Influence of Coulomb interaction of projectile- and target-like sources on statistical multifragmentation

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We show that the fragment partitions and kinematic characteristics of fragments can change in the presence of an external Coulomb field at statistical multifragmentation of highly excited nuclei. There are indications that this effect takes place at intermediate energy peripheral nucleus-nucleus collisions. The phenomenon has general importance for understanding disintegration processes affected by long-range forces.
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The reaction of multifragmentation of highly excited nuclei aroused much scientific interest because of an important overlapping of the traditional nuclear physics with such universal processes as phase transitions, critical phenomena, and behavior of many particle systems. A lot of experimental and theoretical studies were performed and many features of the phenomenon were already established.

Here we point to a successful application of the equilibration hypothesis and statistical approaches [1–3] for understanding this process. It was found that at high energy reactions, both light particle-nucleus [4,5] and peripheral nucleus-nucleus ones [6,7], the multifragmentation resembles very much a thermal process that can be described by statistical models. In the case of central nucleus-nucleus collisions at moderate energies (30–50 MeV/nucleon) the statistical description is also very effective but the flow produced by compression at the initial stage of the reaction must be taken into account [8,9]. The situation is less clear at high energy central collisions where strong dynamical effects exist, but even in these cases the intermediate mass fragment (IMF) production can be explained by assuming a partial thermalization [10]. Statistical nuclear multifragmentation is an example for a transition of a finite many-body system from the (homogeneous) liquid phase into a heterogeneous phase of several nuclear fragments with broad and strongly fluctuating mass distribution. This transition is driven by a rapid gain of entropy with rising excitation energy. Not only is such an entropic transition new within nuclear physics but it is also a beautiful example of a first order transition in small many-body systems in general.

Because nuclei are charged electrically the Coulomb field contributes essentially to their disintegration, and this has already been under intensive theoretical investigation (see, e.g., [1]). However in the statistical approach it was restricted only by self-interaction of fragments produced from one single source. In the present paper we show how an external Coulomb field can change a picture of multifragmentation of a single source. We emphasize that here we consider the effect as a complete statistical phenomenon, though it can be triggered by previous dynamical evolution. We think that such phenomena are important not only for nuclear physics but for all phase transitions influenced by external long range forces (phase transitions under external inhomogeneous fields). This is significant from a general point of view as it is an example of equilibrium statistics with a non-extensive entropy. This is still considered by many statistical physicists (see, e.g., [11]) as contradicting the conventional (canonical) statistics. Evidently, this is possible in microcanonical thermodynamics (for more details see [3]).

As was established by numerous studies multifragmentation is a fast process within a characteristic time around 100 fm/c. In the case of peripheral nucleus-nucleus collisions at intermediate energies the projectile- and target-like sources cannot go far from each other before disintegration. For example, at initial beam energies of 30–50 MeV/nucleon, 100 fm/c after the collision corresponds to the distances around 20–30 fm between the sources. At these relatively short distances the long range Coulomb field of one source influences the breakup of the other.

For this study we use the microcanonical Metropolis Monte Carlo model (MMMC) which allows for correct inclusion of Coulomb interaction by considering exact positions of produced fragments [1,3]. We modified the code: within the MMMC model we consider multifragmentation of a "double" nuclear system. We assumed that at the breakup there are two sources with some charges, masses, momenta, and excitation energies placed at some distance from decaying centers of each other. As a result the Coulomb energy of this system will be different from the Coulomb energy of these two sources if they would disintegrate separately. Moreover the spherical symmetry of the single Coulomb potential is violated and products tend to have symmetry along the line connecting the centers of the sources. Since the two sources each move very quickly with respect to the other (a little bit slower than the beam velocity) we can approximately consider an independent statistical breakup of the sources taking into account only mutual Coulomb influence. The presence of a second source influences considerably the

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charges of the fragments produced at the freeze-out volume of the first as well as their kinematic characteristics after the Coulomb acceleration. One can expect also that the isotopic content of the fragments will depend on their positions in the freeze-out with respect to the sources.

