A systematic study of isotopic effects in the break-up of projectile spectators at relativistic energies has been performed with the ALADiN spectrometer at the GSI laboratory. Searching for signals of criticality in the fragment production we have applied the model-independent universal fluctuations theory already proposed to track criticality signals in multifragmentation to our data. The fluctuation of the largest fragment charge and of the asymmetry of the two and three largest fragments and their bimodal distribution have also been analysed.

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1. INTRODUCTION

One of the most fascinating phenomena in physics is that of a phase transition. Initially observed in macroscopic systems and in electromagnetic interactions, phase transitions have been seen manifesting also in strongly interacting microscopic systems and nowadays two specific areas are receiving a great deal of attention. One involves the loss of stability of excited nuclear systems which, under certain conditions of temperature and density, may lead to the total disassembly of the nucleus into particles and fragments. The second, at much higher energies, concerns the transition from hadrons to quarks and gluons, and the possibility of observing new phenomena in quark matter.

Nucleus-nucleus collisions at intermediate and relativistic energies have been shown [1] to be an ideal tool to produce pieces of finite nuclear matter at extremely different thermodynamical conditions. In order to analyze thermodynamical properties of microscopic systems we need to produce and select samples which can be associated with microcanonical ensembles at high excitation energies.

In a series of experiments [2], multifragment decays of projectile spectators have been studied with the ALADiN forward-spectrometer at the SIS accelerator (GSI-Darmstadt-Germany). In these collisions, energy depositions are reached, which cover the range from particle evaporation to multifragment emission and further to the total disassembly of the system. The most prominent feature of the multifragment decay is the universality of the fragment multiplicities and the fragment charge correlations. The loss of memory of the entrance channel is an indication that equilibrium is attained prior to the fragmentation stage of the reaction. Clearly, new experiments are mandatory for having a better knowledge of the thermodynamics of a finite nucleus and its decay.

Recently a systematic investigation on projectile-spectator fragmentation has been undertaken at the ALADiN spectrometer at the GSI [4]: four different projectiles, $^{197}$Au, $^{124}$La, $^{124}$Sn and $^{107}$Sn, all with an incident energy of 600 AMeV on natSn and $^{197}$Au targets, have been studied.

2. CHARGE CORRELATIONS IN MULTIFRAGMENT DECAY

The fragments emerging from the decay of the projectile spectators are well localized in rapidity. The distributions are concentrated around a rapidity value very close to the beam rapidity and become increasingly narrower with increasing mass of the fragment. The sorting out of the collision according to its centrality is done using the observable $Z_{\text{bound}}$ defined as the sum of the charges of the projectile fragments ($Z > 1$). To first approximation $Z_{\text{bound}}$ is a measure of the charge of the remaining projectile-spectator except for the number of evaporated $Z=1$. It follows that large values of $Z_{\text{bound}}$ correspond to big projectile-spectators, i.e. peripheral collisions, whereas small values of $Z_{\text{bound}}$ correspond to small projectile-spectators, i.e. more central collisions. The excitation of the projectile-spectator depends on the impact parameter, since it occurs via knocking-out nucleons: $Z_{\text{bound}}$ is therefore not only a measure of the impact parameter, but also of the excitation energy.

In the left panel of fig. 1 the charge distributions measured in the fragmentation of $^{124}$Sn for 9 different bins of $Z_{\text{bound}}$ are shown. The shapes of the charge distributions as a function of $Z_{\text{bound}}$ are similar for all the studied systems. We have fitted these charge distributions
with a power-law parameterization $\sigma(Z) \propto Z^{-\tau}$. The fitting range was $3 \leq Z \leq 15$. The right panel of fig. presents the evolution of the $\tau$ parameter as a function of $Z_{\text{bound}}/Z_{\text{proj}}$. The $\tau$ parameter for all the three reactions lies on an almost universal curve and shows a minimum near $Z_{\text{bound}}/Z_{\text{proj}}=0.5$. Specific isotopic effects, even though small, can be nevertheless observed: in particular, the inversion in the hierarchy of the three studied systems by going from small to high values of $Z_{\text{bound}}$ (the values for $^{124}\text{Sn}$ are larger than those for the other two systems in central collisions and become slowly smaller than them by going towards larger impact parameters) has been shown to be related to an isospin dependence of the surface energy as a function of the excitation energy of the system [5].

Since long it has been observed that some characteristics of the exited nuclear-system, such as the largest emitted charge ($Z_{\text{max}}$) and the asymmetry between the three largest-charges $\eta_{\text{asy}} = \frac{(Z_{\text{max}}-(Z_2+Z_3))}{(Z_{\text{max}}+(Z_2+Z_3))}$ vary by going from the evaporation to the vaporization regions through the multifragmentation regime. If the lowly-excited nuclear system evaporates light fragments, large $Z_{\text{max}}$ and $\eta_{\text{asy}}$ are expected, whereas in case of vaporization, both $Z_{\text{max}}$ and $\eta_{\text{asy}}$ are expected to be small. Fig. shows the event distributions in the $Z_{\text{max}}$ and $\eta_{\text{asy}}$ plane for different cuts of $Z_{\text{bound}}$ in the case of the $^{124}\text{Sn}$ projectile. For large values of $Z_{\text{bound}}$, i.e. small excitation energies, the system is in the evaporation regime and therefore almost all the events present high values of $Z_{\text{max}}$ and an $\eta_{\text{asy}}$ value near 1 (lower panels in fig. 2). The distribution of $Z_{\text{max}}$ as well as for $\eta_{\text{asy}}$, is characterized by the presence of a single peak. By going towards smaller values of $Z_{\text{bound}}$, the

