Dynamical multifragmentation and spatial correlations

Jaivir Singh and Rajeev K. Puri
Physics Department, Panjab University, Chandigarh-160 014, India

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The role of spatial correlations (i.e., the range of clusterization) along with the role of the range of interaction is analyzed in multifragmentation within a quantum molecular dynamics model. We find that the effect of different ranges of clusterization and interactions depends on the physical conditions and excitation energy of the system. The impact of different clusterization ranges is more than marginal in the presence of a momentum dependent interaction which is different than that obtained with a static equation of state.

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I. INTRODUCTION

It is now well accepted that multifragmentation is a complex phenomenon in nature which depends crucially on the incident energy of the projectile and on the geometry (i.e., impact parameter) of the reaction [1]. At very low incident energies, the excitation energy deposited in the system is too small to allow the breakup of the nuclei into fragments. With the increase in the incident energy, the nuclei (after collision) can break into dozens of fragments consisting of light, medium, and heavy fragments [1]. The formation of the fragments (and their size) needs a correct understanding of the nucleon-nucleon correlations and interaction among them which differs in different physical conditions depending on the system size and excitation energy available to the nucleons.

Theoretically, one would need to understand the range of the interaction and cutoff limit of spatial correlations for fragments which depends on the average nucleon-nucleon distance in a medium. As we know, all transport models (developed to study the nuclear dynamics at intermediate energies) follow the evolution (and hence the phase space) of the nucleons only [2–13]. Therefore, one has to look for spatial correlations among different nucleons to bind them into groups of clusters. In a simple version of clusterization, one connects nucleons if their centroids are within a certain distance. This chain process is also called the minimum spanning tree method [1–13]. This limit on the distance is related to the cutoff value of the interaction which varies with different authors [2,4,6,8,9,11]. Apart from the simple spatial correlation method, other modifications and new clusterization algorithms are also reported in the literature [11–13]. Among all, the spatial correlation method is the most extensively used method.

One should keep in mind that different clusterization algorithms give the same distribution at very late time where matter is very diluted and the clusters are well separated from each other [13,14]. Similarly, different clusterization parameters (which represent the cutoff limit of the interaction between nucleons) should have a small role to play if the system is very dilute and the nucleons are quite far from each other. The problem, however, is that all transport models are semiclassical in nature where, most of the time, nuclei do not have a true ground state. As a result, the nuclei may emit nucleons and/or may disintegrate into clusters after some time. It has been reported by several authors [2,4,15] that the nuclei (generated in a semiclassical transport model) are stable for a typical time of about 200 fm/c. This time is taken as the freeze-out time. The distribution obtained at the freeze-out time may not represent the final distribution (consisting of cold fragments and nucleons) which depends strongly on the incident energy. At lower incident energies, it takes a very long time whereas a relatively smaller time is needed at higher incident energies. In other words, the nucleons and fragments at the freeze-out time may not be well separated and may still have interactions among themselves. The immediate problem which comes under this physical condition is the choice of the value of the clusterization parameter representing the cutoff limit. This range of clusterization parameter will be different in different physical situations depending upon the excitation energy and density at the freeze-out time. A discussion is also going on about the actual interaction range one should have in a semiclassical model. In a recent study, the longer interaction range in the quantum molecular dynamical model is reported to give much fewer fragments than detected in experiments [10,13,14]. Hence the range for the clusterization and interaction can play a role in the formation of the fragments. The most accepted range of the clusterization parameter R_{clus} is between 2 and 5 fm [2–13]. At low excitation energies, matter is quite compact and, as a result, the effect of different clusterization parameters (on the fragmentation pattern) should be minimal, whereas a clear effect should be visible at mild excitation energy. In several earlier publications, the authors have claimed that the role of different clusterization parameters is marginal whereas some others claim that the effect of doubling the range of the clusterization is less than 25% [2–7,10]. Another quantity related to the interaction range is the width of the Gaussian distribution of nucleons which determines the interaction range of the particles and influences the density distribution of finite systems [4,9]. As discussed in detail in Refs. [4,9], the equation of state for finite matter depends strongly on the value of the width chosen and different Gaussian widths affect the fragmentation by 30–50 % [4,9].

