SYSTEM SIZE EFFECTS IN CLUSTER PRODUCTION AT SIS ENERGIES

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Intermediate mass fragment production has been experimentally investigated in central collisions of Ni+Ni, Zr+Zr, Xe+CsI and Au+Au reactions at bombarding energies going from 90 to 400A MeV. The number of intermediate mass fragments produced per unit of incoming charge is found to be larger in heavier reactions. This system-size effect takes place with the occurence of the radial flow and its magnitude increases as the expansion velocity increases. The observed features indicate that the production mechanism of intermediate mass fragments in central collisions is strongly influenced by the expansion dynamics which seems to favour clusterization.

1 Introduction

The origin of the multifragmentation process is one of the central questions in heavy-ion collisions. A good characterization of this process is of crucial importance for the delimitation of the nuclear equation of state and the possible liquid-gas phase transition in nuclei.

At incident energies of a few hundreds MeV per nucleon, fragmenting nuclear systems can be produced through two types of heavy-ion reactions: peripheral collisions leading to the formation of highly excited spectator nuclei and central collisions in symmetric systems producing a nuclear fireball. Multifragmentation of spectator matter has been extensively investigated over the last decade, in particular by the ALADIN collaboration [1]. It was shown that the decay properties of spectator nuclei exhibit a universal behaviour (beam energy and projectile/target size independence) consistent with a purely thermal process where fragments are emitted from an equilibrated source. In the present work, we study the multi-fragment production in central reactions. Here, in contrast to peripheral collisions, large collective expansion velocities were observed [2,3]. The collective expansion energy was found to represent a significant fraction of the energy available in the center-of-mass (c.m.) frame. The question then arises whether such collective expansion effects may influence the fragment formation process. To explore this question, we compare the fragment yields in different symmetric systems with masses ranging from $A_P = A_T = 58$ to 197 (A_P and A_T are the masses of, respectively, the projectile and the target nuclei): one expects an increasing effect of the compression-decompression process with increasing size of the interacting system.

2 Experimental conditions and event selection

The data presented in this contribution were taken in a series of experiments performed recently using the phase II setup of the FOPI detector [4,5] at the SIS accelerator of GSI-Darmstadt. Four symmetric reactions, Ni+Ni, Zr+Zr, Xe+CsI and Au+Au, were measured at beam energies going from $90A$ MeV to $400A$ MeV. Clusters or intermediate mass fragments, IMF's ($3 \leq Z \leq 15$), were detected in the forward wall [4] covering laboratory polar angles below $30°$, corresponding to the coverage of a very large fraction of the forward c.m. hemisphere.

Central collisions were selected using the E_{RAT} criterium [2,3]. E_{RAT} is determined event wise by including all particles detected by the forward wall: $E_{RAT} = \sum_{i=1}^{M} E_t^i / \sum_{i=1}^{M} E_l^i$, where E_t^i and E_l^i are the transverse and longitudinal energies of the particle i and M is the event multiplicity. The E_{RAT} cut used to select central collisions corresponds to about 2% of the total reaction cross section and to a maximum geometrical impact parameter $b \leq 0.1 \times b_{max}$ (b_{max} being the maximum impact parameter) in a sharp-cut-off approximation.

3 Influence of system size effects on IMF production

Multi-fragment emission in central Au+Au reactions was the object of detailed studies in previous experiments [3,6,7]. It was shown that IMF's are copiously emitted in these reactions. The maximum production was observed at an incident energy close to $100A$ MeV. At this energy, about 13 IMF's on the average are produced per event and a large fraction, about 40%, of the initial charge is emitted in the form of IMF's.

