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DOES ONE CREATE VERY HOT NUCLEI IN HEAVY-ION REACTIONS BELOW 100 MeV/u ?

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Does one create very hot nuclei in heavy-ion reactions below 100 MeV/u?

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Abstract

A meticulous analysis of emitted charged particles in heavy-ion reactions have been carried out in the framework of the dynamical semiclassical Landau-Vlasov approach for the Ar + Al collisions at 65 MeV/u. In accordance with most of the recent experimental results, the binary reaction mechanism is the main reaction feature. Contrary to the expectations that below 100 MeV/u a mechanism reminiscent of low energy deep-inelastic reaction could create two very excited sources (the primary quasiprojectile and quasitarget), the simulation shows that this reaction mechanism is closely connected to the participant-spectator picture. Due to an abundant dynamical (participant) emission mainly centered at midrapidity, the primary quasiprojectile and quasitarget can be identified as not very hot spectators.

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Nowadays it is fully admitted that in the incident energy range between about the Fermi energy and 100 MeV/u, the nucleus-nucleus reaction cross section is dominated by the binary dissipative collision (BDC) leading in the exit channel to two excited nuclei, the quasiprojectile (QP) and the quasitarget (QT). This energy range is a transition region from the low energy deep-inelastic collision (DIC) to the reaction mechanism adopted at much higher energies, the participant-spectator picture. It is still an open question whether the reaction mechanism of BDC's is an extension of DIC's to central collisions or it represents advanced signs of high-energy processes. This question is crucial because the validity of the former hypothesis would lead one to postulate the existence of extremely hot nuclei offering the opportunity of thermodynamic-type studies: the characterization of the nuclear matter equation of state. Contrarily, if later hypothesis is true, a large amount of the available energy would be promptly evacuated from the interaction zone formed by the two overlapping collision partners. That would lead to the substantial reduction of the excitation energy of the primary QP and QT.

Till very recently, most of the experimental results were analyzed following the low-energy hypothesis. The presumed formation of hot nucleus lead to the colossal values for the excitation energy ($E^*/A \sim 25$ MeV/u) and temperature ($T \sim 20$ MeV) of the reconstructed primary QP [1]. The new generation of multidetectors, like INDRA at GANIL, made possible the entirely novel event characterization and analysis [2, 3]. These analyses have shown the existence of the strong, non-equilibrated component at midrapidity which may be interpreted in the spirit of the high-energy hypothesis. The preliminary experimental analysis which takes into account the midrapidity component results in an important modification of the deduced properties of the primary QP and QT [4].

The BDC was generally seen as two-step process: the first *dynamical* stage of the collision accompanied by the emission of a few pre-equilibrium particles at midrapidity, and the second *statistical* stage characterized by the two very excited equilibrated nuclei, the primary QP and QT which decay by statistical emission. The underlying assumption of this scenario is that all emission in the forward hemisphere of the QP comes exclusively from the presumed statistical decay of the primary QP. It is endorsed by the measured flat angular distributions in the QP reference frame for $\theta<90°$ [5, 6]. Such behavior is consistent with the emission of an equilibrated source. The properties of the primary QP (mass, charge, E^*/A, T) reconstructed on the calorimetric manner, can reach the values mentioned above. Before concluding that the so hot nuclei do exist, it is absolutely necessary to well understand the exact role of the dynamical effects.

The answer to the above crucial question could only be given via detailed theoretical analysis using the dynamical model of high performance allowing the close follow-up of the realistic simulation of the collision evolution. That is the aim of the present work in which we investigate the Ar(65 MeV/u)+Al system since it has been extensively studied experimentally [5, 6]. For our analysis we have used the dynamical Landau-Vlasov (LV) model with the realistic nonlocal effective Gogny force [7]. To follow the nuclear dynamics into the second, statistical, reaction stage and, hence, to be able to compare quantitatively calculated and experimental global observables, all the simulations have been carried out up to 800 fm/c, and, beyond this time, up to 8 000 fm/c considering only Coulomb interaction.

The model is able to reproduce several experimental observations. Firstly, the model agrees with the binary character of the reaction mechanism in the sense that whatever the impact parameter is, two nuclei emerge from the reaction [8, 9]. Secondly, in full accordance with what has been observed experimentally [6], there is no fusion-like residue at this incident energy, even in the most central collisions in which the QT vaporizes.