Our present aim is to discuss the impact of the range of the clusterization parameter on multifragmentation. We shall show that the impact of different clusterization parameters depends strongly on a physical situation like on the excitation energy of the system and also on the phase space of

nucleons. We shall discuss its role for asymmetric as well as symmetric reactions where different excitation energies exist. Apart from the excitation energy, the physical ingredients (in a model) like the equation of state, momentum dependence of the interaction, and the nucleon-nucleon cross section (whose magnitude in the medium is still not clear) also influence the nuclear dynamics strongly [4,8,11,12]. We shall discuss the role of different clusterization ranges in the presence of different physical situations. It is important to mention that the studies reported in the past about the impact of the range of clusterization on fragmentation are based on a single physical situation which does not represent the general behavior [2–7,15]. For example, in [4,6], the effect of doubling the clusterization parameter is claimed to be either negligible or its impact is less than 20%. We shall show that this is only true if a simple static equation of state is used. This effect can be drastic if momentum dependent interactions are taken into account. In other words, we shall show that the clusterization parameter needs to be chosen carefully which also depends on the range of the interaction one is using. We shall here use the quantum molecular dynamics (QMD) model [2–10,12–14] to follow the reaction dynamics which is discussed briefly in Sec. II. The details of the formalism can be obtained in Refs. [2,8] The results are discussed in Sec. III and finally we summarize the results in Sec. IV.

II. MODEL

The quantum molecular dynamics model [2,8,9] is based on the molecular dynamics picture where nucleons interact via two- and three-body interactions. The explicit two- and three-body interactions lead to the preservation of the fluctuations and correlations which are important for N-body phenomena like multifragmentation.

In QMD, the (successfully) initialized nuclei are boosted towards each other with proper center-of-mass velocity using relativistic kinematics. Here each nucleon is represented by a Gaussian wave packet with a width $\sqrt{L}$ centered around the mean position $\vec{r}_i(t)$ and the mean momentum $\vec{p}_i(t)$:

$$\phi_i(\vec{r},\vec{p},t)=\frac{1}{(2\pi L)^{3/4}}\ e^{\{-[\vec{r}-\vec{r}_i(t)]^2/4L\}}e^{[i\vec{p}_i(t)\cdot\vec{r}/\hbar]}. \quad (1)$$

The Wigner distribution of a system with A_T+A_P nucleons is given by

$$f(\vec{r},\vec{p},t)=\sum_{i=1}^{A_T+A_P}\frac{1}{(\pi\hbar)^3}e^{\{-[\vec{r}-\vec{r}_i(t)]^2/2L\}}e^{\{-[\vec{p}-\vec{p}_i(t)]^2 2L/\hbar^2\}}, \quad (2)$$

with $L=1.08$ fm^2. In other words, the rms radius of a nucleon is about 1.8 fm and hence is almost twice as large as that obtained from electron scattering. A smaller value of L is excluded because the nuclei would become unstable after initialization. Thus, this value of L presents the limit for a semi classical theory. As noted in Ref. [9], the value of L determines the interaction range of the particle and influences the density distribution of a finite system. In a semiclassical theory, this parameter is chosen by keeping in mind the stability of nuclei generated. Ideally, a time dependent width of the Gaussian should be used. Some attempts with limited success have been made in this direction [16]. Some authors have even used a system dependent Gaussian width [8]. The Gaussian width for a particular nucleon is chosen in a way so that maximum stability of the nucleonic density profile can be achieved. Hartnack [8], for example, used $4L=8.66$ fm^2 for Au whereas it is 4.33 fm^2 for the Ca system. In our present case, a constant value of $4L=4.33$ fm^2 is used. This value is referred hereafter as L^{stand} whereas a double width (i.e., 8.66 fm^2) is labeled as L^{broad}. A detailed study of the effect of different interaction ranges on different observable is carried out in Refs. [4,9]. As discussed in Refs. [4,9], an extended wave packet (i.e., L^{broad}) will connect a large number of nucleons in a fragment and, as a result, it will generate heavier fragments compared to the one obtained with a smaller width. The effect of doubling the width (that is, by taking L^{stand} and L^{broad}) was drastic on fragmentation as the latter reduces the multiplicity of intermediate mass fragments to a large extent. One should, however, keep in the mind that this effect depends on the physical situation and condition.