These studies were extended in the present work to several symmetric reactions: Ni+Ni, Zr+Zr and Xe+CsI in addition to Au+Au. This allowed us to vary the size of the interacting system over a broad range; the number of interacting nucleons increases by a factor of 3.4 from Ni+Ni to Au+Au. IMF multiplicities were extracted for highly central collisions under the same condition on the scaled impact parameter ($b/b_{max} \leq 0.1$), allowing therefore direct comparisons between the four measured reactions. Fig.1 shows exam-

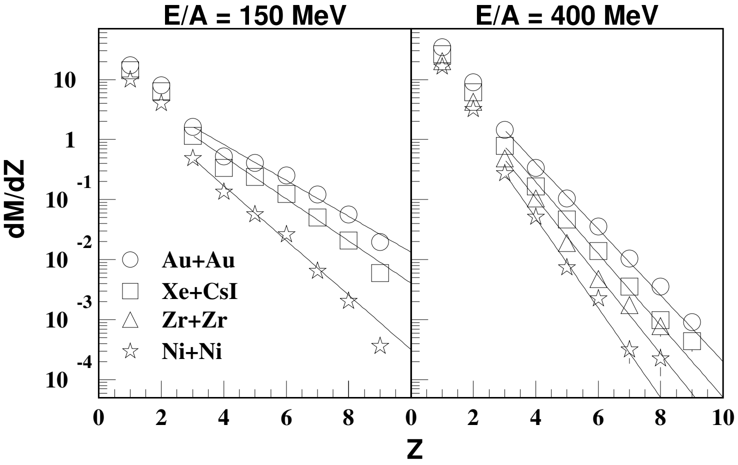

Figure 1. Measured multiplicities in the forward c.m. hemisphere as a function of the particle charge. The data are shown for central collisions of Au+Au, Xe+CsI, Zr+Zr and Ni+Ni at two bombarding energies : 150 AMeV (left) and 400 AMeV (right). The straight lines are exponential fits to the $Z \geq 3$ data points. Statistical uncertainties are smaller than the size of the symbols.

ples of charge distributions, dM/dZ, measured at two incident energies of 150 and 400A MeV. As can be seen, the same typical exponential fall is observed for all reactions. This trend is very different from the power-law dependence characterizing the multifragmentation of spectator nuclei. Another important feature of these dM/dZ-distributions is that their slope becomes steeper as the size of the system decreases: one produces relatively less heavy fragments in smaller systems. This observation is more quantitatively visible in Fig.2 where the results are expressed in terms of the number of IMF's per unit of incoming charge, i.e. IMF multiplicity scaled to the size of the interacting system. It is clearly seen that the production of IMF's raises rapidly, almost linearly, with increasing number of interacting protons. At 400A MeV, the number of IMF's per unit of incoming charge produced in Au+Au collisions is larger by a factor of ~ 2.1 than in Ni+Ni. This striking observation indicates that multifragmentation of the fireball in central collisions does not exhibit the universal behaviour observed for the spectator decay [1]. We will see in the next section that these differences in the properties of multifragmentation between central and peripheral reactions might be attributed to the role of the expansion dynamics.

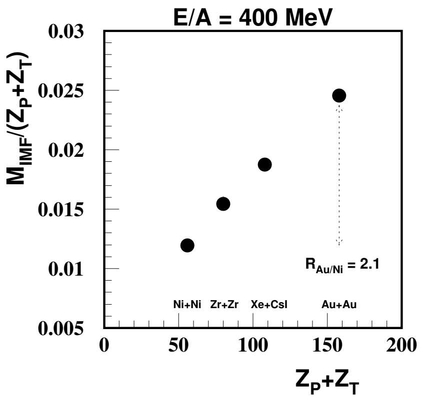

Figure 2. Scaled average IMF multiplicity as a function of the total projectile+target charge. M_{IMF} were measured in the forward c.m. hemisphere and then multiplied by a factor of 2. Data are shown for central collisions at the incident energy of 400 AMeV. Statistical uncertainties are smaller than the size of the symbols.

