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Exotic density shapes in asymmetric heavy ion collisions at intermediate bombarding energies

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Heavy-ion collisions between asymmetric systems are studied in the framework of the Boltzmann-Uehling-Uhlenbeck approach. For central collisions, it is found that different values of the incompressibility of nuclear matter lead to different exotic density shapes after the most violent stages of the reaction.

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Heavy-ion reactions above a few tens of MeV per nucleon allow us to observe nuclear matter far away from the ground state [1]. For central collisions, the breakup of the system into several fragments (multifragmentation) is an important reaction mechanism in this energy domain [2–10]. Many experimental and theoretical efforts (see [2–13] and references therein) have been done in order to clarify the underlying physics responsible for this phenomenon. Recent investigations based on the Boltzmann-Uehling-Uhlenbeck (BUU) approach [11,12], as well as on hydrodynamical calculations [13], pointed out that exotic density shapes may develop soon after the most violent stages of central heavy-ion reactions. More precisely, indications that the dynamical evolution would cause the system to evolve to a configuration in which nuclear matter is found in a very thin disk, which may subsequently break up due to Rayleigh-Taylor-type surface instabilities, have been found by Moretto *et al.* [11]. The formation of unstable bubble and doughnut shapes have also been suggested by Bauer *et al.* [12]. As a consequence, an enhanced multiplicity of intermediate mass fragments compared to the breakup of a homogeneous sphere is predicted in [12,14]. Similar results have been obtained in hydrodynamical calculations in which the emission of the outer layers of an expanding hot nucleus is predicted by Aguiar *et al.* [13]. Surface multifragmentation through bubble formation has also been obtained in hot time-dependent Hartree-Fock TDHF calculations [15]. The development of these exotic shapes might be reflected in the angular pattern of the emitted fragments, as suggested in [16], besides the consequences already pointed out in [12,14].

In this work we extend the investigations carried out in [11,12] by considering collisions between asymmeteric systems. Indeed, up to now, bubble formation has only been observed for collisions between symmetric systems [12] or by following the evolution of initial hot and compressed spherical nuclei [17]. Asymmetric systems are interesting because the development of the exotic density shapes mentioned above might not be strongly dependent on the impact parameter at which the collision takes place, provided the lighter nucleus overlaps almost completely with the heavier one in the initial stages of the reaction. Therefore, the observation of exotic shapes might be associated with a non-negligible geometrical cross section corresponding to central collisions. In this communication, we want to discuss two questions as far as heavy-ion collisions between asymmetric systems are concerned: (1) Do we form bubble nuclei as intermediate stages of the reaction? (2) What is the influence of the compressibility modulus of the equation of state on the formation of these exotic density shapes?

In order to answer the questions raised above, we have used the BUU approach [18,19] in a full ensemble calculation [19]. In our implementation, the one-body density function is represented by a sum of 100 Gaussian packets per nucleon whose root mean square radii are equal to 1.2 fm. The initial nuclei have been prepared as described in [20] with two modifications: (1) The mean positions of the test particles have been sampled within a sphere which is divided in several spherical layers. These layers are successively populated according to the normal density of nucleons. (2) When sampling the initial momenta of the test particles, the condition that the phase-space occupation be smaller than 1 is imposed. We have used the following parametrization of the effective interaction:

$$v(\mathbf{r},\mathbf{r}')=(v_{02}+v_{03}\rho^{\sigma}[(\mathbf{r}+\mathbf{r}')/2])\delta(\mathbf{r}-\mathbf{r}') \ . \quad (1)$$

By assuming a soft equation of state for infinite nuclear matter (compressibility modulus $K=200$ MeV), the parameters read as follows: $v_{02}=v_2\pm v_A$, where $v_2=-2201.62$ MeV fm^3, $v_A=197.62$ MeV fm^3, and the sign $+$ $(-)$ is associated with particles of the same (different) isospin. The coefficient of the density-dependent term is $v_{03}=2346.72$ MeV fm$^{7/2}$ and $\sigma=\frac{1}{6}$. Finally, the Coulomb repulsion between protons is given by the Coulomb potential between two point charges. The mean positions and momenta of the Gaussian packets are propagated as described in [19]. Collisions between test particles have been treated using the energy-dependent free nucleon-nucleon cross section parametrized in [21].