The centroid of each wave packet propagates within classical equations of motion [2,8]

$$\frac{d\vec{r}_i}{dt}=\frac{dH}{d\vec{p}_i}, \quad (3)$$

$$\frac{d\vec{p}_i}{dt}=-\frac{dH}{d\vec{r}_i}, \quad (4)$$

where the Hamiltonian is given by

$$H=\sum_i\frac{\vec{p}_i^{\,2}}{2m_i}+V^{tot}. \quad (5)$$

Our total interaction potential V^{tot} reads

$$V^{tot}=V^{loc}+V^{Yuk}+V^{Coul}+V^{MDI}. \quad (6)$$

Here V^{loc}, V^{Coul}, V^{Yuk}, and V^{MDI} are, respectively, the local Skyrme, Coulomb, Yukawa, and momentum dependent interactions (MDI's). The Yukawa interaction is essential for the surface effects. The momentum dependent part of the interaction (which is obtained by fitting the real part of the optical potential) acts strongly in the cases where the system is mildly excited [4,12]. In this case, the MDI is reported to generate a lot more fragments compared to the static equation of state. For a detailed discussion of the different equations of state and momentum dependent interactions, we refer the reader to Refs. [1,4,8,12]. If two nucleons come too close ($d\leqslant\sqrt{\sigma_{NN}/\pi}$; σ_{NN} is the nucleon-nucleon cross section), they are bound to collide depending upon the available phase space. For a discussion of the different forms of nucleon-nucleon cross sections and their effect on different observables, the reader is referred to Refs. [2,4,8,12].

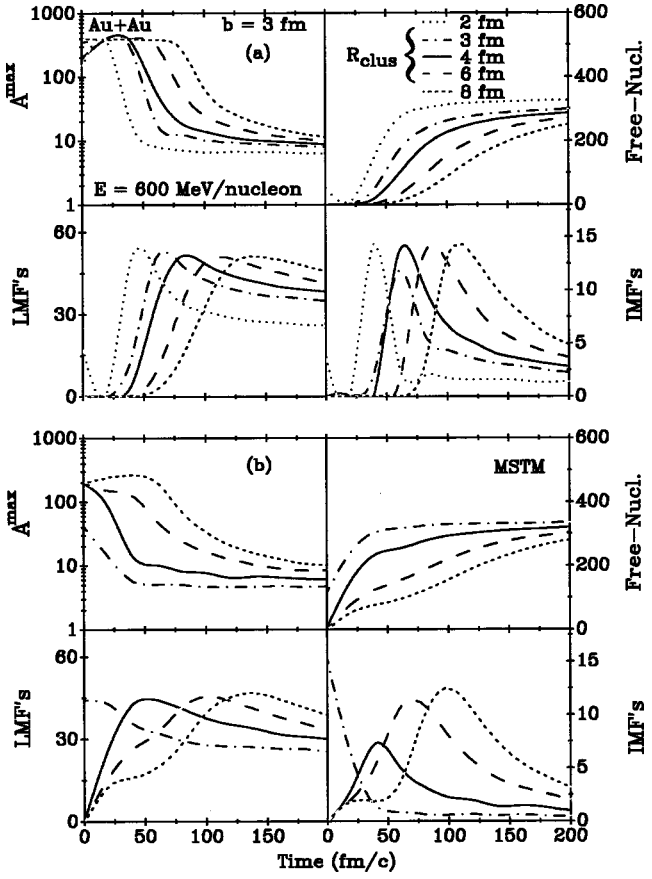

FIG. 1. The time evolution of the heaviest fragment A^{max}, free nucleons, light mass fragments ($2 \leqslant A \leqslant 4$), and intermediate mass fragments ($5 \leqslant A \leqslant 65$) as a function of time. The upper part is using the standard MST approach whereas the lower part denotes the results with a momentum cut (see the text).

III. RESULTS AND DISCUSSION

We here simulate the reactions for different system size effects, excitation energies, and colliding geometry. The nuclear equation of state is fixed as a stiff equation of state until stated explicitly. The energy dependent nucleon-nucleon cross section (fitted by Cugnon) is taken until stated explicitly. We shall also use an isotropic and constant cross section of 40 mb for the discussion. This is denoted by σ^L. The reaction dynamics is followed until 200 fm/c and then clusterization is performed with the minimum spanning tree method until stated explicitly. In some cases, a momentum cut will also be imposed. This extension is labeled as the minimum spanning tree with momentum cut (MSTM) [12].

