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Statistical fragmentation of Au projectiles at $E/A = 600$ MeV

J. Hubele,[1] P. Kreutz,[2] V. Lindenstruth,[1] J. C. Adloff,[3] M. Begemann-Blaich,[1] P. Bouissou,[4] G. Imme,[5] I. Iori,[6] G. J. Kunde,[1] S. Leray,[4] Z. Liu,[1] U. Lynen,[1] R. J. Meijer,[1] U. Milkau,[1] A. Moroni,[6] W. F. J. Müller,[1] C. Ngô,[4] C. A. Ogilvie,[1] J. Pochodzalla,[1] G. Raciti,[5] G. Rudolf,[3] H. Sann,[1] A. Schüttauf,[2] W. Seidel,[7] L. Stuttge,[3] W. Trautmann,[1] A. Tucholski,[1] R. Heck,[8] A. R. DeAngelis,[8] D. H. E. Gross,[8] H. R. Jaqaman,[8] H. W. Barz,[7] H. Schulz,[9] W. A. Friedman,[10] and R. J. Charity[11]

[1]*Gesellschaft für Schwerionenforschung, D-6100 Darmstadt, Federal Republic of Germany*

[2]*Institut für Kernphysik, Universität Frankfurt, D-6000 Frankfurt, Federal Republic of Germany*

[3]*Centre de Recherches Nucleaires, F-67037 Strasbourg, France*

[4]*Laboratoire National Saturne, CEN Saclay, F-91191 Gif-sur-Yvette, France*

[5]*Dipartimento di Fisica dell' Universitá, I-95129 Catania, Italy*

[6]*Instituto di Scienze Fisiche, Universita degli Studi di Milano, I-20133 Milano, Italy*

[7]*Forschungszentrum Rossendorf, O-8051 Dresden, Federal Republic of Germany*

[8]*Hahn Meitner Institut, Bereich Physik, D-1000 Berlin 9, Glienickerstrasse 100, Fachbereich Physik der Freien Universität Berlin, FPS Clusterproduktion, Federal Republic of Germany*

[9]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824*

[10]*Department of Physics, University of Wisconsin, Madison, Wisconsin 53706*

[11]*Department of Chemistry, Washington University, St. Louis, Missouri 63130*

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The mean multiplicity of intermediate mass fragments (IMF) $\langle M_{\mathrm{IMF}} \rangle$ produced by fragmentation of Au projectiles interacting with targets of C, Al, Cu, and Pb at an incident energy of $E/A = 600$ MeV is compared to predictions of statistical multifragmentation and sequential evaporation models. The initial conditions for the calculations were provided by Boltzmann-Uehling-Uhlenbeck simulations. In the high excitation energy regime where the IMF multiplicity reaches its maximum the observed universal correlation between $\langle M_{\mathrm{IMF}} \rangle$ and the total charge Z_{bound} of projectile fragments with charges $Z \geq 2$ cannot be reproduced by a sequential evaporation code. In this regime the data are better described by statistical decay calculations which assume the formation of an expanded nuclear system and a rather fast breakup.

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In a recent experiment performed with the ALADIN spectrometer at SIS [1], the fragmentation of Au projectiles after collisions with C, Al, and Cu targets at a bombarding energy of $E/A = 600$ MeV per nucleon was studied [2,3]. With increasing violence of the collision, measured via the multiplicity of light particles, the so-called *rise and fall* of the mean fragment multiplicity $\langle M_{\mathrm{IMF}} \rangle$ was revealed [2] as predicted, for example, in Ref. [4]. Ordering the collisions according to the summed charge Z_{bound} of projectile fragments with $Z \geq 2$, a remarkable target independence of the intermediate mass fragment (IMF) multiplicity was found [3] where an IMF is defined as a fragment with $3 \leq Z \leq 30$. Figure 1 shows this correlation together with new data from Au + Pb collisions, obtained from the same experiment at $E/A = 600$ MeV. As already observed for the lighter targets the IMF multiplicity observed within the acceptance of the ALADIN spectrometer [3] is also for Au +Pb collisions with decreasing Z_{bound} first increasing up to a maximum value of $\langle M_{\mathrm{IMF}} \rangle \approx 3.5$–4 at $Z_{\mathrm{bound}} \approx 40$. For smaller values of Z_{bound} corresponding to more central collisions [3], the IMF multiplicity is then again declining. Except for a weak systematic decrease of the maximum IMF multiplicity with increasing mass of the target nucleus, no significant target dependence of $\langle M_{\mathrm{IMF}} \rangle$ is observed.

