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Large radial flow in nucleus-nucleus collisions

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Exclusive events for central collision of ^{94}Kr on Ag/Br emulsion at a bombarding energy of 70–120 MeV per nucleon point to an extremely large flow energy of the order of 10 MeV per nucleon for intermediate mass fragments. We show that this large radial flow energy is associated with an explosive breakup of the excited matter in the very early stage of the collision process.

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It is a well established fact that for weakly excited nuclei the dominant decay channels are fission and evaporation of light particles, whereas for excitations exceeding the binding energy of the nucleus the disassembly takes place mostly into nucleons or very light fragments. Between these two limits there is a regime where, depending on the target-projectile combination and incident energy, copious production of intermediate mass fragments (IMFs) with charge $Z > 2$ takes place [1–8].

The breakup of nuclear matter into many fragments is an exciting field, and the mechanisms causing the fragment formation are still being extensively debated. For example, statistical models [9–11] disregard completely the dynamics of the fragmentation process and consider instead complete events with probabilities given solely through the coarse grained entropy. There is also much activity in developing dynamical models which are based on Boltzmann-like approaches for the collision of two nuclei (for recent reviews see Ref. [12] and references therein). However, since the calculated phase space distribution is rather classical and does reflect chiefly the one-body dynamics, it is difficult to include the relevant quantum effects leading to the formation of genuine many-body bound states (see Refs. [13, 14]).

In a recent work [15] central events in ^{36}Ar and ^{16}O induced reactions on Ag/Br emulsion at (50–80)A MeV and (200–220)A MeV bombarding energy have been analyzed. The data were exclusive in the sense that all the fragments' charges, kinetic energies, and emission angles have been measured. These sets of data permitted one to sort out the very central events and to study the multifragmentation process under well-defined initial conditions. In particular, for the ^{36}Ar-induced reaction an average radial flow energy of 3.2 MeV per nucleon has been deduced for intermediate mass fragments. To reconcile such a significant flow energy with a possible fragmentation scenario, we have modeled the system as an expanding fluid blob that undergoes multifragment disassembly. The deduced expansion time turned out to be of the order of 50 fm/c; i.e., it is much less than the typical evaporation time for IMFs, which is at least of the order of $t_{\text{emis}} \gtrsim 200 - 300$ fm/c. Consequently, the existence of a significant radial flow rules out evaporative processes as the origin of the formation of IMFs.

According to such a scenario, clusters are assumed to be formed after the disassembling matter has cooled down considerably by an overall expansion. Therefore, the fragments contain the imprint of both the initial temperature of the disassembling source and the flow stored initially as compression energy [16–18]. The experimentally known fact of distinct internal and kinetic temperatures for the fragments (see Ref. [20] and references therein) may thus be a consequence of the expansion of the matter which induces the formation of a radial flow.

In the present Rapid Communication we will consider the collision of ^{94}Kr on Ag/Br emulsion at $70 - 120$ MeV per nucleon. The data are of the same quality as the ones taken from reactions of lighter ions (for details see Refs. [15, 19]). However, since the incident projectile mass is significantly increased, we expect a larger volume of initially compressed matter and thus a more compressional energy in the system, giving rise to still bigger radial flow effects.

In the upper panel of Fig. 1 we show for central events (full squares) the transverse kinetic energy $E_\perp$ of the fragments as a function of the fragment charge. The data suggest an enormous increase of $E_\perp$ with the mass of the emitted fragments. The associated radial flow energy $\frac{3}{2}E_\perp$ reaches values as large as about 10 MeV per nucleon, i.e., roughly three times the one obtained in the analysis of the Ar-induced reaction at an incident energy of 65 MeV per nucleon [15].

The events showing this large flow pattern have been sorted out by the same method described in Refs. [15, 19], i.e., a flow tensor analysis supplemented with the information available from the measurement of all the fragment emission angles. Applying such a stringent filter for centrality, we are able to select events which belong to nearly the same class of initial conditions.