Figure 1(a) displays the evolution of heaviest fragment A^{max}, freely emitted nucleons, light mass fragments (LMF's) ($2 \leqslant A \leqslant 4$), and intermediate mass fragments (IMF's) ($5 \leqslant A \leqslant 65$) produced in central Au-Au reactions at 600 MeV/nucleon. As expected, a larger value of R_{clus} needs a longer time to detect the stable heaviest fragment A^{max}. For a realistic value of R_{clus} (3 fm$\leqslant R_{clus} \leqslant$5 fm), a typical time of 100 fm/c is needed to pin down the heaviest fragment. On the other hand, the time evolution of free nucleons, LMF's, and IMF's predicts a different picture. Here a typical time of 200 fm/c is needed to pin down the content of free nucleons. Apparently, the heaviest fragment is a remnant of the spectator matter and hence is detached from the rest of system much earlier. Note that the difference in the emission of nucleons at low and high energies is that it is the heaviest fragment which emits the nucleons at lower energies whereas IMF's (and also LMF's to a good extent) are responsible for their emission at higher energies. The LMF's and IMF's in the present case are produced in a coalescence picture and, therefore, these are excited (this point will be further discussed in the following paragraphs). Note that the IMF's (with $R_{clus}=4$ fm) decrease from 13.4 to 2.8 at the end of the reaction. In contrast, the very same distribution is quite stable at 100 MeV/nucleon. The nucleons bound in fragments at 600 MeV/nucleon have a very large relative momentum. Very astonishingly, a small value of R_{clus} ($=2$ fm) does not detect a single nucleus at the start of the reaction, indicating artificial emission of the nucleons.

This point which is further checked for the reactions of Ca+Ca, Nb+Nb, O+Br/O+Ag, and Xe+Sn demonstrates that a large number of nucleons are emitted with $R_{clus}=2$ fm. This result rather points towards the problem of generating cold and stable nuclei in a semiclassical model. It seems that the nuclei produced in QMD are excited and, thus, a very small value of R_{clus} leads to artificial emission of nucleons at the start of the reaction. In another attempt [see Fig. 1(b)] we also imposed a (relative) momentum cut (of the order of the Fermi momentum) on nucleons. We find that now even $R_{clus}=3$ fm leads to an artificial emission of nucleons. We know that the mean distance between nucleons is much smaller than this value; therefore, this artificial emission again points towards the true ground state of a nucleus which is still not achieved in a semiclassical theory. Comparing Figs. 1(a) and 1(b), we see that the pattern in both cases is quite similar. One should keep in mind that the present system is highly excited and, therefore, a larger range of clusterization parameters will yield heavier fragments compared to a smaller range. A smaller range will generate more nucleons compared to larger ranges. As has been noted in Ref. [12], a cut in the relative momentum of nucleons helps in avoiding the creation of weakly bound fragments. Let us take Au-Au at 600 MeV/nucleon as an example and look for IMF production without a momentum cut (with $R_{clus}=4$ fm). The IMF's decrease from their peak value ($=13.4$) to about 2.8 at 200 fm/c, whereas with a momentum cut (i.e., with MSTM), IMF's just decrease from 7.3 to 1.0, indicating that the momentum cut has a clear role to play. From Fig. 1, one also sees that different values of R_{clus} have some effect on the multiplicity of fragments at the freeze-out time. This effect reduces if one goes to 300 fm/c or later times.

It has been discussed in Ref. [9] that different ranges of the interaction force (represented by the width of the Gaussian of nucleons) affect the fragmentation drastically. Naturally, heavier fragments will be formed if a larger value of the width is used. This width is associated with the stability of the nuclei generated in a semiclassical model and a lot of discussion has been made about the range of the interaction. It would be of interest to study the role of different interac-

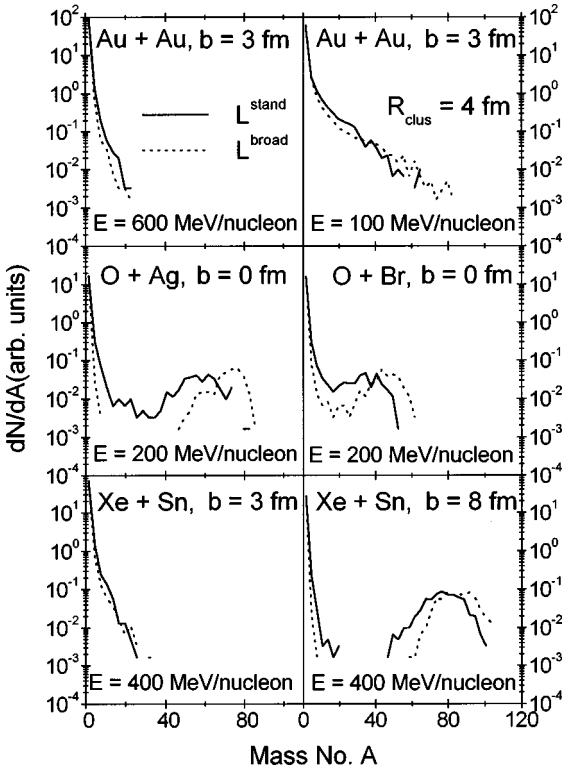

FIG. 2. The mass yields dN/dA using the standard Gaussian width (L^{stand}) and broader Gaussian width (L^{broad}). The displayed reactions are, respectively, the central Au+Au at 100 and 600 MeV/nucleon, central O+Ag and O+Br at 200 MeV/nucleon, and central and peripheral Xe+Sn at 400 MeV/nucleon. Here $R_{clus}=4$ fm is used for the calculations.

tion ranges under different excitation energies.