Figure 1. Left Panel: Charge distributions obtained in the $^{124}\text{Sn}$ fragmentation for different bin of $Z_{\text{bound}}$. Right Panel: The extracted $\tau$ parameters as a function of $Z_{\text{bound}}$ for $^{124}\text{La}$, $^{124}\text{Sn}$ and $^{107}\text{Sn}$ at 600 AMeV, compared with the values of $^{197}\text{Au}$ at the same energy [6].
event distributions start to populate the region at intermediate $Z_{\text{max}}$ and $\eta_{\text{asy}}$ until, in the multifragmentation region, events with high $Z_{\text{max}}$ and $\eta_{\text{asy}}$ and small $Z_{\text{max}}$ and $\eta_{\text{asy}}$ are simultaneously present (middle panels of fig. 2). This is the region where the two variables exhibit the largest fluctuations and correspondingly a bimodal distribution (central panel in fig. 2). When, finally, $Z_{\text{bound}}$ is small enough, all the events are located in the vaporization zone (upper panels in fig. 2) characterized by simultaneously small values of $Z_{\text{max}}$ and $\eta_{\text{asy}}$. Similar behaviors have been found by analyzing other systems [7]. In particular this analysis has also been extended to projectile-spectator systems studied by the Aladin group in previous experiments [2] in order to explore a wider mass-range: for each system the occurrence of a bimodal distribution for a specific impact parameter has been observed.

Whether such results could be interpreted as a genuine bimodal signal characteristic of a first-order phase transition is still a matter of investigation: indeed the observation of a bimodal distribution in the data could be the result of a mixing of residue and multifragmentation emission for some impact parameter bins.

3. $\Delta$-SCALING IN SPECTATOR FRAGMENTATION

Signals of the predicted phase coexistence at low density and temperature ($\rho < \rho_o$ and $T < T_c$), often associated with multifragmentation, may be revealed by abnormal fluctuations of experimental observables [8]. The theory of the universal character of order parameter fluctuations in finite systems [8] addresses this question in a model-independent framework, for systems with a second-order phase transition. Experimental observables that may be related to an order-parameter can be identified, in particular through their $\Delta$-scaling behavior, and recently a model-independent tracking of criticality signals in nuclear multifragmentation data at intermediate energies has been proposed [9].
The $\Delta$-scaling is observed when two or more probability distributions $P_N[m]$ of the observable $m$ for a system size $N$ collapse onto a single scaling curve $\Phi(z(\Delta))$ independent of system size when plotted in terms of the scaling variables:

$$\langle m \rangle^\Delta P_N[m] = \Phi(z(\Delta)) = \Phi\left(\frac{m - \langle m \rangle^\Delta}{\langle m \rangle^\Delta}\right)$$

(1)

where $\langle m \rangle$ is the mean value of the distribution $P_N[m]$ and $1/2 \leq \Delta \leq 1$. $\langle m \rangle$ plays the role of a scale parameter and can replace $N$ as a measure of the size of the system. The scaling law with $\Delta = 1/2$ is associated with low temperature (ordered systems), or with observables which are not related to an order parameter. Scaling with $\Delta = 1$ is seen at high temperature (disordered system) and also for systems at critical conditions. A necessary condition for $m$ to be an order parameter is that it must exhibit a corresponding change of $\Delta$-scaling regime when some suitable control parameter (e.g. available energy, temperature, etc.) is varied.

Using the data from this experiment, it has been investigated whether the $Z_{\text{max}}$ distributions follow the $\Delta$-scaling law. The multiplicity of charged particles measured with the Catania Hodoscope [10] was used as impact parameter selector in order to avoid a possible autocorrelation of $Z_{\text{bound}}$ with $Z_{\text{max}}$. An additional selection has, moreover, been applied to the data by defining two cuts on the asymmetry variable: $\eta_{\text{asy}} > 0.5$ and $\eta_{\text{asy}} < 0.3$ corresponding to the liquid and gas phases respectively. The correlation between the mean value and the fluctuation of $Z_{\text{max}}$ is shown in fig. 3. The dotted lines represent results of the fits providing $\Delta \approx 1$ for high excitation energy (left-hand side of fig. 3) and $\Delta \approx 0.5$ for low excitation energy (right-hand side of fig. 3). The form of the $Z_{\text{max}}$ distributions also evolves with excitation energy: it is nearly Gaussian in the $\Delta = 1/2$ regime (right panel of fig. 4) beside for $\Delta = 1$ the shape is asymmetric with a near-exponential tail for large positive values of the scaling variable, $z(\Delta)$ (left panel of fig. 4): this distribution approaches that of the modified Gumbel-distribution [9].

Interestingly enough the transition from the ordered to the disordered regimes is observed...
Figure 4. Left panel: $Z_{\text{max}}$ distributions for $^{124}$Sn projectile spectator, scaled using $\Delta=1$. Right panel: $\Delta$ distributions for the same system scaled using $\Delta=0.5$. The various symbols refer to different cuts in the hodoscope multiplicity.

for the same impact parameter bin, for which the appearance of a bimodal distribution has been observed (see fig. 2). Similar results have been obtained in the study of the quasi-projectile decay at lower energies \[7\]. The interpretation of the $\Delta$-scaling result is still an open question. The two $\Delta$-scaling regimes seem to suggest that $Z_{\text{max}}$ is behaving like the order-parameter of a second-order phase transition. Moreover, other analyses of similar data have found evidence for multifragmentation being a first-order phase transition, through signals of liquid-gas coexistence in the form, for example, of a flattening of the caloric curve \[11\]. This apparent contradiction could be understood as a finite-size effect \[12\]. The fact that many reactions exhibit a universal behavior, dependent only on the available energy, can again be an indication of a microcanonical equilibrium.

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