In order to demonstrate that the transverse kinetic

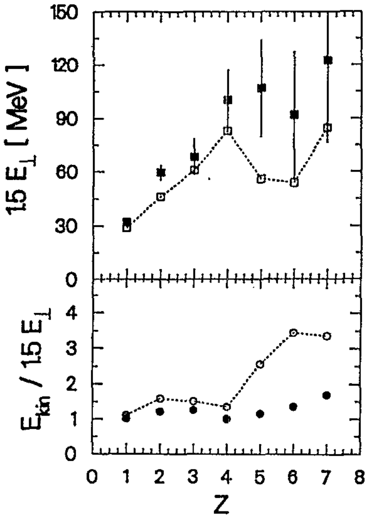

FIG. 1. Upper panel: $E_\perp$ as a function of the charge number for central (full squares) and inclusive (open squares) events for the reaction of ^{36}Ar on Ag/Br emulsion at (95 ± 25)A MeV per nucleon. Lower panel: Same as in upper panel but for $E_{\rm kin}/\frac{3}{2}E_\perp$.

energy $E_\perp$ depends very sensitively on whether central events have been selected or not, we also display in Fig. 1 through open squares the results for $E_\perp$ when all available events which are characterized by a charged particle multiplicity $N_C > 20$ are taken into consideration. One clearly observes that the transverse kinetic energy associated with this broader selection of events, which includes a large variety of impact parameters, seems to level off for fragments with $Z > 4$. This is an artifact of selecting only high multiplicity events. It indicates once more how important it is to have a complete event in order to make firm conclusions. Having such complete events at our disposal, it is easy to find out whether or not the fragments originate from central collisions leading to a hot and compressed transient system by calculating the ratio of the fragment's total kinetic $E_{\rm kin}$ to its transverse energy $\frac{3}{2}E_\perp$ and representing it as a function of the fragments' mass or charge. Such a plot is shown in the lower panel of Fig. 1. We see that for the central events (full circles) this ratio is, within a very good approximation, equal to 1. This indicates that the colliding nuclei must have completely stopped at the beam energy considered. However, taking all the high multiplicity events (open circles), i.e., irrespectively of whether or not they are associated with central collisions, the ratio $E_{\rm kin}/\frac{3}{2}E_\perp$ coincides well for the very light fragments and increases rapidly for charges with $Z > 4$. This steep increase signals that the large mass fragments are predominantly produced in peripheral collisions when the marginally excited spectator matter, which carries a big share of the longitudinal momentum component, decays. It is therefore apparent that a relatively small admixture of noncentral events to the central ones could significantly diminish the calculated flow energy.

The large radial flow energy appearing in the central events of the reaction of Kr on Ag/Br emulsion shown in Fig. 1 clearly indicates that the available energy has not been completely converted into thermal motion of the fragments. Instead, it was partially transformed into radial flow energy, which increases linearly with the mass number of the emitted fragments.

One should keep in mind that for the reaction of Ar on Ag/Br emulsion at (50–80)A MeV recently analyzed [15] the deduced flow energy was about 3 MeV per nucleon, whereby even in central events fragments have been observed with charges $Z = 8, 9$. In the present experiment of Kr on Ag/Br emulsion at 70–120 MeV per nucleon incident energy there are no very central events associated with charges $Z > 3$. This almost abrupt disappearance of the bigger fragments is a direct consequence of the enormous energy deposition caused by the almost full stopping of the colliding ions. It is surprising that relatively big fragments with $Z > 5$ are produced at all in collisions at these beam energies. The production mechanism for these intermediate mass fragments seems to be directly connected with the appearance of the large flow energies deduced for them. In other words, at these relatively large beam energies events with an appreciable number of IMFs can exist only if a great share of the deposited energy has been converted into flow energy of the emitted fragments, otherwise they would not persist.

An immediate consequence of the appearance of a large flow is that the IMFs must be formed in a very early stage of the reaction; otherwise the fragments could not carry away an appreciable part of the available energy in the form of ordered collective flow. If the fragments were formed in a later stage, the radial flow energy would be significantly slowed down due to the partial conversion of flow energy into potential energy.

Let us now discuss under what conditions it is possible to reconcile a flow energy of 10 MeV per nucleon with the commonly adopted fragmentation mechanisms. To get information on how big the flow energy might be, we utilize a Boltzmann-Uehling-Uhlenbeck (BUU) calculation [21] that is expected to give a good estimate of the degree of thermalization in the violent stage of the collision. In this calculation the nucleons are assumed to interact with a collectively generated mean field and pairwise with each other through two-body collisions which respect the Pauli exclusion principle.

In Fig. 2 we show for the collision of ^{94}Kr on Ag/Br emulsion at a bombarding energy of 95 MeV per nucleon results for the flow energy for the nucleons as a function of time. The dashed lines represent the kinetic energies per particle either when all particles are taken into account or when only those particles that move in a medium whose density is larger than $\frac{1}{10}$ of normal nuclear matter density, $\rho_0 = 0.15$ fm^{-3}, respectively, are considered.

