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Early Fragment Formation in Heavy-Ion Collisions

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The fragmentation pattern of central multi fragmentation events observed in the collision of heavy nuclear systems can be recognized already at a time when the system is still dense and the nucleons are still interacting with each other. In peripheral reaction, however, we observe besides these early formed fragments excited spectator matter which tends to break up into several fragments but does not succeed. This is the result of a new approach to fragment recognition applied to the Quantum Molecular Dynamics Model (QMD). It shows that fragment nucleons never pass through a density sufficiently low to allow for a liquid gas phase transition.

Why does a nucleus shatter into to several (up to a dozen) intermediate mass fragments (IMF's) if hit by a projectile nucleus? Is this only a statistical process and hence microcanonical phase space models are the proper tool for its description [1] - [2] or is this a dynamical process as conjectured by [3] - [8]?

Despite of extensive efforts of several experimental groups [9] - [11] , this question is not finally decided yet. However, the results of the recent and up to now most complete experiments by the FOPI collaboration [10] can up to now not be reconciled with the predictions of statistical models. This raises the question of what - if not phase space - is the driving force for multifragmentation. Since the situation of a heavy ion reactions is too complicated to allow an approach starting from first principles the only means at hand are the dynamical models which simulate heavy ion reactions on an event by event basis by following the time evolution of the nucleons. It is all but easy to extract from the complex n body dynamics the underlying physical process. But this is presently the only possibility to identify the physics behind the multifragmentation.

Before one can study the origin of fragments on has to identify the fragments. Up to now the fragments have been identified by a minimum spanning tree (MST) procedure. One first simulates the reaction for about 200 fm/c, using QMD. Then the spatial distance of all nucleons is checked. A nucleon is part of a fragment if there is another one within a distance of r_{min} [7]. This procedure yields stable results, i.e. gives the same fragment pattern for times later than 200 fm/c but cannot be used for earlier times because it only makes sense when the system is very dilute.

Before any conclusions from the simulation models can be drawn one has to verify that they reproduce the experimental results in a qualitative way . For the Quantum Molecular Dynamics (QMD), which will be used in this letter, this has been done extensively [10,7,8] and in the energy range between 50 MeV/N and 400 MeV/N its results agree with the experiments in a way which makes us confident that it contains the essential physics. This verification allows to employ this model to proceed further towards a physical understanding of the production process by taking advantage of the fact, that it contains the time evolution of the n-body phase space The first step towards an understanding of the multifragmentation process is the identification of the time point, at which fragments are formed. This allows then to investigate the environment in which the formation takes place. This requires a fragment identification already at a early stage of the reaction when the MST procedure fails.

Recently, Dorso et.al. [12] proposed a new algorithm to identify the fragments. Their first results (for light system like Ca-Ca) show a quite early formation of the few final fragments. However, for the understanding of multifragmentation the multi fragment events observed in the collision of heavy systems have to be analyzed. Unfortunately the computing time for the algorithm employed [12] increases by roughly $N!$, where N is the number of nucleons in the system. Hence a completely new numerical procedure has to be invented to extend the approach to larger systems.

We here present the first result for the system Au + Au which has extensively been investigated in the last years by the FOPI [9] collaboration. We show that we can recognize the fragmentation pattern also in this reaction at an extremely early phase of the reaction. However, we see clear differences in the result at semi central and peripheral reactions which are due to different physical processes. This is the result if one combines the above algorithm with the N-body Quantum Molecular Dynamics Model (QMD) [7], which has been proven to reproduce most of the fragment observables measured by the large 4π detector collaborations [8].

Our new approach defines the fragments in phase-space. Nucleons can form a fragment if the total fragment

energy/nucl. ζ_i is below a minimum binding energy:

$$\zeta_i = \frac{1}{N^f}\left[\sum_{i=1}^{N^f}\frac{(\vec{p}_i - \vec{p}_{cm})^2}{2m} + \frac{1}{2}\sum_{i\neq j}^{N^f} V_{ij}\right] < E_{Bind}, \quad (1)$$

We take for E_{Bind} = -4.0 MeV if N $\geq$ 3 and $E_{Bind} = 0$ otherwise. In this equation, N^f is the number of the nucleons in a fragment, $\vec{p}_{cm}$ is the center-of-mass momentum of the fragment. This new definition has the advantages that the requirement of a minimum binding energy excludes loosely bound fragments which will decay later. It modifies the definition of Ref. [12], where nucleons can be bound even if the binding energy of the fragment is extremely small. The precise value of E_{Bind} changes slightly the fragment multiplicity at intermediate times but has no influence on the qualitative behaviour and on the asymptotic result.

