Dynamical Evolution Before Multifragmentation

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Central events in ^{36}Ar induced reactions on Ag/Br emulsion at 65 ± 15 A·MeV bombarding energy, indicate the presence of a radial flow energy of 3.2 MeV per nucleon for intermediate mass fragments. Since the emission time for such fragments in evaporative processes is much larger than the radial expansion time scale, these processes can be ruled out as the origin of these mass fragments. For the collision of ^{136}Xe on ^{209}Bi at an incident energy of 28.2 A·MeV we show that, for non-central collisions, the neutron and charged-fragment multiplicity distributions measured can be reproduced by assuming that the colliding nuclei decay independently after a highly dissipative process.

I. Introduction

In recent years there has been collected a large body of data from nuclear fragmentation reactions. However, the nature of the processes leading to multifragmentation remains still unclear. In analyzing the data many models have been applied. Statistical models[1,2] disregard completely the dynamics of the fragmentation process and consider instead an ensemble of fragments in which the possible states for the system are calculated by appropriate statistical weights determined through the total entropy.

On the other hand there is now much activity in developing dynamical models which are based on Boltzmann-like approaches for the collision of two nuclei (for a recent review see Ref. [3] and references therein). These models have in common that they use classical distribution functions and it is therefore not an easy task to comprehend the relevant quantum effects leading to a genuine bound state formation, i.e. to the formation of fragments. But there exists still other models dealing with the description of the dynamical evolution of the system prior to its multifragmentation, some of which will be mentioned below.

To begin, we discuss a few data for ^{36}Ar ions incident on Ag/Br nuclear emulsion at 65 ± 15 A MeV. We will show that these data enable us to draw conclusions about the nature of the multifragment production process, which constrain significantly the range of applicability of the presently used models.

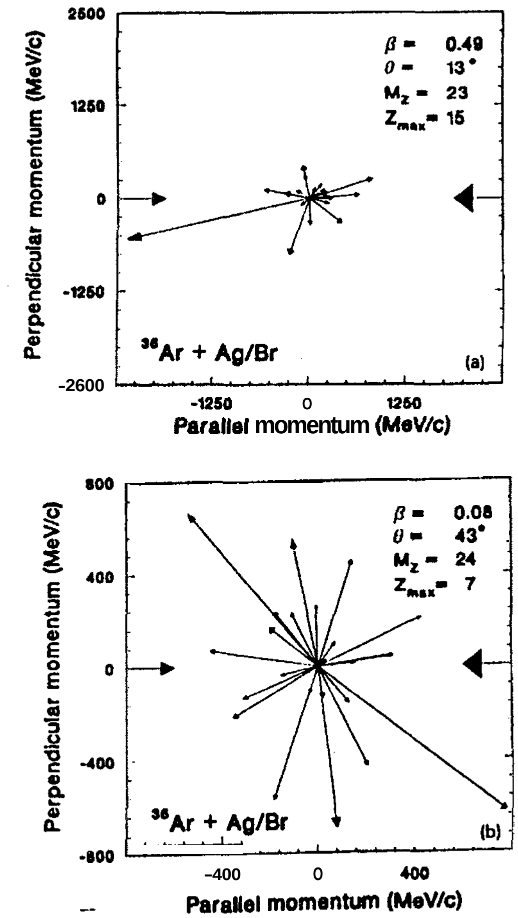

Figure 1: Momenta of charged fragments obtained in the peripheral (a) and central (b) collision of a 65 ± 15 A·MeV ^{36}Ar nucleus with Ag/Br nuclear emulsion.

These exclusive data permit us to classify collisions as peripheral or central ones. This is illustrated in Figs.

1 a and 1 b by means of two typical examples corresponding to high multiplicity events. In Fig. 1 a the existence of a heavy remnant in a direction close to that of the target demonstrates that the collision between the Ar and Ag nuclei was peripheral, whereas the absence of such a fragment in the event displayed in Fig. 1 b suggests a central collision. (Note that in these figures we have depicted the fragment momenta in the center of mass system, as determined by the analysis of their tracks, and not the tracks themselves.) Having at our disposal both the emission angles and the kinetic energies we used a flow tensor analysis to sort out the very central events from the more peripheral ones.