The mass yield is displayed in Fig. 2 for the reactions of central Au+Au at 100 and 600 MeV/nucleon, central O+Br/Ag at 200 MeV/nucleon, and Xe+Sn at 400 MeV/nucleon. The two typical values of the Gaussian width (i.e., L^{stand} and L^{broad}) are taken for discussion. As noted in Refs. [4,9], the Au+Au reaction at 100 MeV/nucleon has a fewer number of IMF's if a broader (extended) Gaussian width is used. At the same time, heavier fragments are obtained. This is understandable because in the case of broader Gaussians, the particles in a cluster are bound to a larger number of other nucleons inside a cluster. A smaller width leads to fluctuations which results in a larger number of light and intermediate fragments. One sees that similar behavior exists for most of the reactions. A careful look shows that the impact of a broader Gaussian is also linked to the excitation energy of the system. The impact of a broader Gaussian width is larger if the system is mildly excited (like O+Br, O+Ag, or Xe+Sn at peripheral geometry). However, the impact of a broader Gaussian decreases if the excitation energy is quite large (like central Au+Au at 600 MeV/nucleon or Xe+Sn at 400 MeV/nucleon). The above dependence on the excitation energy of the system is understandable as larger excitation energies lead to more collisions and scattering which destroys the initial correlations among nucleons. If the nucleons are very far off, no impact of different Gaussians will be there. On the other hand, if the nucleons are

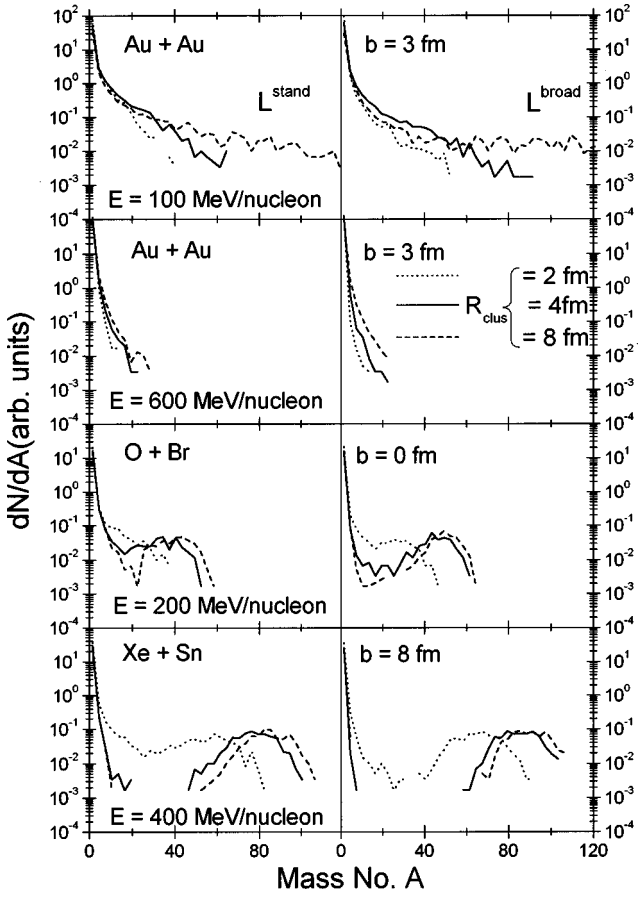

FIG. 3. The mass yields dN/dA using the standard Gaussian width L^{stand} (left part) and broader width L^{broad} (right part). Here three typical values of $R_{clus}=2$, 4, and 8 fm are chosen and central reactions of Au+Au at 100 and 600 MeV/nucleon and O+Br at 200 MeV/nucleon are displayed along with peripheral Xe+Sn at 400 MeV/nucleon.

within the range of the interaction (clusterization), the different values of the Gaussian width will have a role to play. It means that if we go to very low energies (say, 25 MeV/nucleon), matter is so closely placed that no effect of different Gaussians should exist. Clearly, the impact is drastic if the system is mildly excited.