To define the fragmentation pattern we assume:

1 The nucleons from target and projectile group into fragments and into free nucleons.

2 Though the nucleons inside a fragment can interact with each other, they do not interact with the nucleons from other fragments or with single nucleons.

3 The most bound fragmentation pattern (composed of nucleons and fragments) is realized in nature.

To find this configuration among the huge number of possible fragmentation patterns we proceed as follows: We start from a random configuration which is chosen by dividing the whole system into few fragments. The energy of the individual clusters is calculated by summing over all nucleons present in that cluster using eq.1. Note that as we neglect the interaction between fragments, the total energy calculated in this way will differ from the total energy of the system.

Let the total energy of a configuration k be E_k (= $\sum_i N_i^f \cdot \zeta_i$, where N_i^f is the number of nucleon in a fragment i and ζ_i is the energy per nucleon associated with the fragment i (eq.1)). Suppose a new configuration k'(which is obtained by either by a) transferring a nucleon from some randomly chosen fragment to another fragment or by b) setting a nucleon free or by c) absorbing a free nucleon into a fragment) has total energy E_k'. If the difference between the old and new energy ΔE (= $E_k' - E_k$) is negative, the new configuration is always accepted. If not the new configuration k' may nevertheless be accepted with a probability of $\exp(-\Delta E/c)$, where c is called control parameter. This procedure is called the Metropolis algorithm [13]. The control parameter is decreased in small steps. This algorithm will yield eventually the most bound configuration (MBC) [12] [14].

Since this combination of a Metropolis algorithm with a decreasing control parameter is known as simulated annealing we dub our approach Simulated Annealing Clusterization Algorithm [SACA].

In order to avoid the creation of weakly bound clusters we additionally check the validity of eq. 1 for each fragment explicitly. If a most bound configuration is achieved from our simulated annealing mechanism, we control the binding energy condition for each fragment and mark all fragments violating this condition. The nucleons belonging to an 'inhibited' (marked) cluster are further on treated as free nucleons. The minimizing procedure of the simulated annealing mechanism is invoked again till a configuration is found where all fragments fulfill eq. 1.

We present now the results for the reaction of Au-Au at 400 MeV/nucl.. The impact parameters chosen are b=3 fm (corresponding to a semi-central collision) and b=8 fm (corresponding to a peripheral reaction). A soft equation of state coupled with the free nucleon-nucleon cross-section is employed.

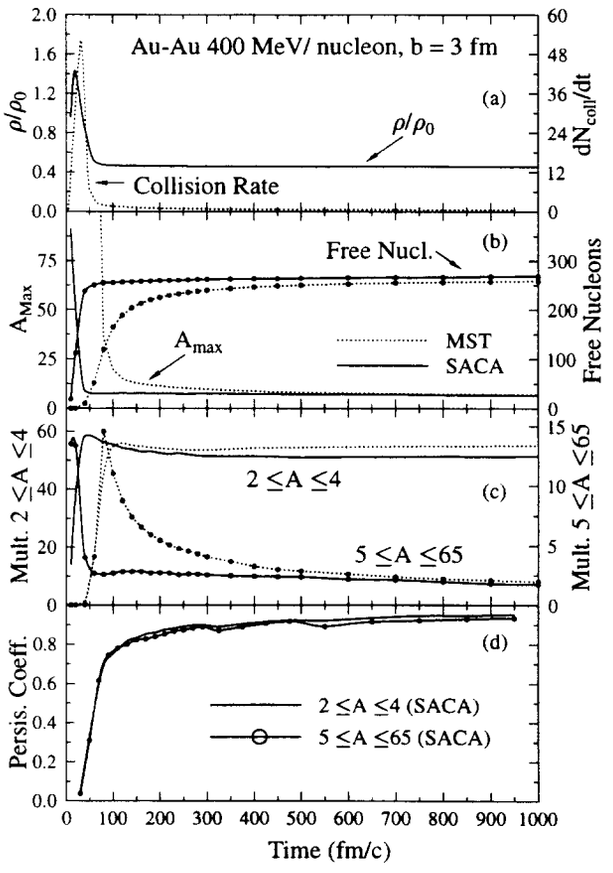

FIG. 1. Evolution of the collision of Au-Au at 400 MeV/nucl. and at an impact parameter b = 3 fm. From top to bottom the rows display the time evolution of the density and of the collision rate, of the size of the heaviest fragments and of the number of emitted nucleons, of the multiplicity of fragments with mass $2 \leq A \leq 4$ and with mass $5 \leq A \leq 65$ and of the persistence coefficient.

