50 MeV/nucleon energy only. The failure of MST method at lower incident energies happen due to its inability to separate fragments which are overlapping in coordinate space due to lower fragment velocities. This leads to one large fragment instead of many intermediate mass fragments. This is supported by the results of normalized charge excluding largest fragment $< Z_1 >$. We see that the

MST method has serious problem at lower incident energies whereas it explains experimental data nicely at higher energies. Nevertheless, QMD + MST model is able to reproduce the onset of vaporization quite nicely which is reported to be around 200 MeV/nucleon. The same kind of results were reported by Souza *et al* [23], but using QMD + RAM model. One should keep into mind that the QMD model used by Souza *et al* have many modifications such as Pauli principle, isospin etc. over the one used in the present study. Further the RAM model used to identify fragments is much more complex compared to MST method [13].

(4)

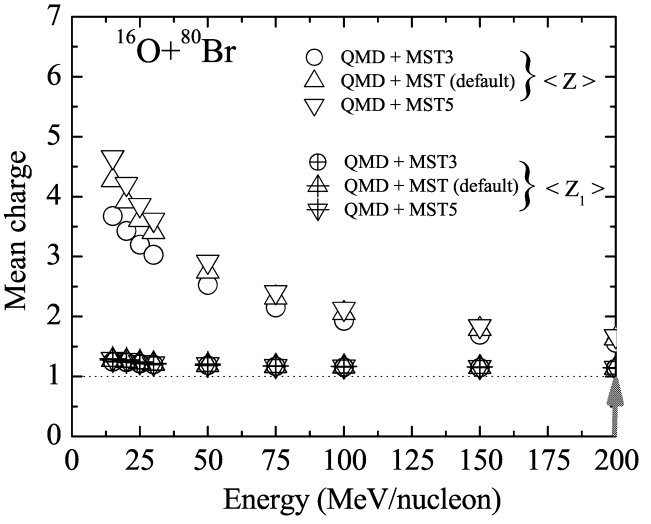

FIGURE 2. Same as Fig.1, but using different R_{clus} values in MST method.

It would be further interesting to see whether spatial range used for constructing the fragments affect the onset

of vaporization or not. For this we performed same calculations using $R_{clus} = 3$ and 5 fm also. We see some effect of altering the clusterization range at lower incident energies where nucleons are still close in the space (see Fig. 2). The effect however vanishes at higher incident energies. On the average, altering the range of clusterization by 25 % changes $< Z >$ by 12 % at 15 MeV/nucleon whereas the effect reduces to 6 % at 200 MeV/nucleon. Further it was evident that the clusterization range do not affect the energy of the onset of vaporization

4. Summary

We have studied the onset of vaporization for the reaction of ^{16}O + ^{80}Br using QMD model coupled with MST algorithm. We showed that QMD + MST model is able to reproduce normalized average charge with and without largest fragment per event qualitatively, whereas quantitative results are reproduced only above 50 MeV/nucleon. The role of different spatial cut values is significant at lower incident energies whereas it does not alter the structure at higher incident energies, therefore energy of the onset of vaporization remains unaltered.

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