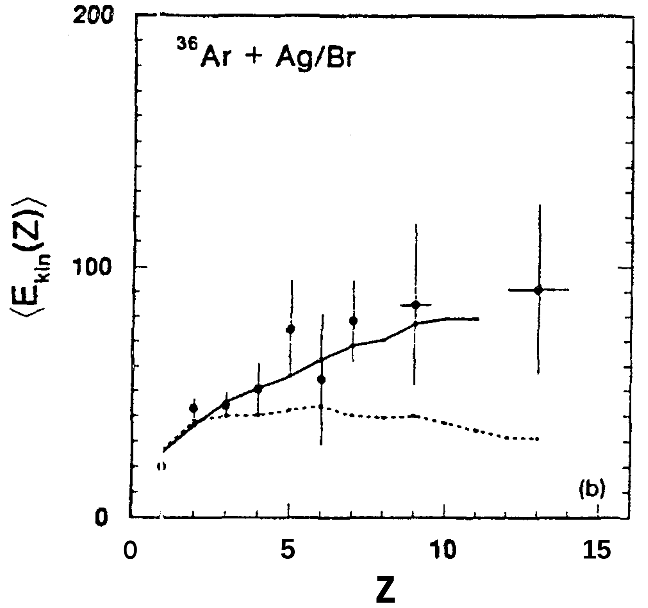

Figure 2: Comparison of the charged fragment kinetic energy distribution for the same system of Fig.1 with statistical multifragmentation model calculations including (full line) or not (dashed line) a 3.2 MeV radial flow.

For the central events the kinetic energy distribution of the fragments is shown in Fig. 2. Despite the fact that the statistics is poor due to the low number of events which can unambiguously be associated with a rather central collisions, we can observe that the kinetic energy of the intermediate mass fragments (IMFs) appears not to be constant.

The mass dependence of the fragments' kinetic energy can be understood by assuming that a noticeable flow is present in the nuclear matter. To get an estimate on the flow energy involved we start with the Copenhagen statistical multifragmentation model[2]. This model samples in a first stage hot fragments within the breakup volume. In a second step the expansion of the system under the influence of the mutual Coulomb forces and the evaporation processes is treated. We assume that the source contains 70 neutrons and 59 protons and that the excitation energy per nucleon is 11 MeV. The breakup density is chosen to be $n_{break-up} = 0.03 fm^{-3}$. Since for central events the maximum energy available is about 13.2 MeV per nucleon, the missing energy has to be associated with pre-equilibrium emission of particles not considered in our model. From a calculation based on the assumption of complete thermal equilibrium at breakup, we deduced an excitation energy of $E^*/A = 7.8$ MeV to account for the observed charge multiplicity of M=24. So, there is an excess energy of 3.2 MeV which is not thermalized and which we add to the translational motion of the hot fragments. We now calculate the kinetic energy spectrum by first considering the breakup at an excitation energy $E^*/A = 7.8$ MeV and then adding to the thermal velocity a radial flow velocity proportional to the distance of the fragments from the center. The velocities are normalized such that the average flow energy is just 3.2 MeV.

The results, presented through the solid line in Fig. 2, show a nearly linear increase of the kinetic energy for small fragment charges Z. For intermediate mass fragments the increase of the kinetic energy is more moderate. This is because of geometrical constraints. In fact, when heavier fragments are formed, their centers cannot be near the surface of the breakup volume. Thus, their radial flow velocity has to be less than for the lighter ones.

The results for the scenario without flow (dashed line), are very similar to those of the first one for the light clusters. This great similarity can be explained by the fact, that many of the lighter particles originate from the evaporation of the slowly moving heavy fragments. Therefore it is difficult to distinguish between the two scenarios, i.e. whether there is flow or not, by comparing the mean kinetic energies of the light particles. The differences of the two scenarios become clearly apparent for intermediate mass fragments with charges $Z > 4$.

The interesting conclusion which we draw from the existence of the radial flow, is that the possibility of evaporative decay processes for IMF production can be ruled out, based on estimates of the time scales for the fragment emission and the expansion of the hot source. In Fig. 3 we show the time evolution of the mass number A, the flow energy E_{flow} and the density n for a blob of nuclear matter formed by the collision of a 65 A MeV ^{36}Ar nucleus with a ^{107}Ag target. We assume that the initial density of the blob is n_0 and its temperature $T_0 = 12.5$ MeV is chosen to reproduce the maximum energy available in the central events. With these initial conditions we obtain a maximum flow energy per particle of about 3.2 MeV per nucleon. This is in reasonably good agreement with the deduced values.