For the different targets, a given value of Z_{bound} corresponds to different impact parameters [3] and hence different reaction geometries. Therefore, the observed universal behavior provides a necessary—although not sufficient—condition for a chemical equilibrium being established during the fragmentation process. In order to address the question whether also the degrees of freedom associated with the kinetic motion might be equilibrated in these collisions, we examined the velocity spectra of the produced fragments. In the present experiment this analysis is restricted to fragments with charge $Z > 7$ [3]. In the top part of Fig. 2 we show the mean fragment velocity $\langle \beta_{\parallel} \rangle$ parallel to the beam direction for Au + Cu reactions. In addition the vertical bars mark the root-mean-square (rms) deviations of the longitudinal velocities. The different symbols correspond to different event classes characterized by Z_{bound}. Consistent with previous studies [5,6], in the limiting fragmentation regime $\langle \beta_{\parallel} \rangle$ deviates for all fragments by less than 1% from the incident beam velocity (see horizontal line) and is independent of the event class. Furthermore, no target dependence was observed. Due to uncertainties in the walk corrections of our time-of-flight system, the absolute

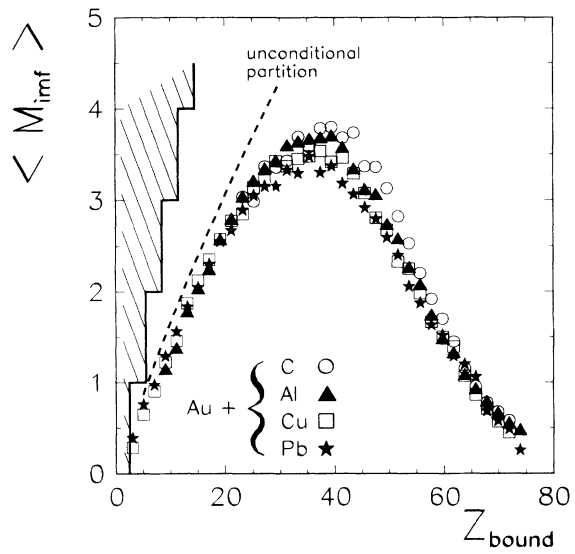

FIG. 1. Correlation between the mean IMF multiplicity $\langle M_{\mathrm{IMF}} \rangle$ and Z_{bound} for Au + C, Au + Al, Au + Cu, and Au + Pb reactions at $E/A = 600$ MeV. The hatched area marks the region which is excluded due to the lower limit of the IMF charge of $Z = 3$. The dashed line is the result of an unconditional Z partition of finite nuclear systems with charges $Z < 40$.

values of the mean fragment velocities may have additional systematic errors of about $\pm 0.004c$ for light fragments with $Z \sim 10$ or projectilelike fragments with $Z \sim 70$ and up to $\pm 0.007c$ for heavy fragments with $Z \sim 40$ (see hatched bars in Fig. 2). Thus, the data indicate little, if any, dependence of $\langle \beta_{\parallel} \rangle$ on the fragment charge.