4 Interplay between IMF formation and the radial flow

The influence of system-size effects in IMF production becomes more and more pronounced as the incident energy increases from 90 to 400 AMeV. This is shown in the upper panel of Fig.3 where the quantity $R_{Au/Ni}$, i.e. the ratio of the scaled IMF multiplicities for Au+Au over Ni+Ni, is plotted as a function of the energy available in the c.m. frame. As is seen in this figure, size effects seem to take place at an available c.m. energy of $E_{cm} \sim 10$ AMeV. The latter value is close to the threshold energy for expansion extracted from the excitation function of the mean radial flow velocity (see lower panel of Fig.3).

Fig.3 shows a remarkable correlation between system-size effects and the collective flow motion. Size effects, characterized by the ratio $R_{Au/Ni}$, take place with the occurence of expansion and their magnitude increases as the expansion velocity increases. This correlation indicates that here, in contrast to the spectator decay, the production mechanism of IMF's is intimately connected to the expansion dynamics of the nuclear system. In the absence of expansion (below the threshold), one expects a system-size independent partition of the nuclear system; this would correspond to a ratio $R_{Au/Ni} = 1$ in Fig.3. Recent results from the INDRA experiment [8], at an incident energy where the expansion effect is negligible, show indeed a system-size independent multifragmentation.

The large production of IMF's in Au+Au collisions, as compared to lighter reactions, can be attributed to the fact that heavy systems are subjected to a larger collective expansion motion which seems to favour clusterization. This is supported by recent preliminary results [9] where the collective flow energy was found to be larger in heavier systems. Within a hydrodynamical picture,

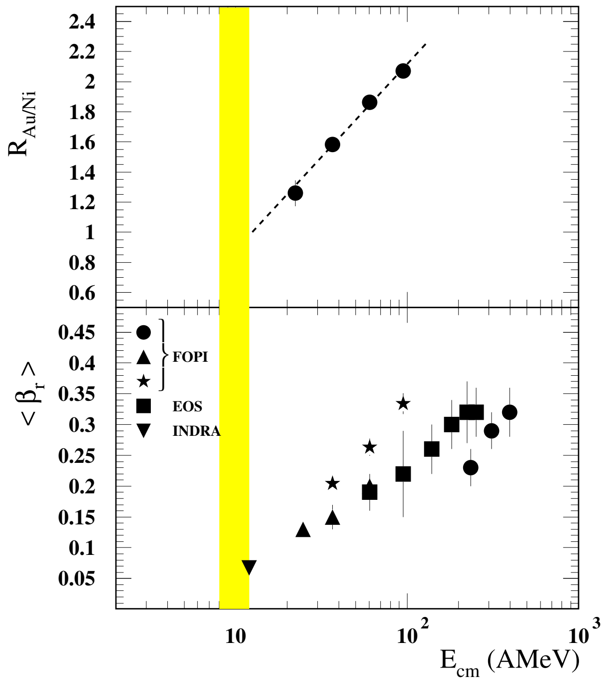

Figure 3. Upper panel: Ratio $R_{Au/Ni}$ of scaled IMF multiplicities measured in Au+Au to those measured in Ni+Ni as a function of the energy available in the c.m. frame. Lower panel: Compilation of radial flow velocities obtained in various experiments as a function of c.m. available energy. Circles, triangles and stars are taken from the FOPI experiment [3,10,11], squares are from the EOS experiment [12] and inverted triangles are from the INDRA experiment [13]. The vertical shadowed area indicates the E_{cm} region where the collective radial expansion sets in.

it is tempting to attribute the observed size effects to the cooling action of bulk expansion which might be responsible for the higher condensation in larger systems [3,14].

5 Conclusion

In this contribution, we have presented a detailed experimental study of the multifragmentation process in central heavy-ion collisions at beam energies from 90 to 400A MeV. The data show evidence for system-size effects: the probability to produce IMF's is larger in heavier systems. These size effects take place with the occurence of expansion and their magnitude increases as the expansion velocity increases. These features depart significantly from the universal behaviour observed in the multifragmentation of spectator nuclei. They indicate that the production mechanism of IMF's in central collisions is intimately connected to the expansion dynamics which seems to favour clusterization.

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