We see that the expansion to a density of about $\frac{1}{5}n_0$ takes only about 50 fm/c. Such a short expansion time implies, that the evaporation of fragments heavier than α-particles is hardly possible. In other words, the relatively rapid expansion which is a consequence of the energy stored initially, rules out that evaporative processes might be the origin for the IMF production and gives strong support for a scenario that assumes that cluster formation is due to the appearance of dynamical instabilities towards which the expanding system has been driven.

It is interesting to see that the model of an expanding and evaporating fluid blob also predicts some kind of instability for an expansion time larger than 70 fm/c. Then the evaporation rate $-dA/dt$ rises sharply to values of several nucleons per fm/c. Such a rate is incompatible with the assumption of a surface emission of fragments on which Weisskopf's evaporation picture is based[4].

Thus far, we have restricted ourselves to the study of central collisions. We found that a large blob is formed, which expands and fragments into several intermediate mass fragments. We now consider the dynamical evolution of the system in the non-central collisions that constitute most of the heavy ion reaction cross section. Recent experimental results for reactions induced by 28.2 A·MeV ^{136}Xe on ^{209}Bi [6] are, in this regard, particularly interesting. Charge distribution of the fragments produced in these collisions measured as a function of the associated neutron multiplicity provide direct information on the relative violence of the processes. This makes it possible to investigate the mechanism for disassembly of hot nuclear matter in a wide interval of excitation energies. As in Ref. [5] the dynamical aspects of the collision are described using the TORINO heavy-ion reaction code[7] which yields the distribution of the dissipated energy in both collision partners.

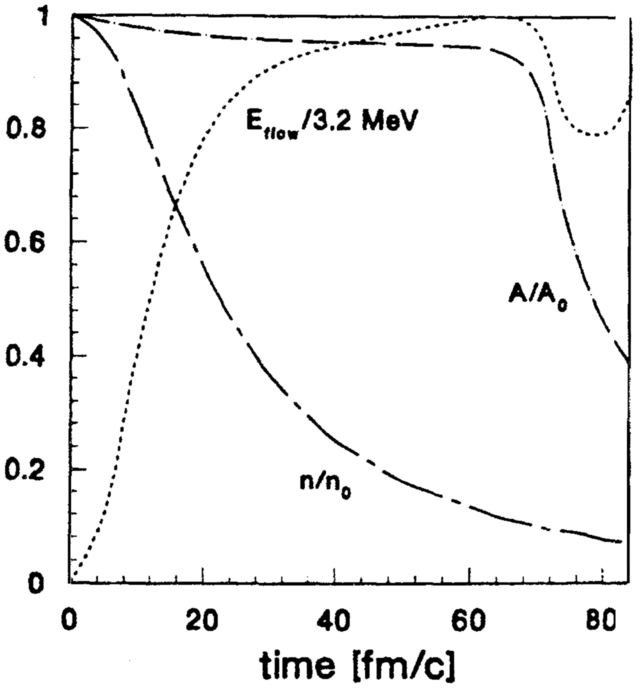

Figure 3: Hydrodynamical evolution of a nuclear system at initial density n_0 and temperature T_0. See text for additional details.

The disintegration of the highly excited systems is calculated with the Copenhagen statistical multifragmentation model which first determines the primordial distribution of fragments after the prompt break-up and then follows their subsequent decay[2]. In Fig. 4 we display the kinetic energy loss as function of the impact parameter. We note that the fluctuations of the excitation energy with impact parameter are quite large and that they extend to excitation energies sufficiently high to crack the colliding nuclei into many small fragments.

The multiplicity distributions of neutrons and charged-particles are given in Fig. 5.