To further investigate this point, we also studied the collision rate for different systems with broader and narrow Gaussians. We found that the maximum collision rate for Au+Au at 100 MeV/nucleon and 600 MeV/nucleon and for O+Ag at 200 MeV/nucleon is, respectively, 10(7), 55(45), and 4(3) with broader (narrow) Gaussians. Because of the larger range of the interaction, a higher collision rate is expected with broader Gaussians. Further, the difference in the collision rate increases when the system is mildly excited, indicating a strong effect in mildly excited systems. It is worth mentioning that a broader Gaussian leads to more excited fragments which needs a much larger time to deexcite compared to narrow Gaussians.

In Fig. 3, we display the mass yields using a narrow and broader Gaussian with different ranges of clusterization parameter. Three typical reactions showing high, mild, and low excitation energies are displayed. A single decreasing slope

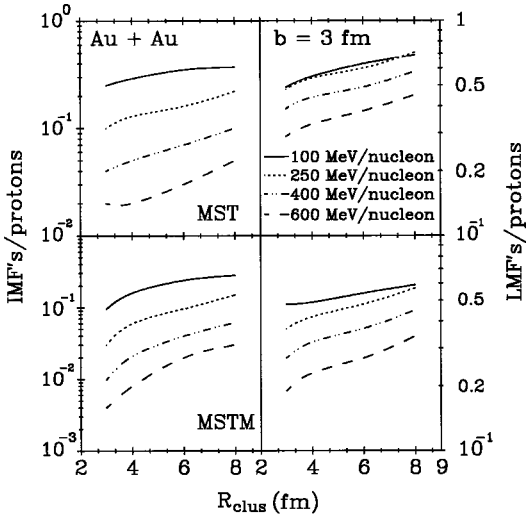

FIG. 4. The ratio of LMF/proton and IMF/proton as a function of R_{clus}. The upper and lower parts define the ratio with MST and MST + momentum cut, respectively.

curves can be seen at very high energy which turns into two-component U-shape curves at lower excitation energies, indicating that partial fusion still exists at lower excitation energies (note that the two-component shape obtained in O + Br reaction is absent in the experiments) [11,14,15]. A comparison of left and right hand sides reveals that the use of a broader Gaussian leads to heavier fragments. For example, the maximum in O+ Br occurs at about 37 and 43 units using narrow and broader Gaussians with $R_{clus}=4$ fm. A close look reveals that the effect of different clusterization ranges is not affected by the choice of Gaussians. One sees that in all cases, a larger value of the clusterization parameter leads to heavier fragments and lesser light and intermediate fragments at low excitation energies, whereas a different picture emerges at higher excitation energies. At 600 MeV/nucleon, we see that a larger value of the clusterization parameter leads to more intermediate and light fragments. This different response of the clusterization parameter at low and higher excitation energies is due to the fact that at low energies matter is compact and most of the initial correlations are preserved. In this case, a smaller value of the R_{clus} does not allow heavy fragments to be formed, therefore leading to a lot of intermediate mass fragments. On the other hand, at higher incident energies, most of the initial nucleon-nucleon correlations are washed away and, hence, a larger value of the R_{clus} binds many more nucleons in a fragment and thus it gives many more intermediate and heavy fragments. The response of a larger value of R_{clus} in all cases is similar to the one obtained with a broader and narrow Gaussian. From Fig. 3 it is quite clear that the role of different clusterization parameters is more than marginal.

Apart from the production of different fragments, the ratio of different fragments also plays an important role in our understanding. In Fig. 4, we display the ratio of LMF/proton and IMF/proton using different values of R_{clus} between 3 and 8 fm. We find that there is an increase in the ratio of LMF/proton and IMF/proton with an increase in R_{clus}. It is understandable when one looks at Fig. 1. Here we find that

