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Microscopic approach to the spectator matter fragmentation from 400 to 1000 AMeV

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Abstract – A study of multifragmentation of gold nuclei is reported at incident energies of 400, 600 and 1000 MeV/nucleon using microscopic theory. The present calculations are done within the framework of quantum molecular dynamics (QMD) model. The clusterization is performed with an advanced sophisticated algorithm namely the *simulated annealing clusterization algorithm* (SACA) along with the conventional spatial correlation method. A quantitative comparison of the mean multiplicity of intermediate mass fragments with experimental findings of the ALADiN group gives excellent agreement showing the ability of the SACA method to reproduce the fragment yields. It also emphasizes the importance of the clustering criterion in describing the fragmentation process within the semi-classical model.

Introduction. – A highly excited system formed in a nucleus-nucleus collision, as a rule, is expected to break into several pieces consisting of free nucleons, light charged particles (LCPs), intermediate mass fragments (IMFs) as well as heavier residues. This phenomenon of breaking of colliding nuclei into several pieces is known as multifragmentation [1–7]. Due to its complex dynamics, the mechanism behind this picture of "explosive" break-up (into several entities) is not yet known completely.

At low incident energies, the excitation energy available to the system is very small. Therefore, a larger impact of collisions is needed to break the system into pieces of different sizes. In other words, fruitful destruction is possible only for the central collisions. On the other hand, mutual correlations among nucleons are preserved in peripheral collisions, therefore, not much deviation from the initial picture will be seen. In contrast, the excitation energy deposited in the system is very large at higher incident energies. Therefore, central collisions break matter into much smaller pieces and rarely one sees intermediate mass fragments or heavy-mass fragments in these events. The maximum number of IMFs can only be seen at semi-central impact parameters. A large number of experiments have witnessed this trend of fragmentation at various incident energies and impact parameters. This change in the behavior of fragment pattern is also termed as a *rise and fall* in the multifragmentation [6,8–10].

As we go further towards higher incident energies, the maximal of IMF multiplicity starts shifting towards peripheral geometries. Such trends have been found and reported in several recent experiments of the ALADiN Collaboration [2,6]. In addition, manyfold aspects of spectator matter fragmentation have also been studied for the collision of ^{197}Au + ^{197}Au on the ALADiN set-up at incident energies varying between 150 and 600 MeV/nucleon. Recently, INDRA experiments extended the energy domain covering the incident energies between 40 and 150 MeV/nucleon [11]. The sole motivation for all these experiments was the fantastic physics that may emerge from the disintegration of excited systems leading to the expansion of matter to low densities. This onset of multifragmentation and afterward transition to vaporization phase has also been linked to the concept of the liquid-gas phase transition of nuclear matter [7,12,13]. Such critical behavior is, however, reported to be influenced by finite size effects [3,14].

All these experimental studies characterize the evolution of heavy-ion reactions from the dominant multifragment decay channel to complete disassembly into light charge particles (LCPs) and free nucleons sometimes also termed as "vaporization". The very recent study by Puri and Kumar [15] analyzed the ^{40}Ca + ^{40}Ca reaction for incident energies between 20 and 1000 MeV/nucleon and

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over the entire impact parameter range. They predicted a clear rise and fall of multiplicity in the incident energy and impact parameter planes.

On the theoretical front, not much success has been reported to reproduce the ALADiN experimental data [6,16,17]. Theoretical approaches which follow the evolution of target and projectile to complete disassembly of nuclear matter need a secondary algorithm to clusterize the phase space. Even afterburners have also been employed to extract fragments. The present study aims to check whether microscopic reaction models can explain the universality reported by the ALADiN group [8] in spectator fragmentation or not. Molecular dynamical models QMD [4] and QPD [18] were found to explain some of the features of this experimental data [6]. This questions the validity of molecular dynamics models (MDM). The fallacy was largely attributed to the lack of advanced secondary clustering models [19–21]. The clustering criterion is one of the basic ingredients that may control the reaction mechanism in semi-classical models like the quantum molecular dynamics model.