As a first investigation, we have studied a head-on collision between the ^{84}Kr$+^{197}$Au system at 65 MeV per nucleon. Let $\rho(x,y,z)$ be the nuclear matter density of the total system. The x axis is the direction of the incident beam. In Fig. 1, we present two cuts of the density: first in the x-y plane $[\rho(x,y,z=0)]$ and second in the y-z plane $[\rho(x=0,y,z)]$ at three different times $t=90$, 120, and 150 fm/c. The maximum compression of the system takes place around 30–40 fm/c. Thus, we are looking at the system in its expansion phase. In agreement with the results obtained in [12], one can notice the appearance of waves at 90 fm/c that cause matter to leave the center of the system (rarefaction waves [12]). Then a bubble grows in the interior of the system and most of the nuclear matter is confined in an external layer at 120–150 fm/c. One can particularly notice that the ring structure begins to break up between 90 and 120 fm/c. This is due to the growth of dynamical instabilities, i.e., Rayleigh-Taylor-type and spinoidal instabilities [22,23].

As we mentioned above, for asymmetric systems, the growth of bubble and/or ring structures should be expected to be observed within a small window of impact parameters. Thus, we have studied the same collision discussed above at an impact parameter equal to 2 fm. Taking into account the size of the Kr and Au nuclei, this impact parameter should be near the maximum value for which indications of bubble formation might be observed. Figure 2 displays the time evolution of the density projected on the reaction plane [$\rho(x,y,z=0)$] for times ranging from 5 to 150 fm/c. At the initial stages of the reaction, one observes a hot and compressed region made up of nuclear matter from the overlapping projectile and target nuclei. The system has expanded to a fair extent at 90 fm/c and one can notice the appearance of rarefaction waves in the region associated with the participants of the reaction. Then, a bubble grows in this region as it separates from the spectator part of the Au nucleus. The ring structure, which begins to appear between 90 and 120 fm/c, has a very short lifetime breaking up, soon after its formation. As already pointed out in [12,13], the velocity of fragments originated from the breakup of a ring structure are roughly the same. In the present case, one should expect to observe two bumps in the velocity spectrum. One of them is related to the breakup of the ring structure. The other one, which should be broader, corresponds to the deexcitation of the spectator part of the Au nucleus. Actually, some indications of the existence of these two bumps in the velocity spectrum have been found in emulsion experiments [24].

So far, we have used a soft equation of state. It is worthwhile to investigate the effect of a larger compressibility modulus. This has been done for the Ar+Ag sys-

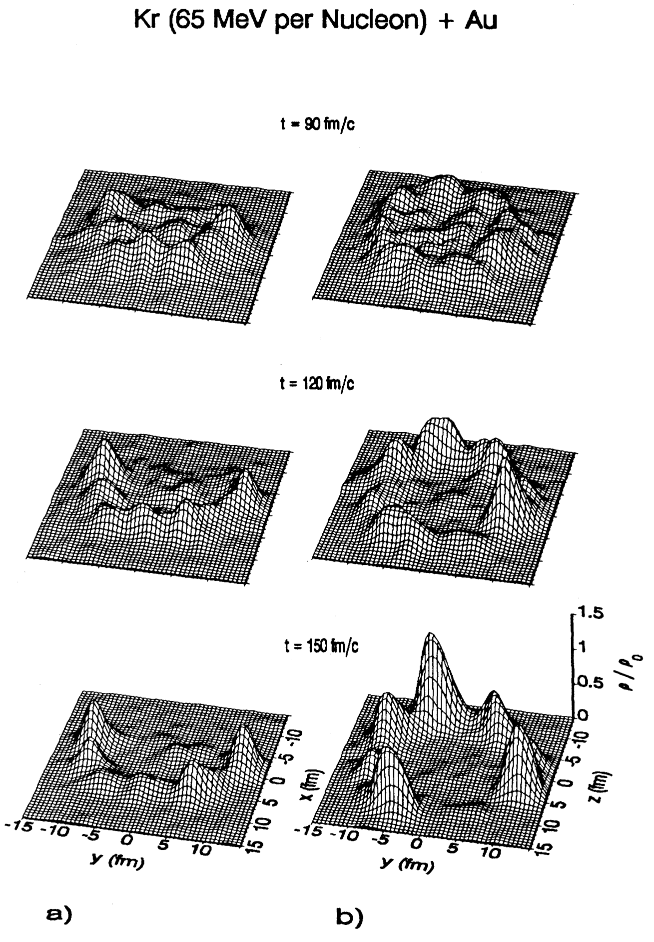

FIG. 1. Time evolution of the nuclear density projected (a) on the reaction plane and (b) on the plane perpendicular to the beam axis x, for a head-on collision between Kr+Au at 65 MeV per nucleon.