One should mention some limitations of this approach. In fact multifragmentation is not exactly a simultaneous process: it can be considered as simultaneous within a statistical model taking into account that the time of fragment formation is much smaller than the characteristic time of changing of the Coulomb field [12]. Since the sources move fast the contribution of the second source to the Coulomb interaction of the fragments decreases quickly. However, by considering a relatively well defined time interval we can see the qualitative effects of the inhomogeneous field. In future studies it would be useful to separate the time when the fragments start to form (similar to the ''saddle'' point in nuclear fission) from the time when they start to propagate under Coulomb forces. Also we should stress that the approach is nonrelativistic, and it is qualitatively sufficient for collisions with energy less than 100 MeV/nucleon. At relativistic energies the Coulomb interaction of the sources must be described in another way.

As an example we consider peripheral collisions in reaction of Au+Au at 35 MeV/nucleon, which are already under investigation [13,14]. It was shown that it is possible to select experimental events corresponding to breakup of projectile- (and target-) like source with mass and charge equal approximately to gold. The velocities and excitation energies of the source found from the characteristics of the produced particles correspond to values obtained from the energy-momentum balance. Of course a dynamical preparation of such sources can lead to particle and energy losses, but these preequilibrium particles have energies very similar to thermal ones and, moreover, it does not affect qualitatively the following IMF production from the thermal sources. Here we do not try to describe this particular experiment (it is a part of a future comprehensive analysis), but rather we would like to point to theoretical conclusions that are general for all intermediate energy peripheral reactions.

We analyze the multifragmentation of two Au sources with excitation energies $E^*=2$ MeV/nucleon and $E^*=5$ MeV/nucleon and moving along the beam axis with relative velocities of $0.23c$ and $0.17c$, correspondingly. The transverse velocities are very small [13,14] and do not influence the results. Assuming the time of multifragmentation around 100 fm/c we fix the relative distances between sources at 23 fm for excitation of 2 MeV/nucleon and 17 fm for 5 MeV/nucleon. In fact the above-mentioned velocities are found after the Coulomb acceleration but the Coulomb addition is negligible in comparison with the initial relative motion at freeze-out. With MMMC we generate multifragmentation events of these sources and simulate coordinate positions of produced fragments taking into account the mutual Coulomb field. In a statistical description the partitions with small Coulomb barrier are more probable because if the available phase space W for translational motion is larger the entropy $S=\ln(W)$ is larger. As a result small fragments tend to take positions in between the sources while the large fragments are shifted to the opposite direction (keeping the center of mass of the double system). The sizes of fragments change also because the disintegration process is influenced by the more strong Coulomb barrier. These effects are especially important at the multifragmentation threshold (around $E^*=2-3$ MeV/nucleon) where decays into two fragments dominate.

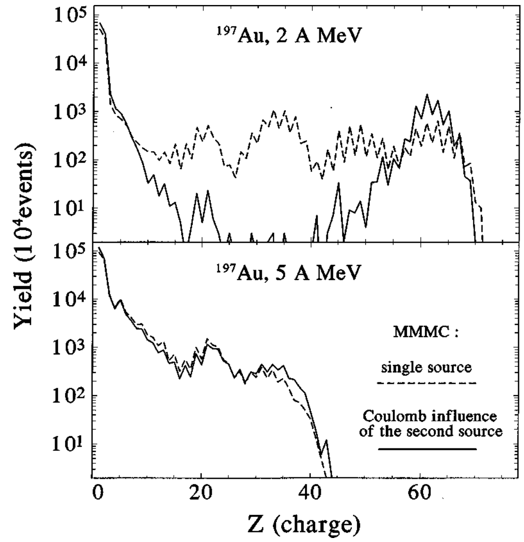

FIG. 1. Charge yields of fragments in ^{197}Au multifragmentation for excitation energies of 2 MeV per nucleon (top) and 5 MeV per nucleon (bottom) with the presence of the second Au source (solid lines) and without it (dashed lines).