Recently, a novel clusterization algorithm based on the energy minimization criteria namely the *simulated annealing clusterization algorithm* (SACA) was proposed [20]. As a first attempt, results with this algorithm were quite promising ones [20]. In ref. [20], the ^{197}Au + ^{197}Au reaction was studied at incident energy of 600 MeV/nucleon. Based on the ALADiN results, there one assumed that the fragment pattern does not change above 400 MeV/nucleon. Therefore, it remains to be seen whether the QMD model can reproduce this universality feature or not. We plan to address this situation in this letter. We apply this algorithm to ALADiN data at incident energies of 400, 600 and 1000 MeV/nucleon in order to see whether our approach can explain the rise and fall phenomenon and the universal behavior in the spectator fragmentation at such higher incident energies. It is worth mentioning that the SACA method has been robust against experimental data at lower tail of incident energies. In our earlier studies [22], the SACA method was reported to reproduce the charge yields at incident energies between 25 and 200 AMeV. In this analysis, O + Ag/Br reactions were taken [22]. In another study, the SACA method was tested against INDRA experimental data at 50 AMeV [23]. In this study, the Xe + Sn reaction was subjected to multifragmentation and various variables, such as charge, proton-like and IMFs yields, angular distribution, average kinetic energies etc. were analyzed. The SACA method explained all these observables quite nicley, whereas the conventional method failed badly [23]. Due to the fact that the interaction energy among fragments is ignored, this approach of SACA cannot be applied to incident energies below the above mentioned one. To study fragmentation in the Au + Au reaction, we followed nuclear collisions within the QMD model [4]. The phase space thus generated is clusterized using the advanced SACA method.

SACA formalism. – To generate the phase space of nucleons, we use the *quantum molecular dynamics* (QMD) model. For the details of the QMD model, the reader is referred to refs. [4,20]. The next essential step is to clusterize the phase space stored at various time steps in each event. The extensively used approach assumes the correlating nucleons to belong to the same fragment if their centers are closer than 4 fm *i.e.* $|\mathbf{r}_\alpha - \mathbf{r}_\beta| \leqslant 4$ fm. This may often lead to wrong results if applied at higher densities and hence cannot address the time scale of multifragmentation. This approach is labeled as minimum spanning tree (MST) algorithm.

In our latest approach, fragments are constructed based on the energy correlations. The pre-clusters obtained with the MST method are subjected to a binding energy condition [20,24]:

$$\zeta_i = \frac{1}{N_f}\sum_{\alpha=1}^{N_f}\left[\sqrt{\left(\mathbf{p}_\alpha - \mathbf{P}^{cm}_{N_f}\right)^2 + m_\alpha^2} - m_\alpha + \frac{1}{2}\sum_{\beta\neq\alpha}^{N_f} V_{\alpha\beta}\left(\mathbf{r}_\alpha, \mathbf{r}_\beta\right)\right] < E_{bind}, \quad (1)$$

with $E_{bind} = -4.0$ MeV, if $N_f \geqslant 3$ and $E_{bind} = 0$, otherwise. In eq. (1), N^f is the number of nucleons in a fragment and $\mathbf{P}^{cm}_{N_f}$ is the center-of-mass momentum of the fragment. The requirement of a minimum binding energy excludes the loosely bound fragments which will decay at a later stage.

To look for the most bound configuration (MBC), we start from a random configuration which is chosen by dividing the whole system into few fragments. The energy of each cluster is calculated by summing over all the nucleons present in that cluster using eq. (1). Note that we neglect the interaction between the fragments. The total energy calculated in this way will differ from the total energy of the system [24].

Let the total energy of a configuration k be $E_k(=\sum_i N_f\zeta_i)$, where N_f is the number of nucleons in a fragment and ζ_i is the energy per nucleon of that fragment. Suppose a new configuration k' (which is obtained by a) transferring a nucleon from a randomly chosen fragment to another fragment or by b) setting a nucleon free, or by c) absorbing a free nucleon into a fragment) has a total energy $E_{k'}$. If the difference between the old and new configuration $\Delta E(= E_{k'} - E_k)$ is negative, the new configuration is always accepted. If not, the new configuration k' may nevertheless be accepted with a probability of $\exp(-\Delta E/\upsilon)$, where υ is called the control parameter. This procedure is known as Metropolis algorithm. The control parameter is decreased in small steps. This algorithm will yield eventually the most bound configuration (MBC). Since this combination of a Metropolis algorithm with a slowly decreasing control parameter υ is known as *simulated annealing*, so our approach is dubbed as *simulated annealing clusterization algorithm* (SACA). For more details, we refer the reader to ref. [24].