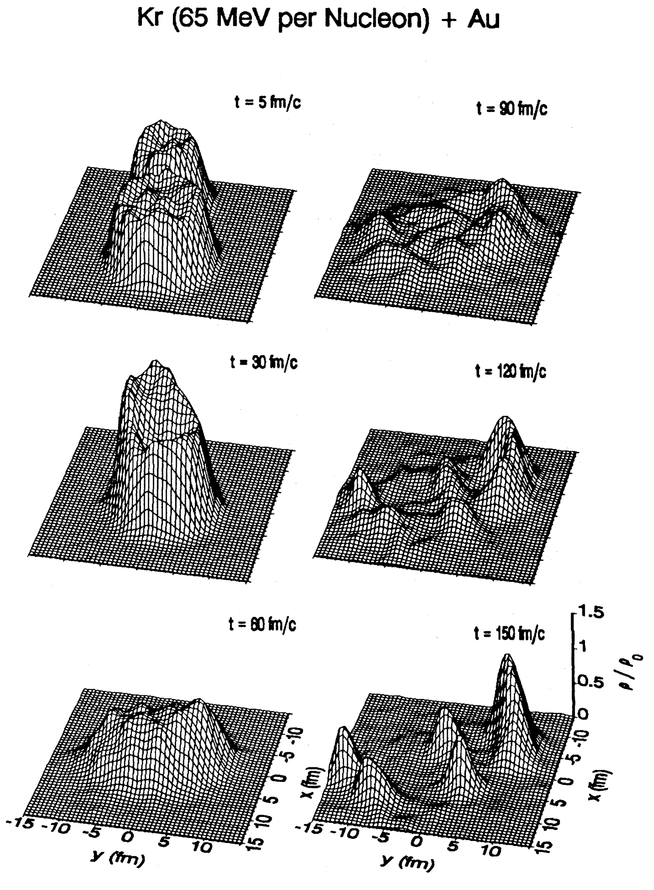

FIG. 2. Time evolution of the nuclear density projected on the reaction plane for a collision between Kr+Au at 65 MeV per nucleon and impact parameter equal to 2 fm.

tem which requires less computational effort and for which emulsion data have been recently analyzed [7]. In order to study this, we have adjusted the parameters of the effective interaction so as to get a compressibility $K=370$ MeV in infinite nuclear matter. Their numerical values are $v_{02}=v_2 \pm v_A$, where $v_2=-760.72$ MeV fm^3, $v_A=197.62$ MeV fm^3, $v_{03}=1801.12$ MeV fm^6, and $\sigma=1$. The sign $+$ ($-$), as mentioned above, is associated with nucleons of the same (different) type. The results for Ar (65 MeV per nucleon) +Ag are shown in Figs. 3 and 4 for a head-on collision. In the first case a soft equation of state is assumed while, in Fig. 4, we have used the parametrization of the effective interaction given above which corresponds to a stiff equation of state. In agreement with the results obtained for the Kr+Au system, one can observe the growth of a bubble in the center of the system when a soft equation of state is assumed. On the other hand, using a stiff equation of state, one can clearly see in Fig. 4 that a thin disk is formed soon after the most violent stages of the reaction. Owing to the higher value of the incompressibility modulus, nuclear matter rapidly escapes from compressed regions by flowing in the plane perpendicular to the beam axis before the system has equilibrated. This leads to the thin disk shape observed in Fig. 4. The development of this thin disk shape is associated with a large transfer of energy from the longitudinal to the transverse motion. Therefore, the kinetic energy of fragments originated from the breakup of this thin disk should be predominantly associated with the motion in the plane perpendicular to the beam axis. However, recent investigations on this system at the bombarding energy considered here [7] showed that the kinetic energy of fragments produced in this reaction is associated with a large radial expansion. Thus, this suggests that this thin disk shape might not be observed on this system at the bombarding energy considered here. On the other hand, a large radial flow is consistent with the growth of the bubble shape shown in Fig. 3. Nevertheless, further experimental analyses are necessary to draw precise conclusions about the development of this bubble shape.