The advantage of a dynamical model is that it offers a possibility to follow in time the evolution of any relevant reaction quantity. The most important time which has to be defined in such binary mechanism is the separation time t_{sep} which in fact corresponds to the birth of the primary QP and QT. It varies from 50 fm/c in peripheral, up to 80 fm/c in the most central collisions [8, 9]. In the following, we will consider all the particles emitted before the t_{sep} as the *dynamical emission* (DE) and all the particles emitted after t_{sep} as the *statistical emission* (SE). To verify that this time cut-off is an adequate manner of selecting both the statistical and the dynamical components, we determined the phase-space origin of these two components by following backward in time the trajectories of the particles belonging to each subset. Let us first consider the subset of the particles emitted before the t_{sep}, i.e. the DE. Plots of density profiles at 35 fm/c, the time at which the total momentum distribution becomes locally spherical [8], in both the configuration

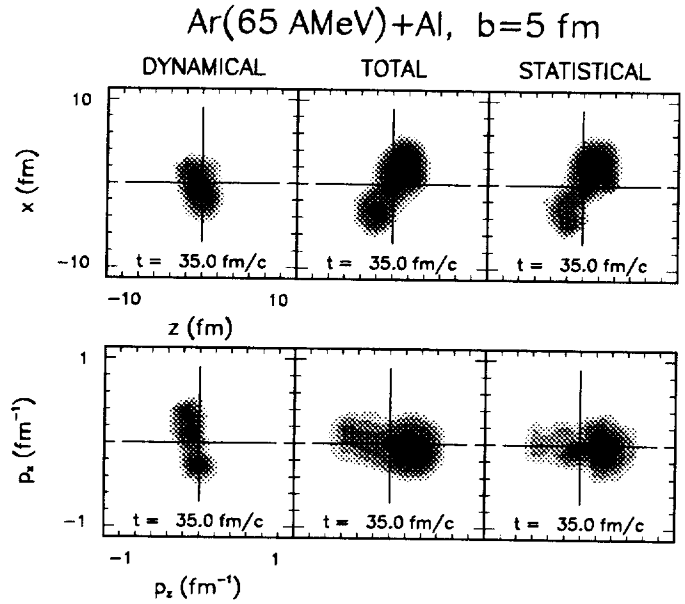

Fig. 1. Equidistant density-profile contours projected onto the reaction plane for b=5 fm at t=35 fm/c in the configuration (top) and the impulse space (bottom) and for the DE subset (left), whole system (middle) and for the SE subset (right).

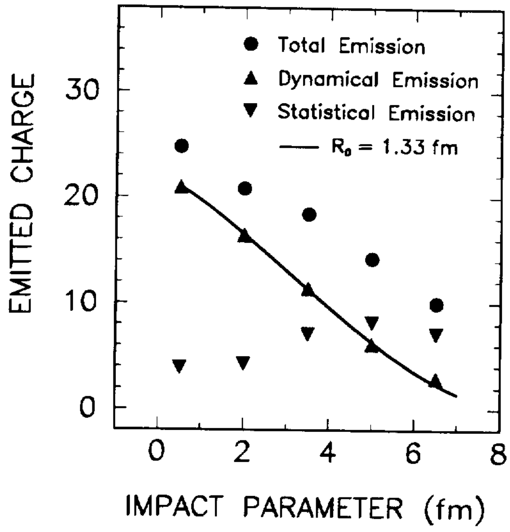

Fig. 2. Calculated multiplicity of emitted charged particles as a function of b for DE (triangles) and SE particles (reversed triangles) and for the sum of both (circles). The curve is due to the participant-spectator assumption weighted with a factor of 0.75.

and the momentum space are displayed in the left column of Fig. 1. To simplify the comparison, the density profiles of the global system are displayed in the middle column. In the configuration space (top) one clearly sees that the particles emitted before t_{sep} come unambiguously from the overlapping zone between the projectile and the target. In the momentum space (bottom), these particles are mainly located at midrapidity. The density profiles of the SE component are displayed in the right columns of Fig. 1. One observes the expected behavior for a statistical emission: the particles come everywhere from the two sources. Indeed, in configuration space, these particles come from the QP and the QT, and, in momentum space, they are located on the average at the QP and QT rapidities. Thus, the statistical and the dynamical appellation are fully justified.

