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Size and excitation energy distributions of projectile spectators in multifragmentation data

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The size and energy distributions of spectators in ALADIN fragmentation experiments with gold projectiles are inferred from experimental data. For the most violent collisions of Au on Cu, the mean projectile spectator has the size of an iron nucleus, with an excitation energy of about 23 MeV/nucleon. We claim that a correct interpretation of these data should take into account the large range covered by the extracted distributions, which are in good agreement with the prediction of the Boltzmann-Uheling-Uhlenbeck calculations and with those of a new diabatic abrasion model.

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Noncentral heavy-ion collisions at bombarding energies above a few hundred MeV/nucleon are believed to proceed in two steps with different time scales. First a rapid abrasion step (10^{-21} sec) leaving behind the fireball and the excited spectators, then a slower (10^{-20}–10^{-19} sec) ablation step in which the spectators break up in fragments and nucleons. The modelization of the ablation step requires as input parameters the knowledge of the primary mass and excitation energy distributions and the correlation between them. Unfortunately this information is not yet directly available from experiment. This is the case for the ALADIN results [1–5] which are the most complete piece of data available on the fragmentation of a heavy projectile (Au) at bombarding energies of the order of 600 MeV/nucleon. In this work we show that with plausible assumptions it is nevertheless possible to deduce this information from the experimental data.

First we consider the charge distribution of projectile spectators. Because of the acceptance of the ALADIN detector [2], the fragments detected come (mostly) from the projectile spectator, but some of them are missed: in particular all fragments with $Z=1$ (see [2,5]). In order to determine the size of the spectators, we have to estimate how many are missed. We will use an ansatz based on a continuity argument, extrapolating to $Z=1$ the measured number of fragments $n(Z)$. A reliable extrapolation is obtained by using the sum rule,

$$\langle F(s)\rangle=\sum_{Z=79}^{s} Z\langle n(Z)\rangle \ . \tag{1}$$

Then the estimated mean size of the spectator is $\langle Z_{\text{spec}}\rangle=\langle F(1)\rangle$. The symbol $\langle\ \rangle$ means the statistical average of events of same class. The ALADIN Collaboration [1] have defined classes of events through the quantity

$$Z_{\text{bound}}=\sum_{Z=79}^{2} Zn(Z). \tag{2}$$

Adopting this classification means that one calculates $\langle F(1)\rangle$ for the events with same $F(2)=Z_{\text{bound}}$. Figure 1 shows a log-log representation of $\langle F(s)\rangle$ calculated with the ALADIN data on Au+Cu at 600 MeV/nucleon [1], the various curves corresponding to averages with different values of the Z_{bound} parameter ($5\pm5, 15\pm5, \ldots, 75\pm5$). We have made use of the efficiency corrections recommended in [2]. We see that the extrapolation of $\langle F(s)\rangle$ to $s=1$ is not very hazardous. The resulting correlation between $\langle Z_{\text{spec}}\rangle$ and $\langle Z_{\text{bound}}\rangle$ can be parametrized (see Fig. 2) as

$$\langle Z_{\text{spec}}\rangle=25+Z_{\text{bound}}-0.004Z^2_{\text{bound}}. \tag{3}$$

One sees that for collisions with the lowest Z_{bound} the breaking spectator is likely to be a nucleus in the iron region. Similar relations can be obtained for the other target nuclei used in these experiments [1]. The extrapolation to $s=1$ shown in Fig. 1 is obviously not uniquely defined. We have looked at different extrapolations (for example, using a linear-log representation) but the result (3) suffers little change because the two extreme values of $\langle Z_{\text{spec}}\rangle$ are well defined.

Using the experimental probability distribution of Z_{bound} and the relation (3) we calculate the probability distribution of spectator sizes $P(Z_{\text{spec}})$. In Fig. 3 we show this "experimental" quantity (dots), as well as the prediction of a simple abrasion model (full line). In this model [6], the mass of the spectators is given by the nonoverlapping volume of two spherical and uniform distribution of matter situated at a distance b. Z_{spec} is then calculated by assuming the same charge asymmetry than for the projectile. From the probability distribution of the impact parameter b one calculates $P(Z_{\text{spec}})$. We see in Fig. 3 that this simple prediction is in good agreement with our "experimental" distribution. It is interesting to notice that a Boltzmann-Uheling-Uhlenbeck (BUU) calculation [7] (dot-dashed line) also predicts a very similar $\langle Z_{\text{spec}}(b)\rangle$. These converging results give some confidence on the validity of the deduced spectator size distribution.