The bottom part of Fig. 2 shows the ratio between the

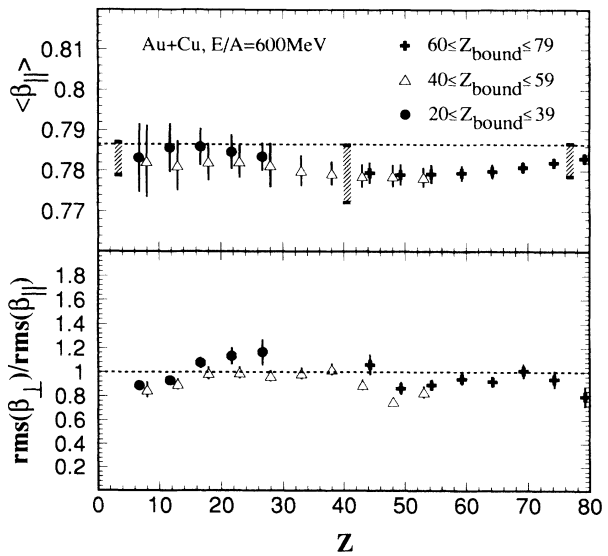

FIG. 2. Mean longitudinal velocity $\langle \beta_{\parallel} \rangle$ (upper part) and ratio of the transverse and longitudinal rms velocity (lower part) as a function of the fragment charge Z. The different symbols correspond to different gates on Z_{bound}. The horizontal line in the upper part marks the beam velocity. The hatched bars indicate systematic errors of $\langle \beta_{\parallel} \rangle$ which are due to uncertainties in the walk corrections of the time-of-flight system (see text for details).

rms deviations of the transverse and longitudinal velocity distributions. The data have been corrected for the beam divergence and multiple scattering broadening. For all event classes and all fragment charges the ratio deviates by less than 20% from unity.

The rather similar mean longitudinal velocities of the different fragments and the almost isotropic velocity distributions are compatible with the assumption of a kinetic equilibrium being accomplished prior to the decay of the primary projectile spectator. It seems, therefore, worthwhile to confront the observed fragment distributions with predictions of statistical models. We will first concentrate on nondynamical descriptions which can be considered as a basis for more elaborate models. In particular, we performed calculations with the sequential evaporation code GEMINI of Charity and co-workers [7] which is based on a transition state theory [8], and the statistical multifragmentation (SMF) models of Bondorf and co-workers (Copenhagen SMF) [9,10] and Gross and co-workers (Berlin SMF) [11] which describe the simultaneous decay of an expanded nuclear system.

Without additional model input the masses, charges, and the excitation energies of the decaying projectile fragments are not known. Therefore, in a first step, excitation functions for a series of nuclei located along the valley of stability were calculated. The excitation energy was varied between 2 and 20 MeV per nucleon. Angular momentum effects were neglected and an initial angular momentum of $J = 0$ was assumed for all calculations. In the case of the GEMINI calculations it has been checked that in account of the rather high excitation energies for an angular momentum of $J = 50\hbar$ the IMF multiplicity increases by approximately 15% (see also Ref. [12]). Ignoring any dynamical correlations between fragments within a given event, the generated Monte Carlo events were filtered by a simple efficiency function depending essentially on the charge Z of the fragment

$$\epsilon(Z) = 1 - \alpha \exp(-Z) \ . \tag{1}$$

For simplicity, the parameter α was kept constant at a value of $\alpha = 2$. A variation of α within the range from 1 to 4, which covers the possible variation of the detection efficiency for projectile fragments in the ALADIN spectrometer [3], affects the mean IMF multiplicity by less than 5%.

The lines in Fig. 3 show representative results of these calculations for primary nuclei $(A_1, Z_1) = (100,40)$, (131,54), and (190,75). For orientation, the squares represent the correlation between Z_{bound} and $\langle M_{\mathrm{IMF}} \rangle$ measured for the Au + Cu reaction. Qualitatively, all calculations exhibit a rise and fall of the IMF multiplicity: At low excitation energies Z_{bound} is close to its maximum value of Z_1 and $\langle M_{\mathrm{IMF}} \rangle$ is small. With increasing excitation energy, $\langle M_{\mathrm{IMF}} \rangle$ is first increasing up to a maximum at an excitation energy of approximately 10 MeV per nucleon and—for even higher excitation energies—again declining. Whereas the Berlin [11] and Copenhagen [10] multifragmentation codes (see center and right parts of Fig. 3) predict rather similar relations between Z_{bound} and $\langle M_{\mathrm{IMF}} \rangle$, the IMF multiplicities deduced from the sequential decay program GEMINI are