In conclusion, we have studied the development of different exotic density shapes (bubbles and disks) in heavy-ion collisions between asymmetric systems using a BUU approach. In agreement with previous results obtained by Bauer *et al.* [12] using a soft equation of state, we found that bubble and doughnut shapes develop in central reactions. However, this is no longer the case if a stiff equation of state for nuclear matter is assumed. We have checked that, for reactions between asymmetric systems, the growth of bubble shapes is associated with a

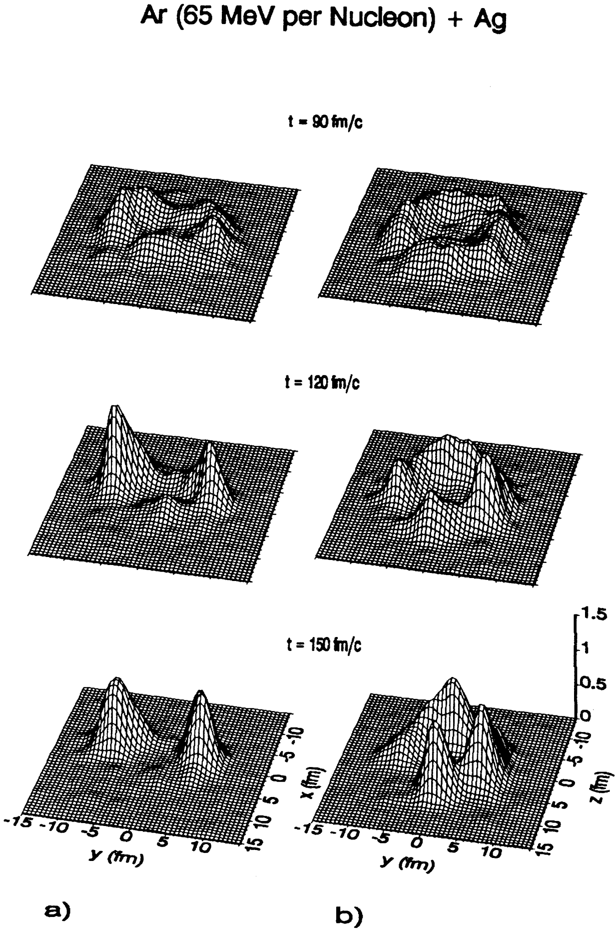

FIG. 3. Same as Fig. 1, but the system is Ar+Ag.

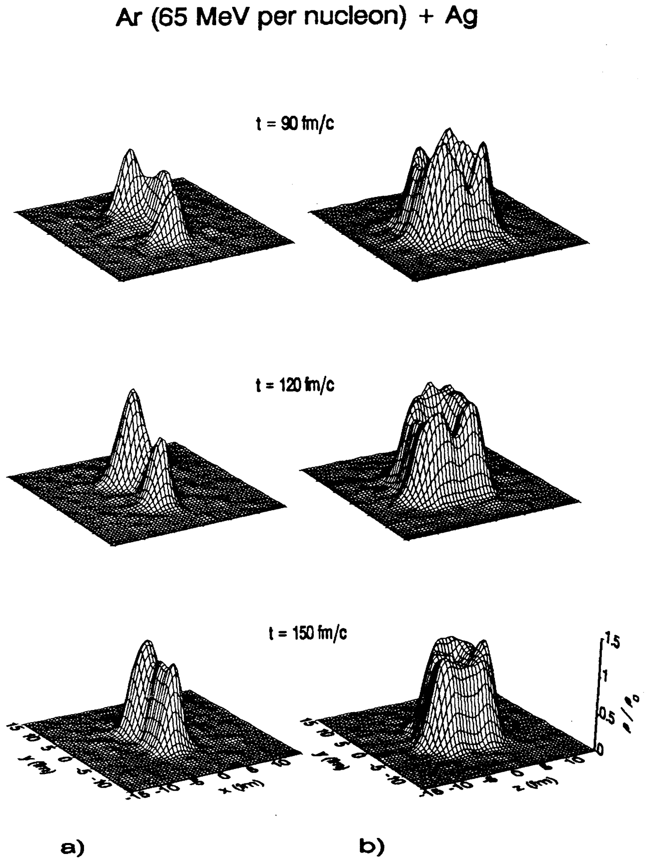

FIG. 4. Same as Fig. 1, but the system is Ar+Ag and a stiff equation of state for nuclear matter is assumed.

finite window of impact parameter. We have also performed other calculations based on more involved effective interactions (including a short range Yukawa-type interaction, for example). The results are qualitatively not changed. The important point is that the formation of bubbles seems to be quite sensitive to the nuclear equation of state. Thus, experimental indications of the development of those exotic shapes in heavy-ion collisions could help in obtaining further information about the nuclear equation of state.

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