The results displayed in Fig. 2 show clearly that the maximum transverse flow energy $E_\perp$ is of the order of 6 MeV per nucleon, and does not depend on whether or not the spilled off particles are included. Their contribution to IMF formation is not essential due to their relatively small number in the violent initial phase, and they are expected to build some of the light composites such as deuterons, tritons, helions, and α particles via a coalescencelike mechanism [18]. For orientation we show also

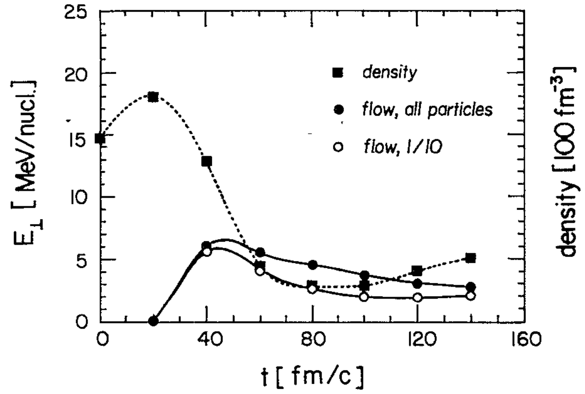

FIG. 2. Transverse flow energy for ^{36}Ar on Ag at 95A MeV calculated by means of the BUU approach [21] as a function of time, when either all nucleons are taken into account (full circles) or only those in a region with $\rho/\rho_0 > 0.1$ (open circles), where $\rho_0 = 0.15$ fm^{-3}. The average nuclear density is given by the full squares.

in Fig. 2 the average density of the colliding nuclei. One sees that the nuclei stop when the maximum density is reached and that the maximum flow energy is attained shortly afterwards.

It is interesting to observe that the flow energy extracted from the data coincides reasonably well with the prediction of the BUU approach for the maximum flow energy. We think that this agreement is not accidental and points to the reliability of the BUU approach, even despite the fact that this approach is not able to calculate fragment formation, which requires the inclusion of at least two-body correlations (see Ref. [14] and references therein). However, the collective nucleon flow has previously been shown to be described adequately by BUU-type calculations [22, 23], pointing to the fact that it is essentially due to the one-body nuclear mean field. At higher energies, flow is sensitive to the nuclear compressibility [12, 22], but at the beam energies under consideration here it was shown that the nuclear compressibility has only a minor influence on the flow observables [23]. We have chosen a compressibility of $\kappa =$ 240 MeV for the present work.

Assuming that the time evolution of the expanding transient nuclear system is reasonably described by the BUU, then from the theoretical results shown in Fig. 2 and the flow energy deduced from the data it is conjectured that (i) fragment formation must happen in a very early stage of the collisions when the matter is not yet fragmented, but the relevant fluctuations causing fragmentation build up, and that (ii) fragment formation takes place in a short time interval of about 20 fm/c.

These findings suggest that, already in the violent initial stage, some type of fluctuations are built up [24, 25] surviving even in an explosive expansion leading finally to IMF formation. Such a scenario is supported by a many-body treatment of intermediate energy heavy ion collisions. These calculations indicate that, already very early in the collision, the nucleons form a changing pattern of inhomogeneities. The final IMF multiplicity turns out to be close to the number of the most bound primordial inhomogeneities [26].

The effects of the collective expansion on the light-fragment emission from central heavy ion collisions have also been studied recently in Ref. [27]. For that purpose a transport model was used including a dynamic production of clusters with masses $A \leq 3$. It remains to be seen to what extent such a more refined model is able to reproduce the experimentally observed flow pattern for the lightest fragments.

In summary, we have shown that exclusive events taken from central collision of ^{94}Kr on Ag/Br emulsion at a bombarding energy of 70 – 120 MeV per nucleon point to an extremely large flow energy of the order of 10 MeV per nucleon for intermediate mass fragments. This large flow energy is associated with an explosive breakup of the excited matter into fragments in a very early stage of the collision and agrees well with the maximum flow energy predicted by the BUU approach. This particular type of fragment formation mechanism has to be seen in contrast to the usual one which assumes that an expanding fluid blob becomes dynamically unstable in the late stage of the collision process that determines the IMF formation.

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