In Fig. 1 we show how the charge distributions of fragments produced in multifragmentation of an Au source at excitation energies of 2 and 5 MeV/nucleon change in the presence of the second Au source at a distance of 23 and 17 fm, respectively. It appears that at the small excitation energy the partitions change drastically: the usual quasifission channels are suppressed and the system prefers to breakup into a large fragment (a compound-like one associated usually with an initial liquid phase of nuclear matter) and a small fragment. In this case a Coulomb energy contribution from the second source is rather important: around 50–60 MeV. As was mentioned the decay is strongly ''polarized'' in space: the small fragments are positioned mainly between the large one and the second source, and that configuration provides a minimum Coulomb barrier. As a result of this spatial anisotropy we have an anisotropy of fragment velocities with respect to the center of mass of the source after the Coulomb acceleration. This is unlike the conventional isotropic Maxwell velocity distribution and a typical signal of a non-extensive thermodynamics. The intermediate mass fragments (IMF) with charge $Z=3-20$ fly mainly from the center of mass to the direction of the second source, i.e., IMF tend to fill the midrapidity kinematical region for this reaction. The velocities of the largest fragments are shifted a little bit to the opposite direction. This is illustrated in Fig. 2 where we show parallel velocity distributions for the fragments.

At high excitations (5 MeV/nucleon) the compound-like fragments disappear and the system changes into a new phase [1,2]. Here the partitions change not so strongly since the share of the interaction Coulomb energy of the sources is smaller respective to the excitation energy of the system. However it also affects the fragment positions, and IMF ve-

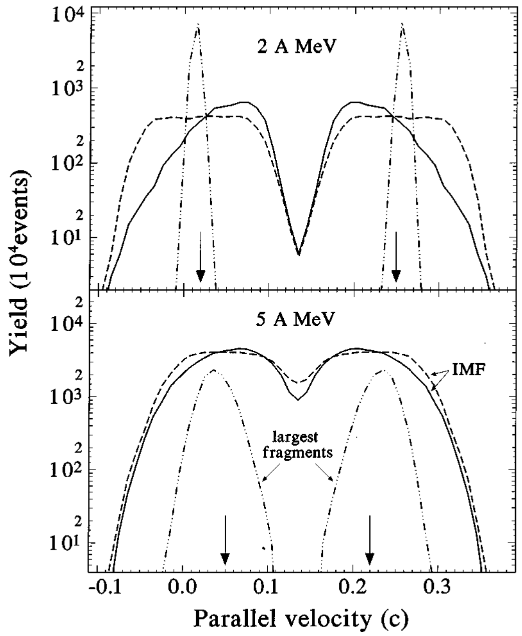

FIG. 2. Yield of fragments versus their parallel velocities in laboratory system for peripheral collisions in the Au+Au reaction at 35 MeV/nucleon. The velocities of excited Au sources (top: $E^*=2$ MeV/nucleon, bottom: $E^*=5$ MeV/nucleon) are shown by large arrows (see text). Solid lines: IMF with $Z=3-20$; dot-dashed lines: the largest produced fragments. Dashed lines are IMF calculated without mutual Coulomb influence of the sources.

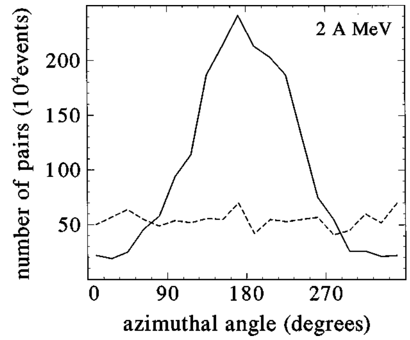

FIG. 3. Azimuthal distribution of light IMF in the projectile-like residue coordinate system (see text) in the case of fragmentation of a projectile Au source at $E^*=2$ MeV/nucleon into the two fragments. The solid line is the MMMC calculation with the Coulomb influence of the target source, the dashed one is without the influence.

locities are also shifted to the midrapidity region. Without Coulomb interaction of the projectile- and target-like sources all produced fragments would be symmetric around the centers of mass of the sources (see dashed lines in Fig. 2).