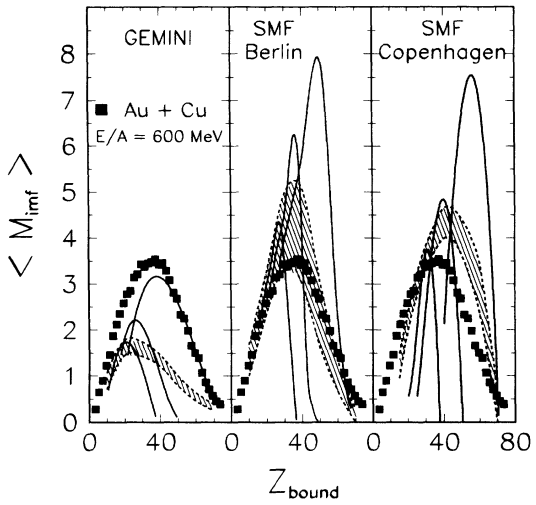

FIG. 3. Comparison of the $\langle M_{\mathrm{IMF}}\rangle$-$Z_{\mathrm{bound}}$ correlation observed for Au + Cu reactions (squares) with predictions of the sequential decay code GEMINI (left part) and of the statistical multifragmentation models of Gross and co-workers (center part) and of Bondorf and co-workers (right part). The lines represent excitation functions for different initial systems $(A_1,Z_1)=(100,40)$, (131,54), and (190,75). The shaded bands are predictions based on initial conditions provided by BUU simulations.

lower by a factor of 2–3. These observations are in line with previous studies at lower beam energies [13,14]. Note that independently of the size of the system the GEMINI calculations slightly underestimate the IMF multiplicity for $Z_{\mathrm{bound}}<30$. This implies that irrespective of the primary size and excitation energy distribution of excited prefragments (see below), this model can only account for the experimental $\langle M_{\mathrm{IMF}}\rangle$-$Z_{\mathrm{bound}}$ correlation for small Z_{bound} if fluctuations are significant.

For high excitation energies, $E_x/A>15$ MeV, the Berlin SMF model and—although less distinct—the GEMINI code predict a nearly proportional relation between Z_{bound} and $\langle M_{\mathrm{IMF}}\rangle$ which only weakly depends on the size of the decaying system. This feature signals a high-temperature regime where—except for varying finite size effects—the relative weights of the different decay channels become rather independent of the excitation energy. As an immediate consequence of this characteristic almost any reasonable smooth distribution of primary fragments having excitation energies larger than 15 MeV per nucleon will show the same correlation between the mean IMF multiplicity and Z_{bound}. The slope of this correlation reflects essentially the inverse of the mean fragment charge averaged over the whole phase space. Obviously the Berlin SMF model reproduces the experimental behavior in the high temperature region rather well. On the other hand, decay calculations with the GEMINI code and the Copenhagen multifragmentation model show notable deviations from the observed $\langle M_{\mathrm{IMF}}\rangle$-$Z_{\mathrm{bound}}$ relation at small Z_{bound} values. The steep decline of the curves toward small $\langle M_{\mathrm{IMF}}\rangle$ at finite Z_{bound} values predicted by the Copenhagen code can be traced back to a relative large number of α particles produced in these calculations. Since those are included in the definition of Z_{bound}, this results—despite a low IMF multiplicity—in relatively large values for Z_{bound}. Finally, it is worth noting that in the high-temperature regime at small Z_{bound} the IMF multiplicity $\langle M_{\mathrm{IMF}}\rangle$ is close to the relation which is expected for an unconditional Z partition [15] of finite nuclei (dashed line in Fig. 1).