It is very important to take into account the broadness of this distribution when comparing with theoretical predic-

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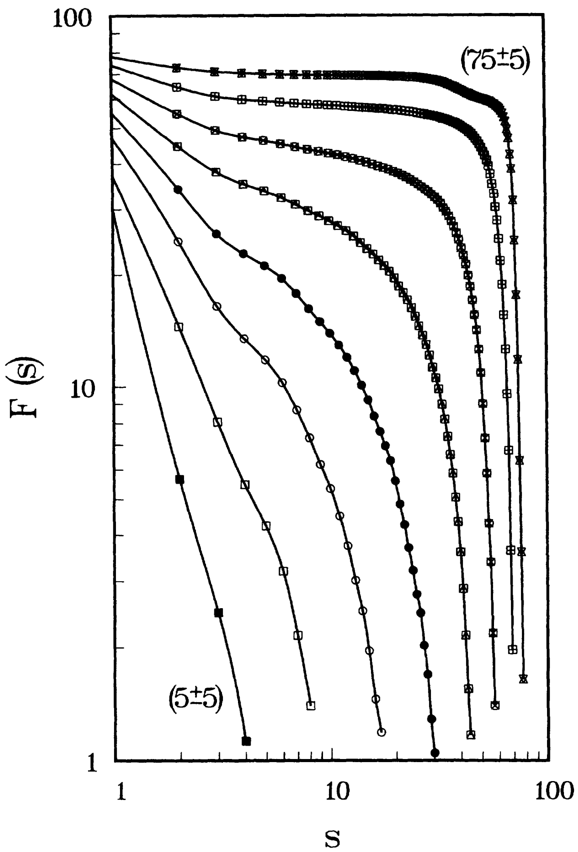

FIG. 1. The average value of the sum rule $\langle F(s) \rangle$ [Eq. (1)] for events of Au+Cu at 600 MeV/nucleon. The various curves correspond to averages with different values of the Z_{bound} parameter $(5\pm5, 15\pm5, \ldots, 75\pm5)$.

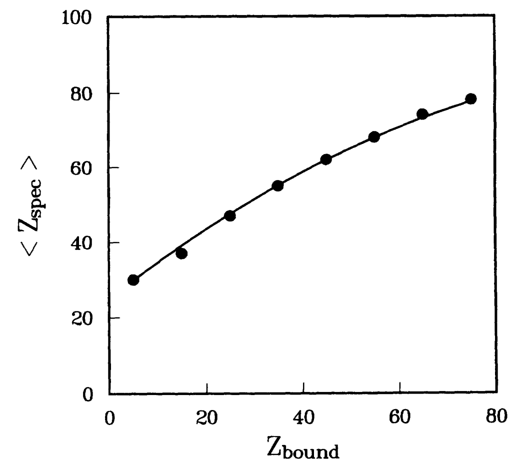

FIG. 2. The mean spectator size $\langle Z_{\mathrm{spec}} \rangle$ as a function of Z_{bound}. The full line corresponds to the fit given by Eq. (3).

tions. This has been done correctly in the statistical equilibrium calculations [7,11] because BUU spectator distributions have been used. The site-bond percolation calculation of [3] also mimics the distribution of Z_{spec} through the random variation of the site-occupation parameter p_{site}.

One should note that the relation (3) is valid *on average* and that large fluctuations of Z_{spec} are possible for events with same Z_{bound}. This feature makes the analysis and the interpretation of the fluctuations of fragment distributions [8,9] much more delicate.

After having determined the charge of the projectile spectators, the next step is to estimate their excitation energy. This of course is somewhat more difficult since the mechanisms by which these nuclei are excited are largely unknown. However, several reasonable assumptions can be made with which some estimation can be given.

The idea is to estimate the energy that is needed to produce the observed fragmentation. This energy can be decomposed into two terms:

$$E^* = Q + E_k. \quad (4)$$

The first term corresponds to the binding energy balance of the fragmentation, and the second corresponds to the sum of the kinetic energies of the particles and nuclei at infinity.

The binding energy balance is the energy needed to separate the spectators into fragments and put them at infinity with zero kinetic energy. This can be estimated with confidence, assuming (i) that the neutron to proton ratio of the spectators is the same as the one of the projectile $^{197}_{79}$Au, and (ii) that after decay the detected fragments belong to the valley of stability. Figure 4 shows the result, in MeV per nucleon, of this calculation for all the ALADIN events (Au+Cu at 600 MeV/nucleon) as a function of Z_{bound}. The "error bars" for this calculation correspond to the variance calculated for given Z_{bound} events. As Z_{bound} vanishes, corresponding to the total "vaporization" of the smallest primary nuclei into protons and neutrons, the binding energy balance reaches the canonical value of 8 MeV/nucleon.

The values of the excitation energies thus obtained must be considered as the lowest bound, since any departure from the valley of stability would result in larger values.

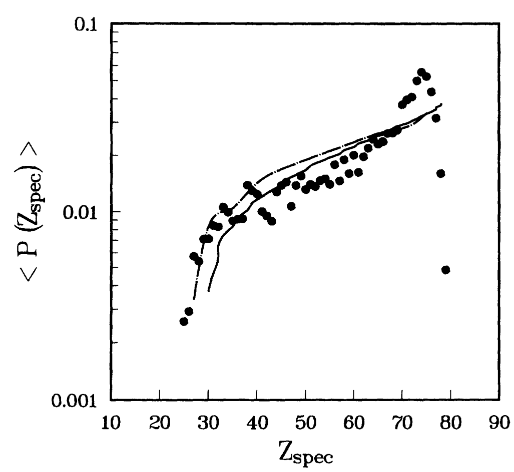

FIG. 3. Probability distribution of the mean spectator size (see text). Shown are the "experimental" results obtained with the present method (dots), the predictions of the abrasion model [6] (full line), and the predictions of BUU calculations [7] (dot-dashed line).