Fig. 1 displays the results for Au + Au 400 MeV/nucl b=3 fm. The first row shows that the mean density (average over all nucleons independent whether bound or not) and the collision rate reach a maximum value at about 30 fm/c and about 60-70 fm/c, respectively. Afterwards the collision rate becomes negligible whereas the mean

density stays constant at about 0.4 ρ_0. This value is an average over all nucleons.It includes the free nucleons which will finally have see a density equal zero as well as the fragment nucleons which feel the density of their fellow nucleons.

The second row shows that SACA finds the heaviest fragment rather early, at a time when the system is still quite dense and interactions among the nucleons are still continuing. This gives an indication that the heaviest fragment is formed from the spectator matter, a conclusion which is supported by the analysis of ref. [8]. Note that the MST needs as long as 200 fm/c to find the surviving heaviest fragment. As a consequence SACA predicts also already the asymptotic single particle multiplicity at around 60 fm/c, much earlier than MST. There the heaviest fragment emits continuously loosely bound nucleons until 250 fm/c. These nucleons are still around the heaviest fragment therefore MST counts them as belonging to the heaviest fragment but are very loosely bound and therefore the most stable configuration is obtained if one consider them no longer as part of the heaviest fragment.

From the third row we see that also the light fragments $2 \leq A \leq 4$ are formed quite early before they are visibly separated in coordinate space. SACA finds the stable pattern at about 50 fm/c, whereas MST identifies them at about 100 fm/c. The formation of intermediate mass fragments ($5 \leq A \leq 65$) is finished after 50 fm/c as well. The MST, however, needs very long (about 300-400 fm/c) until it can identify the final fragments. This is again due to loosely bound fragment nucleons. Their relative velocity with respect to the fragment momentum is small, therefore they rest for a long time in the vicinity of the fragments until they get eventually sufficient energy to escape.

In order to quantify the change of the nucleon content of the fragments between two successive time steps we introduce the persistent coefficient [12,14].

We define the number of pairs of nucleons in cluster C at time t $b_C(t) = 0.5 * N_C(N_C - 1)$. At the time Δt later, some of the nucleons may have left the cluster and are part of another cluster or singles and others may have entered the cluster. Let N_{C_A} be the number of nucleons which have been in the cluster C at time t and are at $t + \Delta t$ in the cluster A. We define $a_C(t + \Delta t) = \sum_A 0.5 * N_{C_A}(N_{C_A} - 1)$, where the sum goes over all clusters A present at time $t + \Delta t$.

As persistence coefficient for the cluster C we define

$$P_C(t + \tfrac{\Delta t}{2}) = a_C(t + \Delta t)/b_C(t) \qquad (2)$$

If the fragment is unchanged $P_C(t + \frac{\Delta t}{2}) = 1$, if it disintegrates completely $P_C(t + \frac{\Delta t}{2}) = 0$. If we remove one nucleon from a fragment C the persistence coefficient is $P_C(t + \frac{\Delta t}{2}) = (N_C - 2)/N_C$, i.e .333 for $N_C = 3$ and .8 for N_C=10.

The persistence coefficient for the fragments $2 \leq A \leq 4$ and $4 \leq A \leq 65$ is displayed in the last row.

One can conclude that the final fragments are formed as early as at 50 fm/c. The persistent coefficient reaches its asymptotic value later due to the (mainly potential) interaction between fragments and between fragments and free nucleons. This interaction changes the details but not the general structure of the fragmentation pattern.

This early recognition of the final pattern of fragments is very promising. It indicates that the fragment formation is lead by the fluctuations occurring during the reaction. As soon as the violent phase of the reaction is over the fate of the final fragments is already determined. There are first indications from FOPI analyses that the fragment pattern can be formed before the interactions ceases to exits [9].