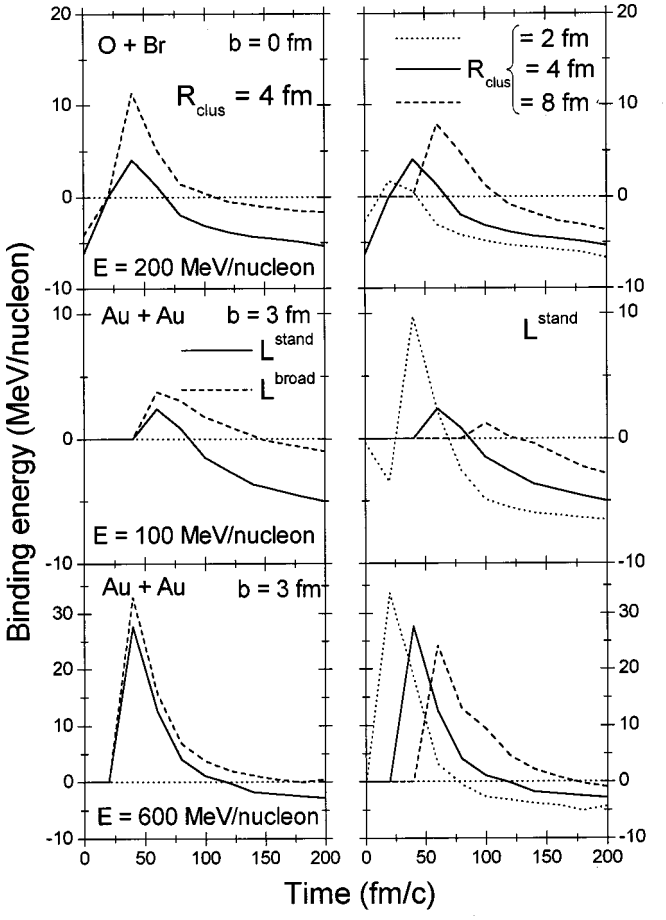

FIG. 5. The average binding energy per particle as a function of time. The left part displays the result with the standard Gaussian width L^{stand} and broader Gaussian width L^{broad} at $R_{clus}=4$ fm whereas the right-hand side displays the curves using different values of R_{clus} and the standard Gaussian width.

the multiplicity of LMF/IMF increases with an increase in R_{clus} whereas emission of nucleons decreases with R_{clus}, which leads to an overall increase in the ratio of LMF/proton and IMF/proton. One also sees that the ratios are maximum for lower incident energies which decreases with an increase in the incident energies. With the increase in the energy, more nucleons are emitted. The different values of R_{clus} have an effect at higher incident energies.

We have also analyzed the stability of the fragments by plotting the time (in fm/c) at which the fragment yield is within $\pm 10\%$ of its preceding time. Our analysis of Au + Au at 100, 250, 400, 600 MeV/nucleon at $b=3$ and 8 fm indicates that this critical time is about 140 fm/c for MST (at 4 fm) which increases to 200 fm/c with $R_{clus}=8$ fm. In addition, central collisions need the shortest time for the emission of free nucleons whereas the longest time is needed in peripheral collisions. Because of the very violent reaction in central collisions, most of the nucleons are emitted quite early (between 20 and 40 fm/c), whereas in peripheral collisions, first a compound nucleus is formed and, then, the emission of nucleons takes place. Similar results are also obtained for the Nb+ Nb reaction at different incident energies.

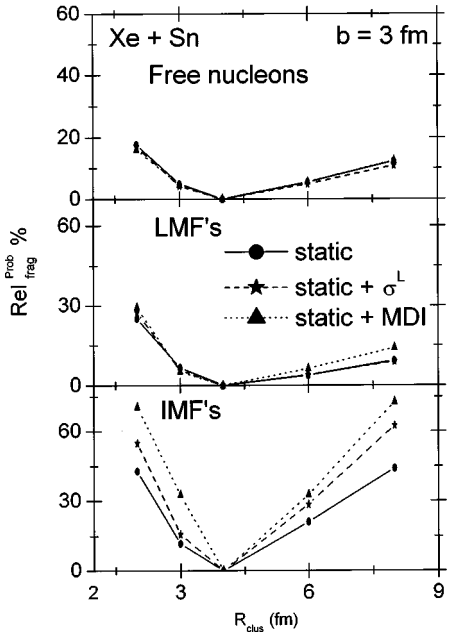

FIG. 6. The relative probability $\mathrm{Rel}_{frag}^{Prob}$ % as a function of R_{clus} for the central reaction of Xe+Sn at 400 MeV/nucleon. The upper, middle, and lower parts are for free nucleons, LMF's, and IMF's. Here we show the results calculated using the static (stiff) equation of state (EOS) with standard nucleon-nucleon cross section, static EOS with isotropic cross section of 40 mb, and static EOS with momentum dependent interaction, respectively.