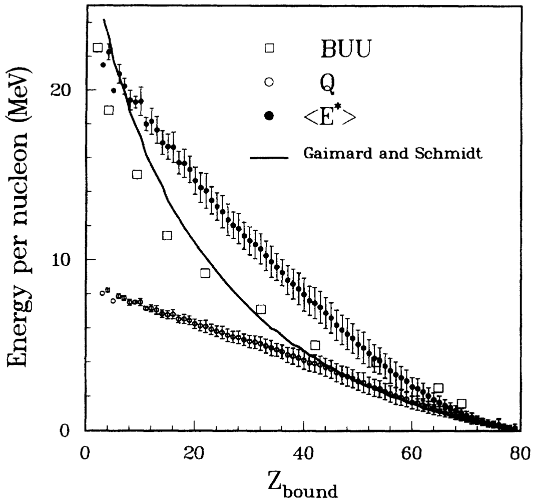

FIG. 4. Spectator excitation energy per nucleon as a function of Z_{bound} (Au+Cu at 600 MeV/nucleon). Open dots: mean values of the binding energy balance calculated from the ALADIN events. Solid dots: sum of energy balance and estimated kinetic energies (T = 10 MeV; see text). The "error bars" represent the variance of these quantities. Full line: calculations with the abrasion model [6]. Open squares: values from BUU calculations [3].

The kinetic energy E_k term is somewhat more difficult to estimate. The simplest case to consider corresponds to the extrapolation to $Z_{\text{bound}}=0$ events since total dissociation is achieved and only proton and neutron kinetic energies have to be considered. Although no direct proton spectra have been measured by ALADIN, similar experiments have been performed by other groups. Bastid *et al.* [10] have analyzed the energy spectra of $Z=1$ particles (Ne+Pb and Ne+NaF at 400 and 800 MeV/nucleon) and have extracted a "spectator component" which they have fitted by an analytical formula based on an effective slope parameter T [Eq. (2) of [10]] and from which an average kinetic energy can be calculated numerically ($\langle E_k\rangle \approx 1.8T$). Their analysis gives various values of T depending on the centrality of the reaction. The value given for the most violent peripheral collisions is $T=10$ MeV (see Table 4 of [10]).

The mean energy for the neutrons can be estimated along the same lines by subtracting the Coulomb contribution to the proton kinetic energy. This can be reasonably done by assuming the potential Coulomb energy at "freeze out" to be given by that of a uniform charged sphere of reduced radius R_0. With the above value for T and a reduced radius of $R_0=2$ fm, the mean total excitation energy [Eq. (4)] for $Z_{\text{bound}}=0$ events comes out as $\langle E^*\rangle = 23$ MeV/nucleon. Whereas the dependence of E_k on T is almost linear ($\langle E^*\rangle = 15$ MeV/nucleon for a value of $T=6$ MeV), varying R_0 has limited effects (a 20% decrease of E_k when varying R_0 from 2 to 1.2 fm).

For nonzero values of Z_{bound}, a conservative estimate for E_k can be obtained by applying the same, T dependent, kinetic energy to all charged fragments and by assuming that the value of T decreases linearly to zero as a function of increasing Z_{bound}. The mean excitation energies $\langle E^*\rangle$ resulting from event by event calculations are given by the full dots in Fig. 4. The "error bars" reflect the variance observed. As stated above, the values of the E_k component of E^* will essentially scale with T.

Other estimations of E^* can be obtained from various models. The diabatic abrasion model of Gaimard and Schmidt [6], because it applies well to projectile spectators in this energy regime, is of particular interest. The full line in Fig. 4 shows the values obtained for the present system (in this calculation, we took 13.3 MeV for the average excitation energy per hole). BUU calculations reported in [3] predicts excitation energies in a similar range ($E^* \leqslant$ 22 MeV/nucleon). In contrast, the energies that are needed in statistical equilibrium models [7,11,12] to reproduce the fragment size correlations are much smaller. The values given, $E^* \approx 6-8$ MeV/nucleon for the most central collisions, are very close to the binding energy balance Q. This implies that the fraction of E_k due to the thermal kinetic energy vanishes. Most of the final fragment kinetic energies (E_k) would then come either from flow energy [7], or from preequilibrium [12]. Obviously, our "experimental" estimation of the total excitation energy [Eq. (4)] includes all possible contributions.

We have suggested a simple method to deduce the average size of the spectator prefragment from the experimental ALADIN data. A simple relation between the Z_{bound} parameter and the mean spectator size is given. We have also estimated the excitation energy of the spectators by reconstructing the energy that is necessary to produce the observed fragmentations. BUU calculations and a modern version of the abrasion model predict very similar spectator sizes and excitation energies distributions. We believe that it is important in theoretical calculations to take into account the wide range of these distributions and in particular the size and excitation energy of the spectator nuclei resulting from the most central collisions.

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