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The role of dynamical correlations in fragment formation in heavy-ion collisions

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Abstract

We use the Quantum Molecular Dynamics model to investigate the formation mechanism of protons and composite fragments in intermediate-energy heavy-ion collisions. We demonstrate that dynamical correlations result in the production rate for final state nucleon clusters (and hence composite fragments) being higher than would be expected if statistics and the properties of the available phase space were dominant in determining composite formation. This finding contradicts assumptions which underlie models based on either the one-body phase-space density or on statistical equilibrium. Hybrid models, which treat the initial violent collisions in an intranuclear cascade or a Boltzmann-Ühling-Uhlenbeck approach and then change to a statistical model may be used for central collisions at higher energy (e.g. 600A MeV) but fail for semiperipheral reactions and for all impact parameters at lower beam energies.

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The multifragmentation of nuclei excited in collisions with protons or heavy ions is one of the most interesting and challenging topics in present-day heavy-ion physics. Despite extensive experimental efforts, the underlying physical explanation for why a nucleus disintegrates into many (up to 15) intermediate mass fragments (IMF) remains controversial. Among the puzzling aspects is that some observables (like the mass yield curve or the energy spectra) are found to be rather independent of the beam energy, the mass of the projectile-target combination and the impact parameter of the reaction, even though mechanisms seem to change. The models advanced to describe multifragmentation invoke practically all imaginable physical processes. They include statistical models[1,2,3] which neglect all dynamics of the reaction and assume that the interaction in the initial state populates all possible exit channels with equal probability. Phenomenological models have been proposed which assume that the cold spectator matter of the target nucleus is cleaved by fast penetrating nucleons from the fireball[4]. In coalescence models[5], the fragments are formed in the late expanding stage of the reaction by nucleons which are by chance close in momentum space. Other models assume that the nucleus is driven into a region of instability (determined by the nuclear equation of state)[6].

Besides these models which rely more or less on ad hoc assumptions about the time-evolution of the system, calculations have been advanced which describe the time-evolution of the system, beginning with the projectile nucleus incident on the target, and ending with the final disintegration into nucleons (and fragments). The first generation of this kind of model was the so-called Boltzmann Ühling Uhlenbeck approach (BUU)[7] which describes the time-evolution of the one-body Wigner density. A more recent development is the Quantum Molecular Dynamics (QMD) [8] which follows the time-evolution of the full multi-nucleon phase space distribution. The agreement of the predictions of this model with experiments is generally quite good and hence it is fair to conjecture that it contains the essential physics. However, this calculation is very involved and it is not easy to interpret the results in terms of simple physical processes.

In this letter, we report on an analysis to determine the nature of the multifragmentation phenomenon. We investigate whether multifragmentation is a process in which correlations between the nucleons play an important role (and hence requires an n -body theory for its description) or whether it is completely determined by the one-body distribution function only. The latter is a prerequisite for the coalescence model, BUU-type calculations, as well as for any statistical model. Thus, this investigation may rule out some

of the above-mentioned models.

One method which is frequently applied in experimental analyses for determining the presence of true multibody correlations is the event mixing technique. Mixed events are generated by randomly choosing fragments from different observed events, and these fragments are selected under the constraint that the single-particle-inclusive spectra are the same. If two-body (or many-body) quantities constructed from observed events are distinguishable from the same quantities for mixed events, then the physics is completely determined by the one-particle phase space density; otherwise, deviations can be attributed to true correlations. As we will see later, this method is not only appropriate for experimental results but may also serve to extract the correlations in event-by-event simulations of the experiments as provided by BUU or QMD calculations.

In this letter, we apply this method to heavy ion events generated by the QMD model. In this n -body approach, nucleons are represented by Gaussian wave packets which move under the influence of mutual density-dependent two-body interactions (the real part of the Brückner g -matrix) and collisions (the imaginary part of the Brückner g -matrix). This model preserves all correlations which are present initially or are built up in the course of the reaction. It avoids the introduction of mean fields as present in one-body transport models such as those based on the BUU approach.[7] Consequently, QMD is uniquely suited for studies involving the interplay between cluster formation and collision dynamics at the nucleon level.

For the present investigation, we have employed this model to simulate Au on Au reactions at 60A MeV and 600A MeV, using a soft equation of state. For details, we refer the reader to reference [8]. The process of interest is the formation of low and intermediate mass fragments (IMF). As discussed above, they may be created by coalescence in the final state of the reaction or by correlations which are present from the beginning or are built up during the reaction. If the former conjecture is true, we do not expect differences between results obtained for QMD events before and after mixing; on the other hand, deviations are expected if correlations play a significant role.