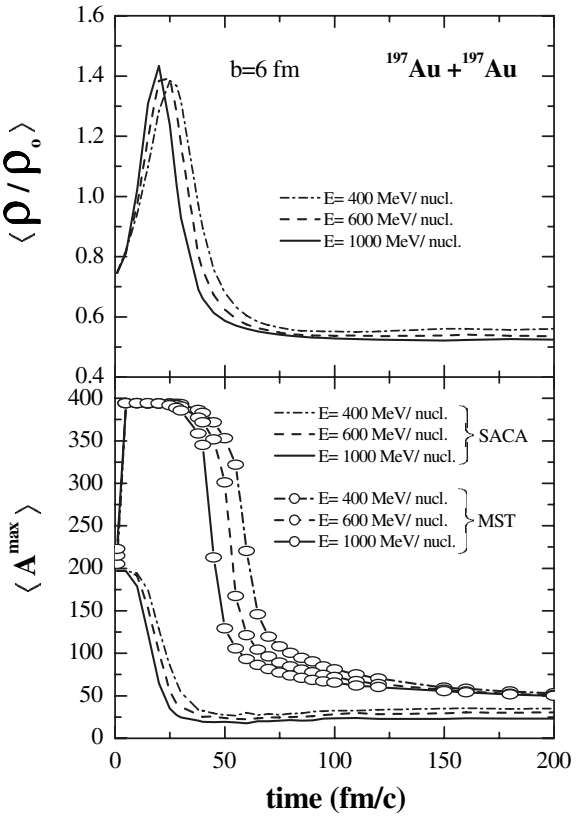

Fig. 1: Top panel: time evolution of the average nucleon density $\langle \rho/\rho_o \rangle$ reached in the ^{197}Au + ^{197}Au collision. Bottom panel: the heaviest fragment $\langle A^{max} \rangle$ obtained with the SACA and MST analysis as a function of time in the ^{197}Au + ^{197}Au collision.

Results. – For the present study, we use a soft equation of state (EoS) along with the standard energy-dependent n-n cross section [25]. The soft EoS has been advocated by many studies [5,6,16,17,20,26]. The phase space is generated and stored at many time steps and is then subjected to the above mentioned clusterization procedures. To address the time scale of multifragmentation of the spectator matter, we employed the SACA method as well as the spatial correlation method (*i.e.* MST).

The density of the environment is often correlated with the prediction of breaking of nuclear matter into pieces. One can also look density distribution in coordinate space to investigate the formation of fragments. We here compute the average density of the system as

$$\langle \rho \rangle = \left\langle \frac{1}{A_T + A_P} \sum_{i=1}^{A_T+A_P} \sum_{j>i}^{A_T+A_P} \frac{1}{(2\pi L)^{3/2}} \times e^{-(\mathbf{r}_i(t)-\mathbf{r}_j(t))^2/2L} \right\rangle, \quad (2)$$

with $\mathbf{r}_i$ and $\mathbf{r}_j$ being the position coordinates of the i-th and j-th nucleons. The Gaussian width L is fixed with a standard value of 1.08 fm. Figure 1 (top panel) shows the time evolution of the average nuclear density $\langle \rho/\rho_o \rangle$ for the Au + Au system at incident energies of 400, 600 and 1000 MeV/nucleon and at an impact parameter of 6 fm. The average nuclear density reaches its maximal around 25 fm/c. This time domain also witnesses the maximum collision rate and nuclear interactions which are going on between target and projectile nucleons. This maximal density shifts towards later times as we go down to the incident energies. The fine point is that there is an insignificant change in the density profile while enhancing the incident energy by a factor of 2.5 times, *i.e.* going from 400 to 1000 MeV/nucleon. At the final stage of the reaction, we do not see any significant change with the incident energy. The bottom panel of fig. 1 shows the time evolution of the heaviest fragment $\langle A^{max} \rangle$ using MST and SACA techniques. The MST method gives one big cluster at the time of maximum density, whereas one sees the striking ability of the SACA method in identifying the heaviest fragment quite early when the violent phase of the reaction still continues. This suggests that the evolution of multifragmentation is an intricate process. In other words, fragmentation starts at a quite early stage when nucleons are still interacting among themselves vigorously. The early recognition of the heaviest fragment $\langle A^{max} \rangle$ rules out its formation out of the neck region, *i.e.* the geometrical overlap between projectile and target. This suggests the emission of $\langle A^{max} \rangle$ from the spectator region. Similar trends of transition from the participant to spectator fragmentation has also been observed and reported by the ALADiN Collaboration [8]. This finding also confronts the common standpoint of the thermal origin of fragments, *i.e.* fragments are created after the thermalization sets in. Further after the violent phase of reaction is over (*i.e.* after 60 fm/c), the binding energy of all clusters in the SACA method is greater than E_{bind}, the minimum binding energy needed to bind the group of nucleons into a cluster. Fragments after 60 fm/c leave the reaction zone without nucleon-nucleon correlations being destroyed further. Hence the fragment configuration obtained at the earlier time can be compared with experimental data. Strikingly, an earlier detection of fragments (not shown here) at all incident energies upto 1000 MeV/nucleon gives us the possibility to look into the n-n interactions when nuclear matter is still hot and dense. Further, one is also free from the problem of stability of fragments. The failure of the MST method to detect the fragments also questions its validity at incident energies as high as 1000 MeV/nucleon. The simple correlations method fails to detect the fragments even at these high excitation energies. The further rise in $\langle A^{max} \rangle$ after 60 fm/c using the SACA technique is due to the reabsorption of the surrounding light fragments by the heavier fragments. We see that heavier $\langle A^{max} \rangle$ survive at smaller incident energies than at higher incident energies. The capability of the QMD model clubbed with the SACA method is illustrated in fig. 2 where we display the mean multiplicity of intermediate mass fragments $\langle N_{IMF} \rangle$ as a function of the impact parameter of the reaction. Also shown are the