In the rest of this paper, we will mainly focus on the properties of the DE. The first result concerns the evolution of the amount of the DE with b (triangles in Fig. 2). The most striking feature is that the contribution of DE strongly increases with the violence of the collision and becomes dominant at b<4 fm. This behavior can be very well reproduced in the participant-spectator scenario (curve in Fig. 2). The curve has been obtained by calculating the number of particles included in the intersection of two spheres of radii $R = 1.3A^{1/3}$ fm and resulting value was multiplied by 0.75. This result shows that the geometrical effects already at energy as low as 65 MeV/u play a major role in the emission process. A similar study carried out for various systems (Ar+Al, Ar+Ni, Ar+Ag and Xe+Sn) at several incident energies lead to a similar conclusion [10]. The second striking feature is that the SE (reversed triangles in Fig. 2) does not increase with the violence of the collision. This is a qualitative indication that the total excitation energy of the primary QP and QT is not maximal in central collisions.

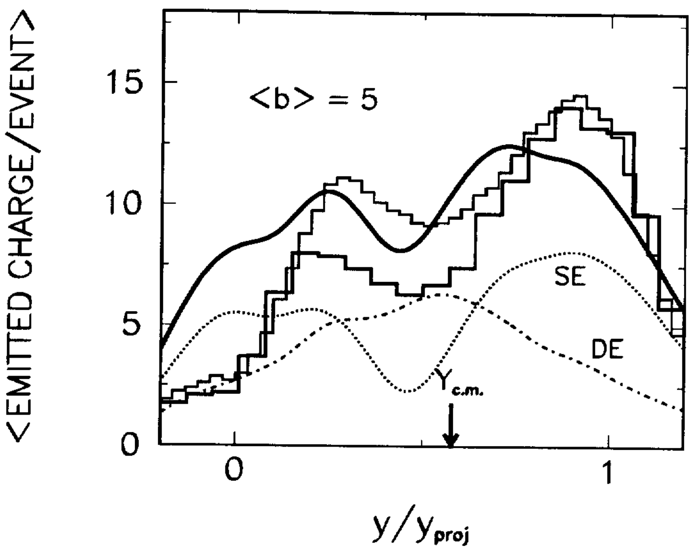

Fig. 3. Charged-particle rapidity distributions for b=5 fm collisions. Curves are due to the simulation and histograms are obtained by summing up experimental Z=1 and Z=2 distributions [11]. The thin and heavy histograms in the upper panel are due to the two different event-sorting procedures. Dash-dotted curve shows the distribution of DE particles, dotted of SE and their sum is represented by the heavy solid curve. The particle rapidity y is normalized by the projectile rapidity $y_{\rm proj}$. Zero stands at the target rapidity and unity at the projectile rapidity. The c.m. rapidity is marked by an arrow.

Figure 3 displays both the calculated and experimental rapidity distributions at 5 fm. The two histograms correspond to experimental data obtained using two different impact parameter sorting procedures [11]. The overall agreement between the experimental data and the global calculated distribution (solid line) is rather good even if each detail of the experimental distribution is not perfectly reproduced. The most important point is that the DE is not only located at midrapidity where it is dominant, but spreads over the whole rapidity domain and especially at rapidity greater than the QP rapidity, where in the experimental studies it is generally considered as negligible. The rapidity distribution of SE is characterized by two components located near the projectile rapidity and the target rapidity, respectively. This is the expected behavior for the emission from two equilibrated sources.

Let us now determine the share of the DE in the QP forward hemisphere as a function of b (Fig. 4). The grey zone corresponds to experimental data: the lower edge is obtained when only the Z=1 and Z=2 particles are taken into account; the upper edge is obtained when $Z \geq 3$ are added [6]. The agreement between the data and calculated global emitted charge (circles) is very good. The dynamical contribution is negligible for the most peripheral collisions, but it increases rapidly with centrality and becomes dominant in the most central collisions. Its variation with b is quasi linear (see dotted line). On the other hand, the SE is nearly constant with b displaying a slight maximum around 3.5 fm. Thus, the simulation does not support the assumption that in the QP forward hemisphere only statistical emission is present. Moreover, the contribution of the DE is maximal in central collisions, where it is generally admitted that the hottest nuclei are formed.