The microcanonical temperature of the disintegrating system changes also as a consequence of a new energy balance with new partitions. If the second source exists the temperature increases slightly more rapidly at small excitations (from $T=3.46$ MeV to $T=3.71$ MeV at $E^*=2$ MeV/nucleon) than at high energies (from $T=5.01$ MeV to $T=5.20$ MeV at $E^*=5$ MeV/nucleon), and a plateau-like caloric curve [1,2] results.

Here we should point to one problem in the interpretation of experimental data. There are some indications (e.g., [15,16]) that IMF really tend to be concentrated in the midrapidity kinematical region for peripheral collisions. Obviously this phenomenon does not correspond to a traditional picture of statistical decay of two independent sources. The authors [15,16] assumed a dynamical ''neck'' emission. We think that generally such an emission could exist. However, up to now, there were no comprehensive comparisons between dynamical models and the experiments. The statistical midrapidity emission pointed out in the present work can essentially contribute to the observed phenomenon. One should take into account that the IMF velocities depend on assumptions about the freeze-out density and distance from the other source. The present MMMC calculations were done at the density around 1/6 of the normal nuclear one. Increasing density provides more strong repulsion and larger shifts to midrapidity region. Larger distances between sources at the beginning of the Coulomb acceleration of IMF favors also the filling of the midrapidity gap.

The Coulomb interaction of the sources influences other characteristics of the fragmentation events. For example, an azimuthal anisotropy of light IMF respective to projectile-like residue (PLR) was found in [15]. Following their prescription we have considered breakup channels only with these two fragments (besides light particles) and take a standard right-handed coordinate system based on the Cartesian axes: $z'=(\vec{V}_{\rm beam}\times\vec{V}_{\rm PLR})/|\vec{V}_{\rm beam}\times\vec{V}_{\rm PLR}|$ and $x'=\vec{V}_{\rm PLR}/|\vec{V}_{\rm PLR}|$. In this coordinate system we have looked at the azimuthal distribution of the light IMF (with charge $Z=4-10$) with respect to the PLR (with $Z\geqslant 33$). In Fig. 3 we show the azimuthal distribution for the case of the gold projectile source with excitation energy of 2 MeV/nucleon. When a target-like source is present there is a prominent peak at 180 degrees similar to the experimental data [15]. The reason is that the Coulomb trajectories of IMF and PLR are influenced by the second source: in this particular case the velocities of the three bodies tend to be in plane with the beam axis and both IMF and PLR get an additional Coulomb push to the direction of the beam.

In conclusion, the process of statistical multifragmentation of an excited nuclear system changes under external Coulomb forces. We have considered a particular example of multifragmentation of a double system produced in peripheral nucleus-nucleus collisions at intermediate energies, a process now under intensive experimental study. We have found a statistical fragment emission preferable to the midrapidity kinematical region, which was up to now associated only with a preequilibrium dynamical process. Besides offering a new explanation to phenomena that were viewed as typical *dynamical* effects by a completely equilibrium mechanism that is ruled solely by the available phase space under inhomogeneous conditions, our example also offers a new application of thermodynamics and equilibrium statistics to inhomogeneous non-isotropic and non-extensive systems far away from the thermodynamic limit. In this situation the use of the microcanonical ensemble was crucial. This phenomenon can be called a non-extensive ''Coulomb-oriented'' phase transition. The study of these reactions is also a natural way to study the behavior of and the phase transitions in finite systems under long range forces—a genuine phenomenon in nature, from the evolution of charged metallic clusters to the disintegration of astronomical objects under gravitational forces [3,17]. The microcanonical statistical approach provides an adequate tool for a theoretical treatment of these phenomena. For some first microcanonical equilibrium studies of astronomical objects see, e.g., [18].

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