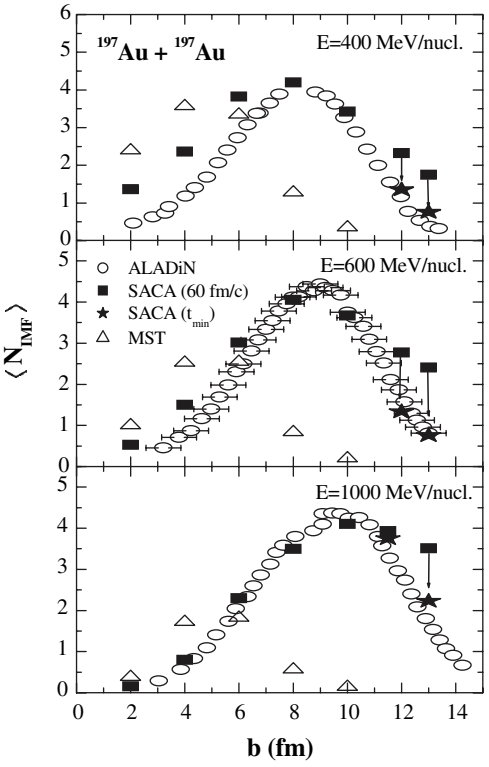

Fig. 2: The mean multiplicity of intermediate mass fragments $\langle N_{IMF}\rangle$ as a function of impact parameter b for the reaction ^{197}Au + ^{197}Au. The model calculations with SACA (solid squares) and MST (open triangles) methods are compared with the experimental data (open circles) reported by the ALADiN group [8].

results obtained with the MST method. Our model calculations with the SACA method are in close agreement with the ALADiN data [8] for the ^{197}Au + ^{197}Au reaction at all incident energies 400, 600 and 1000 MeV/nucleon. As seen in fig. 2, we also achieved a reasonable reproduction of the shape of the impact parameter dependence of $\langle N_{IMF}\rangle$. Due to shallow minima sometimes, we also see second minima before 60 fm/c in peripheral collisions. We show also the calculations at these minima marked by star symbols. We see that the fragment structure at these minima is further closer to the data. Further, the peak value of $\langle N_{IMF}\rangle$ and the corresponding impact parameter b is also well estimated with the QMD + SACA method. The prominent feature of the spectator decay is the invariant nature of the IMF distribution with respect to the bombarding energy. The SACA method successfully reproduced the universal nature of the spectator fragmentation at all the three bombarding energies. It is interesting to note that these universal features observed in multifragmentation of gold nuclei persist upto much higher bombarding energies than explored in this work [27]. On the contrary, the normal spatial correlation method fails badly to explain the production of intermediate mass fragments at all incident energies. This questions the validity of the MST method in explaining the fragmentation pattern in heavy-ion collisions.

Summary. – We have studied multifragment-emission in the ^{197}Au + ^{197}Au reaction at incident energies of 400, 600 and 1000 MeV/nucleon, where ALADiN experiments showed universality in the production of intermediate mass fragments. For this study, we employed the QMD model clubbed with the energy minimization algorithm (SACA) along with the conventional spatial correlation method. Our findings reveal that SACA is able to reproduce the universal nature of multifragmentation of the excited spectator over the entire impact parameter-energy plane whereas the spatial correlation method failed to reproduce the IMF multiplicity. For the first time the QMD + SACA approach is able to reproduce the entire energy domain. It also shows that the mass and multiplicity of spectator fragments remain invariant to the range of bombarding energies. This also resolved the earlier discrepancy where the QMD model underestimated the fragment yield [6,16] at large impact parameters even after 200 fm/c. In our case, the SACA method is successful in breaking the spectator matter into intermediate mass fragments. Our results show that the QMD model contains the necessary ingredients to describe the physics of the spectator decay. The clustering algorithm one uses, however, holds the key tenet to explain the reaction mechanism.

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