The theoretical cross sections (full-drawn histograms) incorporate no adjustable parameters to fit

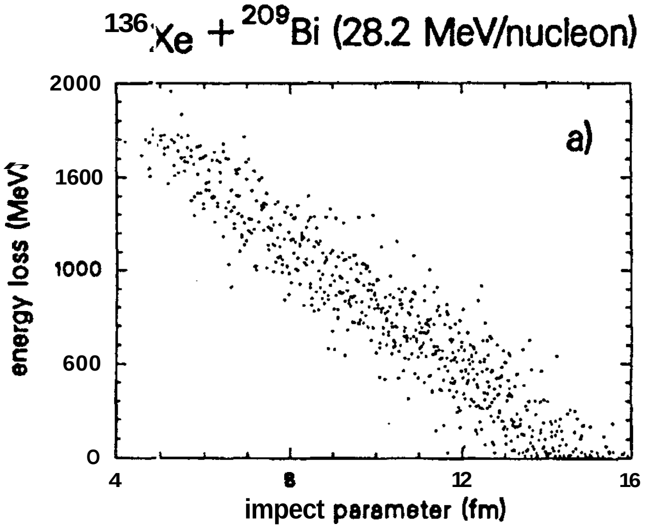

Figure 4: Kinetic energy loss as function of the impact parameter for the 28.2 A·MeV $^{136}Xe+^{209}Bi$ nuclear system.

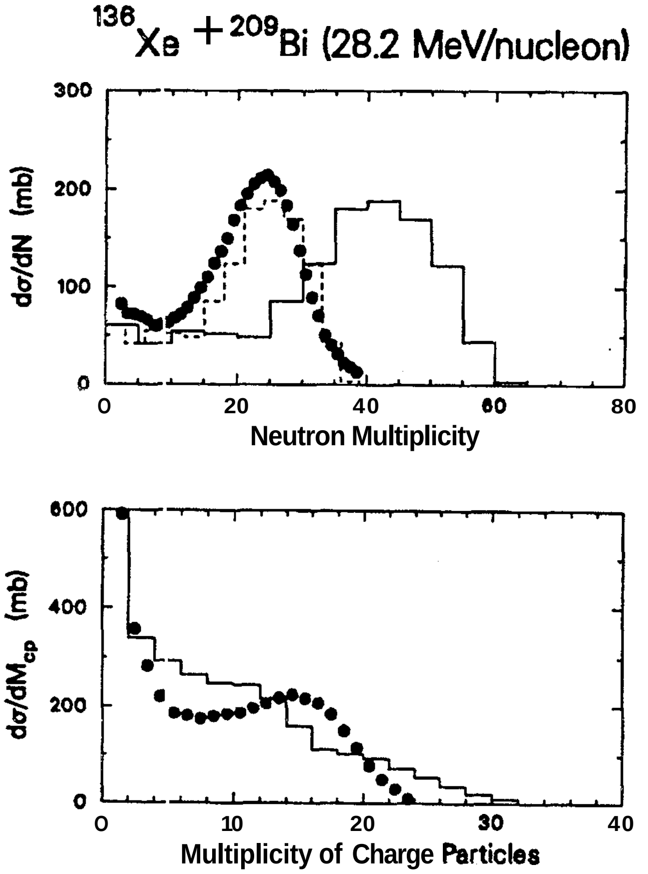

Figure 5: Neutron (a) and charged particle (b) multiplicity distributions for the same system of Fig. 4. The dots indicate the experimental results, the full histograms our uncorrected calculations, and the dashed histogram in (a) the correction for neutron detection efficiency.

the data and, in particular, have not been corrected to take into account experimental limitations. Using a neutron detection efficiency of $\approx$ 60%, as quoted in[6], yields the dashed histogram in Fig. 2a, which agrees well with the measurement. A similar, simple scaling for the charged-particle distribution is not possible because of the wide diversity of mass partitions that feed the histogram bins. The correspondence between theory and experiment appears to be, in any case, not as close as in the neutron case. There is a clear experimental indication for a bump at a multiplicity of about 15 charged particles which is not present in our results.

This structure could be associated with the decay of a composite system formed in very central collisions. We recall that about fifteen percent of the reaction cross section – corresponding to these events – cannot be reliably ascribed by this binary formulation[5]. Thus, although peripheral collisions can be described by this simple binary approach, there is an obvious need for a dynamical model for the central events, since the simple hydrodynamical expansion discussed above is only schematic.

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