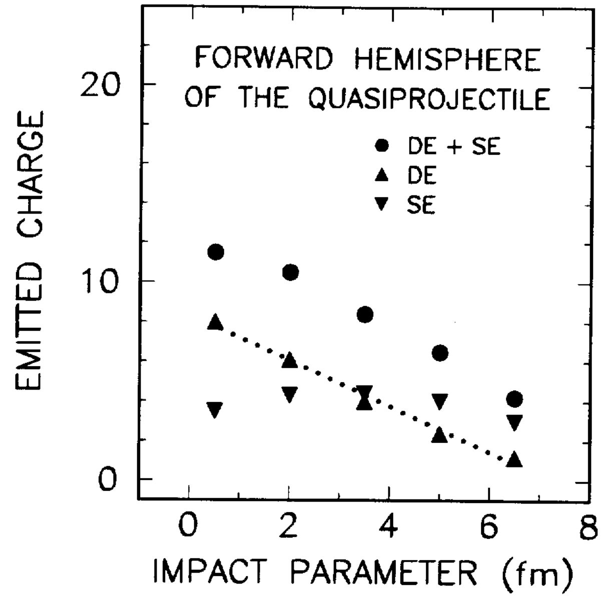

Fig. 4. Reconstructed charge ”emitted by primary QP” as a function of b for DE (triangles) and SE particles (the genuine primary QP emission; reversed triangles) and for the sum of both (circles). The grey area represents the experimental multiplicity [6]. The lower edge is exclusively due to the contribution of the $Z = 1$ and 2 particles, whereas the upper edge includes all detected species. For further details, see text.

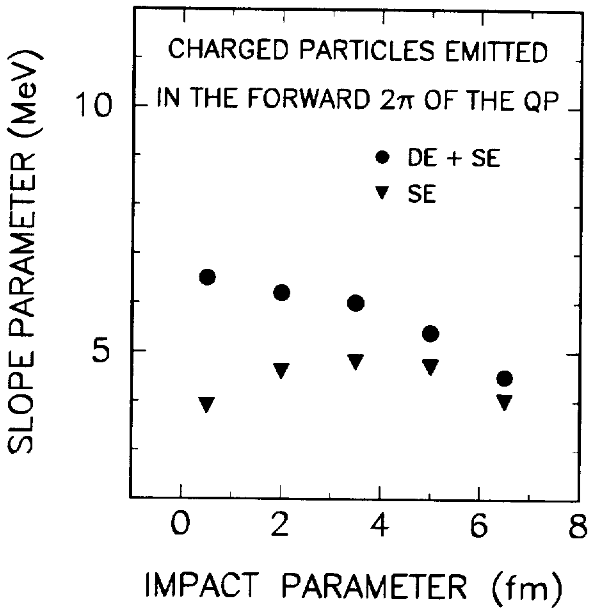

Fig. 5. Slope parameter as a function of b deduced from the fit with a Maxwellian distribution of the calculated kinetic-energy spectra in the QP reference frame for SE (reversed triangles) and all emitted particles (DE+SE; circles). The spectra were integrated between 0° and 90°. The grey area represents the values extracted in two different experimental analyses [5, 6]. For further details, see text.

Let us finally examine the comparison between predicted and measured slope parameters of kinetic energy spectra, which is one of the methods to determine the nuclear temperature (Fig. 5). The grey zone corresponds to experimental data (the lower edge is corresponding to the results of Ref. [5] and the upper one to those of Ref. [6]). The difference between these two sets of data comes mainly from the fact that two different methods for the determination of b and the source velocity were used. From the simulation, we have calculated the kinetic-energy spectra in the QP reference frame for SE (reversed triangles) and all emitted particles (DE+SE; circles). The spectra were integrated between 0° and 90°. Slope parameters have been extracted by fitting every spectrum with the Maxwellian distribution

$$W(E) \sim \alpha \frac{E-B}{S^2} \exp(-\frac{E-B}{S}), \tag{1}$$

where α is a normalization factor, S is the slope parameter, E the energy, and B the Coulomb barrier taken as a fit parameter. Although the grey area is large, the agreement between the calculated and experimental data is rather good. The slope parameters of the statistical component do not follow the same behavior. They do not increase for the lower impact parameters, indicating that the hottest primary QP's are not formed in the most central collisions.

In conclusion, let us recall the two most important results of this work:

1. The BDC are closely connected to the participant-spectator scenario rather than to the low-energy deep-inelastic phenomena. As a consequence one concludes that:

2. If predictions of our simulations are correct, the properties of hot nuclei deduced in experimental studies are questionable. The burning question concerning the striking difference of the GANIL and ALADIN caloric curves can probably be attributed to the dynamical effects observed below 100 MeV/u.

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