In the QMD model, the clusters are determined by a minimum spanning tree procedure in coordinate space. After the reaction has taken place, the fragments separate from each other and can be easily recognized in coordinate space. We assume that a nucleon is member of a cluster if at the end of the simulation there is another nucleon within a distance smaller than $r_{\min}$. The value for $r_{\min}$ should satisfy $3 \text{ fm} < r_{\min} < 5 \text{ fm}$. These limits

are determined by the average distance of two nucleons in nuclear matter and the range of the interaction. At the lower beam energy considered here (60A MeV), as well as for non-central impact parameters at the higher beam energy (600A MeV), the IMF yield does not depend on $r_{\min}$. For central collisions at the higher beam energy, we observe that the IMF yield varies on the order of 25% over the possible range of $r_{\min}$; such a variation is unimportant in the context of the present investigation.

Fig. 1 presents the energy spectra for protons and light fragments. The upper panel displays results for 60A MeV central collisions ($\langle b \rangle = 2$ fm), the middle panel is for 600A MeV central collisions, and the lower panel is for 600A MeV semiperipheral collisions ($\langle b \rangle \simeq 8$ fm). In each graph, we show spectra for protons, deuterons and α particles (whose yields decrease in this order), with the solid line indicating unmixed events and the dashed line indicating mixed events. Note that the orientation of particles with respect to the event reaction plane is preserved in the mixed events. We observe that for all particles, the event mixing yields quite different results compared to true events. At low energy, the mixed events yield a higher rate of light fragments, since many nucleons are bound in larger clusters in the corresponding unmixed events. For higher energy α particles we observe the opposite; it is relatively improbable for four nucleons in a mixed event to be close enough to form a stable cluster. In contrast, these particles exist from the outset in true events, and are propagated as an entity up to the final time of the simulation (200 fm/c). The difference between protons in true and mixed events is smaller for collisions at 600A MeV simply because there are fewer fragments and therefore the protons constitute the majority of the particles present. In mixed events at the higher energy, we also observe an underprediction of the deuterons and a dramatic underprediction of α particles.

The multiplicity distribution for intermediate mass fragments in the same three categories of interaction are presented in Fig. 2 with the same meaning for solid and dashed lines. We observe, first of all, that event mixing produces intermediate mass fragments. This means that certain regions of phase space are still densely populated at the end of the interaction. However, the average multiplicity of the fragments is too low. At 60A MeV, we observe about 5 more fragments for true events as compared to the mixed events. Mixed events at 600A MeV result in drastically reduced IMF yield relative to unmixed QMD events, especially for central collisions.

It has been claimed that intranuclear cascade (INC) or BUU models are suitable for describing fragment production, provided that at some stage

of the time-evolution, a switch is made to another model which explicitly treats the clusters. Since the INC/BUU models are intrinsically unable to describe the formation of composite fragments, the nucleons are rearranged into clusters after the switch by either a restructured aggregation algorithm or by coalescence. From then on, each fragment is treated as an entity with a certain excitation energy which can lead to the emission of light particles. Hence, cold stable fragments and nucleons are present in the final state, and their distributions can be compared with experiment. In these hybrid models, the decisive parameter is the time at which the switch is made from one model to the other.

The analysis we have performed so far cannot rule out the applicability of these hybrid models because the composite fragments have to be formed long before we terminate our QMD calculation. At this earlier time, the distance between nucleons is shorter. Some nucleons which can be considered part of a cluster at this earlier time are too distant at the time when we apply our minimum spanning tree procedure. In order to judge the applicability of the hybrid models, we need to trace back the nucleons of the mixed events, or equivalently, we may increase the value of $r_{\min}$. We therefore investigate the abundances of deuterons, α s, and IMFs relative to protons as a function of $r_{\min}$. The prerequisite for the applicability of the hybrid models is the requirement to find a single value of $r_{\min}$ at which all three observables for mixed events agree with the results obtained for the true events.

Fig. 3 presents result of the calculations described above. At 60A MeV, we see that a common radius $r_{\min}$ as required by the hybrid models cannot be found. In fact, it is impossible to find a radius $r_{\min}$ that satisfies the requirement of even one of the three ratios above, while still assuming a physically acceptable radius $3 \text{ fm} < r_{\min} < 5 \text{ fm}$ in the calculation for the true events. Regardless of the assumed radius, the mixed events grossly underpredict the yield of intermediate mass fragments. A very large $r_{\min}$ cannot boost the IMF yield to the required value, because these $r_{\min}$ values result in a loss of IMFs via increased production of heavy fragments ($A \geq 32$). Thus, as indicated above, the correlations are the driving force for multifragmentation. Since this result was obtained for central collisions of Au on Au, where statistical behavior is most likely to occur, we can expect the same conclusion to hold even more decisively for lighter projectile/target systems or non-central collisions at this beam energy. We now turn to the case of Au on Au collisions at 600A MeV, where the result for central collisions is quite different. Here we see that the yield ratio for true events with $r_{\min} = 4 \text{ fm}$ corresponds in all three cases to that of $r_{\min} = 9 \text{ fm}$ for

mixed events. For semi-peripheral collisions ($7 \text{ fm} < b < 9 \text{ fm}$), we find an intermediate result: it is possible to find a radius $r_{\min}$ that satisfies any one of our three criteria for the applicability of hybrid models, but cannot simultaneously satisfy the other two. Thus we can conclude that for central collisions of heavy systems at beam energies on the order of $600A \text{ MeV}$, the system is close enough to being decorrelated that one can obtain the fragment distribution from the final one-body density coupled to a spanning tree method (note however that one cannot a priori extend this conclusion to lower mass systems). Nevertheless, a question remains with respect to the use of BUU-like approaches. What should be the prescription for the clusterisation radius?