The binding energy of the IMF's produced with different clusterization parameters and widths of the Gaussian is checked in Fig. 5. We find that a larger value of the clusterization parameter or a broader Gaussian produces more excited fragments compared to a smaller value of the clusterization parameter or a narrow Gaussian. The simple cause for this different behavior lies in the fact that a large value of the clusterization parameter (say, $R_{clus}=8$ fm) or a broader Guassian binds a large number of neighboring nucleons into fragments. These nucleons have a large relative momentum and thus are bound to decay. A nominal value of R_{clus} gives a binding energy of at least 4 MeV/nucleon in all cases. It is worth mentioning that if a momentum cut is imposed, a drastic improvement in the binding energy of the fragments can be seen.

In order to quantify the effect of different ranges of clusterization, we define a relative probability as

$$\mathrm{Rel}_{frag}^{Prob}\ \% = \left| \frac{[Mul]_{R_{clus}} - [Mul]_{R_{clus}=4\ \mathrm{fm}}}{[Mul]_{R_{clus}=4\ \mathrm{fm}}} \right|_{frag} \%\ .$$

This quantity gives us the change in the multiplicity of different fragments produced in one kind of equation of state over the $R_{clus}=4$ fm distribution. We choose the central and peripheral reactions of Xe+Sn at 400 MeV/nucleon. This peripheral reaction has a mild excitation energy where one expects a large role of the different ranges of clusterization. In Fig. 6, we display the free nucleons (upper part), the light mass fragments (middle part), and intermediate mass

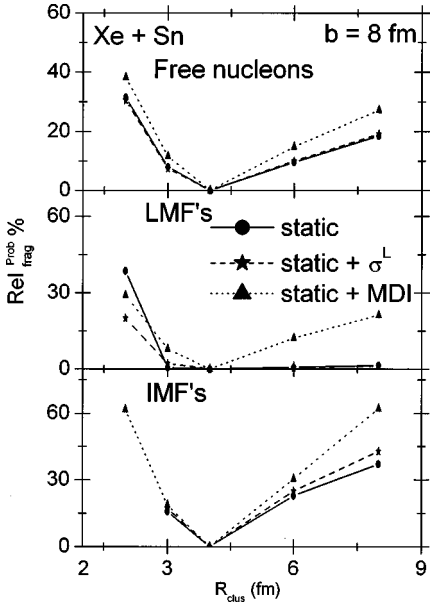

FIG. 7. Same as Fig. 6, but for Xe+Sn at $b=8$ fm.

fragments (lower part) as a function of R_{clus} (we chose $2 \leqslant R_{clus} \leqslant 8$ fm for the discussion). We noticed a very small effect of different clusterization ranges with a static equation of state (EOS). The matter is compact with a static equation of state and, therefore, a larger value of R_{clus} does not play a role. In contrast, the momentum dependent interactions (which act during the initial phase of the reaction when the relative momentum is quite large) deflect the nucleons into the transverse direction, leading to a scattering of nucleons. In this case, a larger value of R_{clus} will bind more nucleons into fragments and, therefore, one would expect a drastic effect. The interesting point is that the nature of the effect is similar in central and peripheral collisions (see Fig. 7). Looking at the variation in the yield with $R_{clus}=3$ and 4 fm, we see that the static EOS yields about a 15% difference whereas the MDI leads to about 30%. Similarly while going from 4 to 6 fm, the static EOS changes the IMF production by about 27% whereas with MDIs it goes to about 40%. By doubling R_{clus} (i.e., going from 4 fm to 8 fm), the static equation of state gives about a 30–40 % change whereas this goes to about 65–70 % when the momentum dependent equation of state is used. In other words, different physical conditions and situations give a different response to the different values of the clusterization parameters. The results with the static equation of state are in agreement with Peilert *et al.* [4] who have reported a change of the order of 25%. A similar impact was also found in Ref. [11] where a study was carried out for different radii used in the aggregation model. Very little effect exists for the emission of nucleons and light mass fragments. Note that a maximum effect exists for the production of intermediate mass fragments where nucleon-nucleon correlations and fluctuations play a very important role in their production.

IV. SUMMARY

We have presented a detailed analysis of the role played by spatial correlations and the range of interaction on frag-

mentation using the quantum molecular dynamics model. Several different system sizes and physical pictures were considered for a deeper understanding. We find that the broader Gaussians have a stronger effect if the system is mildly excited whereas its impact decreases if the system is highly excited as noted in Ref. [9]. The impact of different clusterization parameters is also more than marginal and goes in the same direction as broader Gaussians. We further find that the different clusterization parameter has a great effect if the momentum dependent interactions are present.

ACKNOWLEDGMENTS

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