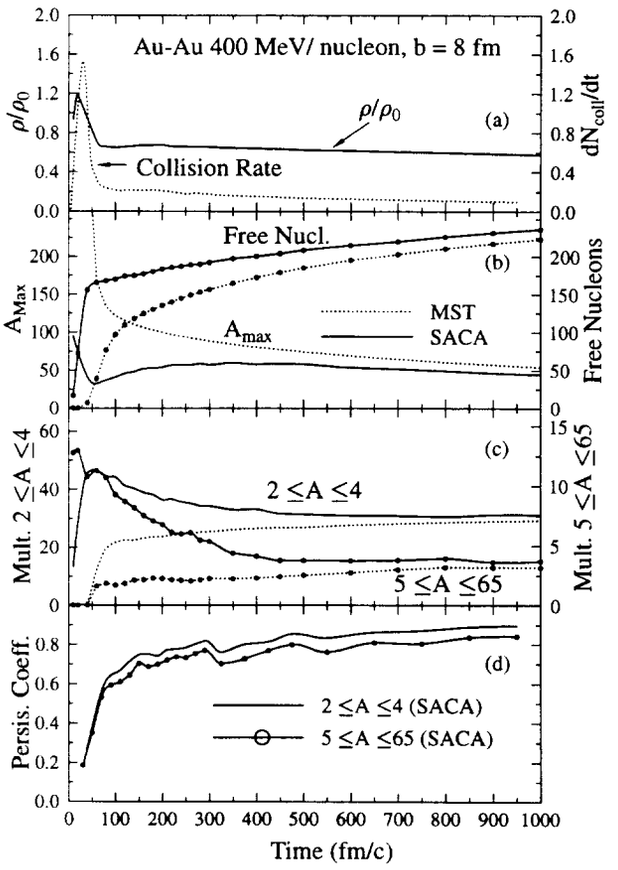

FIG. 2. Same as fig 1, but for Au-Au at 400 MeV/nucl. and at an impact parameter b = 8 fm.

Let us now turn to more peripheral collisions. Fig. 2 displays the same quantities as fig. 1 for Au-Au at 400 MeV/nucl. and at impact parameter b = 8 fm. The mean density saturates at about 0.6 times the normal nuclear matter density. This value is higher than in central collisions due to the fact that more nucleons are bound in heavy clusters. The nucleons continue to collide up to the end of the reaction. These are, however, soft colli-

sions inside the large clusters. In contradistinction to the central collision SACA is not able to identify the size of the largest fragment before 150 fm/c, however, the MST need still much longer. SACA seems to fail completely for the small clusters as compared to the minimum spanning tree. It takes as well very long ($> 400 fm/c$) before a persistent coefficient of .8 is obtained. Before that time there is a strong exchange of nucleons between the fragments.

How can this result be interpreted? The fact that the minimum spanning tree recognizes most the final fragments already at 80 fm/c means that at this time these fragments are clearly separated from the rest of the system and each other in coordinate space. The additional fragments observed by SACA are not separated in coordinate space but only obtained because this configuration gives the lowest binding energy. Shortly after the interaction between projectile and target the both large remnants (the spectator matter) are perturbed in a way that dividing them into small fragments is energetically favourable. Therefore also the size of the largest fragment is below the asymptotic value. The nucleons entrained in these by SACA detected fragments continue to interact (as can be inferred as well from the low value of the persistence coefficient) and smoothen finally the perturbation in a way that some nucleons get emitted and the rest of the system forms a single large fragment.

Is this realistic? Between the time steps analyzed by SACA the nucleons propagate on trajectories as calculated in the QMD program. Despite of the local interaction due to the Gaussian form of the wave function the range of the interaction is finite and different from zero even at large distances between the nucleons. This is of no importance if the excitation energy of the system is large. Here, however, we deal with excitation energies of a couple of MeV/nucl. were these details may play a role.

It was reported in a recent analysis of ALADIN experiments at 600 MeV/nucl. that the MST method applied to QMD simulations overpredicts the size of the heaviest fragment and at the same time underestimates the multiplicity of all (small and large) fragments [11]. Since SACA gives at intermediate times a smaller heaviest fragment and more medium mass fragments than MST it may be that the disagreement found between QMD and experiment is caused by an artificial equilibration of the excited spectator matter in QMD which in reality breaks up into several fragments.

We have furthermore analysed the time evolution of several dynamical observables (stopping, flow, etc.) for different fragment classes and found agreement between an analysis performed very early (at 50 fm/c) and very late (at 1000 fm/c). This indicates as well that the observables of the reaction reach their asymptotic values already quite early. For a detailed discussion we refer to ref. [14].

We have presented an extended algorithm for cluster recognition based on the simulated annealing method. This algorithm is able to recognize the stable structure of fragments in reactions between heavy ions at a very early time in central collisions. This extremely early recognition of fragments gives us new strong evidence that the fragments are formed just due to preserved correlations between the nucleons and fluctuation which are build up in the violent phase of the reaction. In peripheral reactions in addition to the fragments formed at the time when projectile and target are in contact with each other the SACA algorithm also finds that it is energetically preferable to subdivided the spectator matter into smaller fragments. During the further time evolution the QMD propagation equilibrizes the spectator matter. Hence finally only one large fragment is left. Whether this equilibrium is an artificial QMD feature has to be investigated later.

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