Having drawn some conclusions from global yields, we next investigate more detailed quantities associated with those particles. In Fig. 4, we compare the energy spectra of true events for protons, deuterons and α ($r_{\min} = 4 \text{ fm}$) with those for mixed events and optimal $r_{\min}$ (9 fm for central $600A \text{ MeV}$, and 10 fm for semi-peripheral $600A \text{ MeV}$). For central collisions, we find very good agreement, and compared with Fig. 1 ($r_{\min} = 4 \text{ fm}$), there is a dramatic improvement. For semi-peripheral reactions, the agreement is also better than for $r_{\min} = 4 \text{ fm}$, but there are still inconsistencies. In Fig. 5, we plot the multiplicity distribution of intermediate mass fragments for true and mixed events, under the same circumstances as in Fig. 4. One obtains exactly the same conclusions from the comparison of Fig. 5 and Fig. 2 as from Fig. 4 and Fig. 1.

In conclusion, we have shown that many-body correlations are essential for the production of protons and intermediate mass fragments. In general, fragments are not formed by coalescence and they cannot be described by models of the Boltzmann Ühling Uhlenbeck type, which provide only the one-body phase space density distribution. These one-body phase space density calculations give the correct description only where mixed and unmixed events give the same cluster distributions. Our results also invalidate the applicability of statistical models, which are based on the assumption that no correlations are present besides those imposed by the conservation laws. Rather, the system preserves some memory of its individual initial-state configuration by showing strong correlations, and evidently does not evolve by populating the available configuration with the proper statistical weight.

Hybrid models, which treat the initial violent collisions using INC or BUU calculations and then apply a mechanism to determine the clusterisation, can be applied for central collisions at high energy. In these reactions,

the protons dominate and the system is close to what is expected from a statistical description. However, questions remain about how to determine clusterisation radii without the guidance of a true multi-body calculation if one would like to avoid to consider this - probably mass, energy and impact parameter dependend - quantity as a pure fit parameter. More peripheral reactions or those at lower energies are not suited for hybrid models; in these cases the correlations dominate and there is no alternative to an explicit treatment.

Figure Captions

- Fig. 1: The energy distribution for protons, deuterons and α particles in mixed events (dashed line) and true events (full line) for Au + Au. The upper panel displays results for central collisions at 60A MeV beam energy, the middle panel is for central collisions at 600A MeV, and the lower panel is for semi-peripheral collisions at 600A MeV.
- Fig. 2: The intermediate mass fragment distribution for the same reactions as displayed in Fig. 1.
- Fig. 3: Deuteron/proton, α /proton and IMF/proton ratios obtained in central collisions at 60A MeV (upper panel), central collisions at 600A MeV (center), and semi-peripheral collisions at 600A MeV (lower panel) for mixed (dashed line) and true events (full line) as a function of $r_{\min}$.
- Fig. 4: Energy distribution of protons, deuterons and α s for true events (full line) with $r_{\min} = 4$ fm and mixed events (dashed line) with optimal $r_{\min}$: 9 fm for central collisions at 600A MeV (top) and 10 fm for semi-peripheral collisions at 600A MeV (bottom).
- Fig. 5: The intermediate mass fragment distribution under the same conditions as displayed in Fig. 4.

References

- [1] D. H. E. Gross, Rep. Prog. Phys. 53 (1990) 605, and references therein.
- [2] J. B. Bondorf, R. Donangelo, I. N. Mishustin, C. J. Pethick, H. Schulz, K. Sneppen, Nucl. Phys. A443 (1985) 321.
- [3] D. Hahn and H. Stöcker Nucl. Phys. A476 (1988) 717.
- [4] J. Aichelin *et al.*, Phys. Rev. C30 (1984) 107.
- [5] L. Csernai and J. Kapusta, Phys. Rep. 131 (1986) 223.
- [6] M. W. Curtin *et al.*, Phys. Lett 123B (1983) 289.
- [7] J. Aichelin and G. Bertsch, Phys. Rev. C31 (1985) 1730; W. Cassing *et al.*, Phys. Rep. 188 (1990) 361; H. Kruse, B. Jacak and H. Stöcker, Phys. Rev. Lett. 54 (1985) 289; H. Stöcker and W. Greiner, Phys. Rep. 137 (1986) 277; F. Seibille *et al.*, Nucl. Phys. A501 (1989) 137.
- [8] J. Aichelin, Phys. Rep. 202 (1991) 233, and references therein.

Differential Yield versus C.M. Kinetic Energy

IMF(5-31) Multiplicity Distribution

Fig 2

Differential Yield versus C.M. Kinetic Energy

Fig 4

IMF(5-31) Multiplicity Distribution