We expect for all reactions that the mass of the prefragment decreases when going from peripheral to the most violent reactions. Therefore, the lines in Fig. 3 mark only the possible boundaries for the actual dependence of the IMF multiplicity on Z_{bound}. A more quantitative comparison between the data and the statistical model calculations requires an interpolation between the excitation functions of Fig. 3. Our findings illustrated in Figs. 1 and 2 are consistent with a simple two-step scenario: In a first, fast stage of the reaction the participant nucleons from the target and the projectile interact and remove ΔA nucleons from the (gold) projectile. In a second stage the pre-fragments decay and form the observed particle stable nuclei. Nuclear cascade calculations or geometrical models like the abrasion-ablation model predict that the excitation energy of the prefragment $A_1=A_{\mathrm{proj}}-\Delta A$ is in first order proportional to the number of removed nucleons, i.e.,

$$\langle E_x\rangle=\epsilon\,\Delta A\ . \tag{2}$$

Assuming an abrasion process in the initial step, the removal of a nucleon from the projectile results in an excitation energy of $\epsilon\approx 13$ MeV [16]. Early CASCADE simulations of proton induced reactions [17] predicted an average energy deposition of $\epsilon\sim 40$ MeV by the removal of one nucleon. Recent calculations with the CASCADE code ISABEL gave values for ϵ of about 28 MeV [18].

More realistic descriptions of the primary projectile spectator may be obtained by microscopic calculations solving the Boltzmann-Uehling-Uhlenbeck (BUU) equation. In the present simulations [19] a projectile spectator was defined as all the nucleons within a sphere in coordinate space. The position and size of this sphere was such as to include all projectile nucleons that have yet to undergo a nucleon-nucleon collision. The deposited energy was calculated from the momentum and potential energy of all nucleons within this sphere minus an estimate of the ground-state energy. By 60 fm/c most of the fireball-like nucleons have left the reaction zone. Between 60 and 100 fm/c the deposited energy per nucleon varies by less than 10%. An average deposited energy was calculated during this time interval (60–100 fm/c) for all impact parameters. According to these simulations, ϵ lies between the crude estimates given above and falls from about 28 MeV in peripheral collisions leading to $A_1\approx 180$ down to 12 MeV in more central collisions with $A_1<100$. The density of the spectator is predicted to decrease from about 0.8 times normal nuclear density ρ_0 at large impact parameters $b\approx 8$ fm to less than $0.3\rho_0$ at $b\leq 4$ fm and its angular momentum varies between $20\hbar$ and $30\hbar$.

Since the three statistical models mentioned above assume different initial densities of the decaying systems, impact-parameter-dependent matching conditions, which

are in addition different for the various decay calculations, would be required. For example, for the GEMINI code a rather early coupling to the BUU code seems to be more appropriate. However, in this case there would be still some nucleons from the interaction region within the sphere which defines the projectile spectator and would artificially increase the excitation energy. In the present Rapid Communication, we will for simplicity use for all decay calculations identical matching conditions which are characterized only by the excitation energy and size input parameter. We neglect the varying density (see, however, Ref. [10] and below), the angular momentum and a possible deformation of the prefragments. Furthermore, in all calculations standard parameters were used. Thus, the present investigation cannot provide a unique interpretation of our data. The calculations rather represent well-defined reference points for more detailed future studies.

In order to estimate the $\langle M_{\mathrm{IMF}} \rangle$-$Z_{\mathrm{bound}}$ relation, which is comparable to our experimental observations, we interpolated between the excitation functions calculated for the various initial systems using the primary projectile spectators predicted by the BUU simulations. The result of this interpolation is marked by the shaded areas in Fig. 3. The widths of the bands reflect the differences in the initial conditions for the four targets [20]. Clearly, the GEMINI calculations do not reproduce the experimental data. This code underestimates the IMF multiplicity by about a factor of 2. On the other hand the Copenhagen model slightly overestimates $\langle M_{\mathrm{IMF}} \rangle$ for Z_{bound} between 40 and 60. The best overall description of the observed Z_{bound}-$\langle M_{\mathrm{IMF}} \rangle$ correlation is given by the Berlin calculations.

It remains, of course, questionable whether the idealized conditions assumed in these quasi-static statistical decay calculations are indeed realized directly after the fast reaction stage. Furthermore, it is doubtful whether the dynamics of the fragment formation process itself can be neglected during the decay process [21]. As a first step beyond these static phase space calculations we present in Fig. 4 predictions of the schematic *rapid massive cluster formation* model (RMCF) described in Ref. [22]. This code simulates the statistical decay of an *expanding* nuclear system. The expansion is driven by the thermal pressure and is controlled by the nuclear compressibility. Although the emission of the fragments is treated sequentially, most fragments are emitted within a short time window at rather low densities [22]. Thus these calculations mimic the main effects of a lower initial density in a GEMINI-like evaporation calculation [23].

The left and right parts of Fig. 4 show results for $K = 144$ and 200 MeV, respectively, where K denotes the compressibility constant of a finite nucleus. For a given initial mass and charge the shape of the Z_{bound}-$\langle M_{\mathrm{IMF}} \rangle$ correlation is obviously rather insensitive to K. However, for the two compressibilities shown in Fig. 4, a given point $(Z_{\mathrm{bound}}, \langle M_{\mathrm{IMF}} \rangle)$ corresponds to initial excitation energies which differ significantly. For orientation the circles connected by dashed lines indicate excitation energies of 5, 10, and 15 MeV per nucleon. Due to this sensitivity on the spring constant K the mean IMF multiplicities calculated for the initial conditions determined by the BUU simulations differ by about a factor of 2. Whereas for $K = 144$ MeV the maximum IMF multiplicity is in reasonable agreement with the experimental data, the calculations with the stiffer equation of state—and hence a weaker expansion—results in a maximum multiplicity which is comparable to the GEMINI predictions.

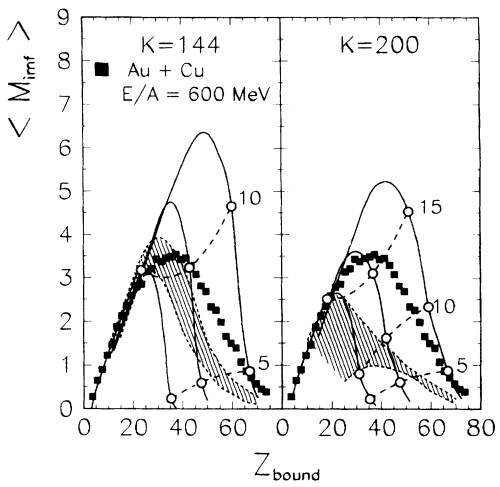

FIG. 4. Comparison of the $\langle M_{\mathrm{IMF}} \rangle$-$Z_{\mathrm{bound}}$ correlation observed for Au + Cu reactions (squares) with predictions of the rapid massive cluster formation model of Friedman using a spring constant of $K = 144$ MeV (left) and $K = 200$ MeV (right). The dashed lines connect points of the same excitation energy per nucleon. The other lines have the same meaning as in Fig. 3.

The apparent success of the statistical multifragmentation models or of the RMCF model using a small spring constant could be taken as evidence for the formation of a nuclear system at low density. However, it is important to realize that the statistical calculations presented in this work disregard fluctuations and correlations which have been generated during the early pre-equilibrium stage of the reaction and which may influence the fragment formation in the decay stage [21,24]. It will, therefore, be interesting to confront the experimental observations with calculations which combine, e.g., quantum molecular dynamics calculations [25] with the various statistical decay models in order to address the question whether these initial—and perhaps nonthermal—correlations are relevant for the fragmentation process. The strong sensitivity of the fragment multiplicity on the expansion dynamics emphasizes the necessity of a complete dynamical treatment of the decay process. In turn, this feature raises the hope that these studies—complemented by more systematic experiments—may lead to a quantitative understanding of the disintegration process.

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[20] This simple interpolation procedure neglects fluctuations due to the extended distribution of the size as well as the excitation energy of the primary projectile spectators. However, it was verified that the Z_{bound}-$\langle M_{\text{IMF}}\rangle$ correlation calculated for a full distribution of initial nuclei lies within the limits of the shaded areas. In a subsequent paper we will investigate this in detail.

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