The N/Z dependence of projectile fragmentation at relativistic energies has been studied in a recent experiment at the GSI laboratory with the ALADiN forward spectrometer coupled to the LAND neutron detector. Besides a primary beam of $^{124}$Sn, also secondary beams of $^{124}$La and $^{107}$Sn delivered by the FRS fragment separator have been used in order to extend the range of isotopic compositions of the produced spectator sources. With the achieved mass resolution of $\Delta A/A \approx 1.5\%$, lighter isotopes with atomic numbers $Z \leq 10$ are individually resolved. The presently ongoing analyses of the measured isotope yields focus on isoscaling and its relation to the properties of hot fragments at freeze-out and on the derivation of chemical freeze-out temperatures which are found to be independent of the isotopic composition of the studied systems. The latter result is at variance with the predictions for limiting temperatures as obtained with finite-temperature Hartree-Fock calculations.

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1. Introduction

The present interest in isotopic effects in nuclear multifragmentation is partly motivated by the importance of the nuclear equation of state for astrophysical processes. Supernova simulations or neutron star models require inputs for the nuclear equation of state at extreme values of density and asymmetry for which the predictions differ widely.\(^1\text{--}^5\) Fragmentation reactions are of interest here because they permit the production of nuclear systems with subnuclear densities and temperatures which, e.g., largely overlap with those expected for the explosion stages of core-collapse supernovae.\(^6\) Laboratory studies of the properties of nuclear matter in the hot environment, similar to the astrophysical situation, are thus becoming feasible, and an active search for suitable observables is presently underway. Of particular interest is the density-dependent strength of the symmetry term which is essential for the description of neutron-rich objects up to the extremes encountered in neutron stars (refs.\(^3\text{--}^9\) and contributions to this workshop).

Here, new results from a recent experiment performed with the ALADIN spectrometer at the GSI laboratory will be discussed in which the possibility of using secondary beams for reaction studies at relativistic energies has been explored. Beams of \(^{107}\text{Sn},\) \(^{124}\text{Sn},\) \(^{124}\text{La},\) and \(^{197}\text{Au}\) as well as \(^{\text{Sn}}\) and \(^{\text{Au}}\) targets were used to investigate the mass and isospin dependence of projectile fragmentation at 600 MeV per nucleon. The neutron-poor radioactive projectiles \(^{107}\text{Sn}\) and \(^{124}\text{La}\) were produced at the Fragment Separator FRS by fragmentation of a primary beam of \(^{142}\text{Nd}\) and delivered to the ALADIN experiment.

The results presented in the following, after a brief discussion of global observables, will be restricted to quantities deduced from the measured yields of resolved isotopes. They will, in particular, include isoscaling and its relation to the properties of hot fragments at the low-density freeze-out, as well as chemical temperatures deduced from double ratios of isotopic yields and the consequences for the limiting-temperature concept in multifragmentation. Preliminary results from the present experiments have been presented previously.\(^10\text{--}^12\)

2. N/Z dependence of global fragmentation observables

The dependence on the isotopic composition of the system is rather small for global observables of the studied reactions. This is shown in Fig. 1 for the multiplicity of the produced intermediate-mass fragments and for \(Z_{\text{max}}\) as a function of \(Z_{\text{bound}}.\) Here \(Z_{\text{max}}\) denotes the largest atomic number \(Z\) within a partition while the sorting variable \(Z_{\text{bound}} = \sum Z_i\) with \(Z_i \geq 2\) is related to the impact parameter and inversely correlated with the degree of excitation of the produced spectator system. The multiplicities exhibit the universal rise and fall of fragment production\(^13\) (Fig. 1, left panel), and only a slightly steeper slope in the rise section distinguishes the neutron-rich case of \(^{124}\text{Sn}\) from the other two systems. As confirmed by statistical model calculations, this difference is related to the evaporation properties of excited heavy nuclei.\(^10\) Neutron emission prevails for neutron-rich nuclei which leads to a
Fig. 1. Mean multiplicity $<M_{IMF}>$ of intermediate-mass fragments $3 \leq Z \leq 20$ produced in the fragmentation of $^{107,124}$Sn and $^{124}$La at 600 A MeV as a function of $Z_{\text{bound}}$ (left panel). The right panel shows the correlations of the mean $Z$ of the largest fragment with $Z_{\text{bound}}$ with both quantities being normalized with respect to the projectile $Z$.

concentration of the residue channels, with small associated fragment multiplicities, in a somewhat narrower range of large $Z_{\text{bound}}$ than in the case of the neutron-poor systems. The evaporation of protons reduces $Z_{\text{bound}}$ since protons are not counted therein.

This effect is, nevertheless, small and nearly invisible in the correlation of $<Z_{\text{max}}> \text{ with } Z_{\text{bound}}$ (Fig. 1 right panel). There, the transition from predominantly residue production to multifragmentation becomes apparent as a reduction of $<Z_{\text{max}}> \text{ with respect to } Z_{\text{bound}}$ which occurs between $Z_{\text{bound}}/Z_{\text{proj}} = 0.6$ and 0.8. The range of isotopic compositions of the studied nuclei $N/Z = 1.14$ to 1.48 is not large enough for significant variations of the reaction mechanism to appear. A shrinking of the coexistence zone in the temperature-density plane is predicted for neutron-rich matter but observable consequences can only be expected for asymmetries far beyond those presently available for laboratory studies.\textsuperscript{14,15} This fact, on the other hand, has the important consequence that the basic reaction process is the same for all the present systems, a prerequisite for the interpretation of isoscaling and its relation with the symmetry energy. This point will be further quantified in the section on temperatures.

3. $N/Z$ dependence of light fragment production

The mass resolution obtained for projectile fragments entering into the acceptance of the ALADIN spectrometer is about 3\% for fragments with $Z \leq 3$ and decreases to 1.5\% for $Z \geq 6$. Masses are thus individually resolved for fragments with atomic number $Z \leq 10$. The elements are resolved over the full range of atomic numbers up to the projectile $Z$ with a resolution of $\Delta Z \leq 0.2$ obtained with the TP-MUSIC IV detector.\textsuperscript{10}
Fig. 2. Inclusive mean values $<N>/Z$ of light fragments with $3 \leq Z \leq 9$ produced in the fragmentation of $^{107,124}\text{Sn}$ (600 A MeV, ALADIN), $^{56}\text{Fe}$ and $^{238}\text{U}$ (both 1 A GeV, FRS, from refs. [16,18]) as a function of the fragment $Z$ (left panel). The right panel shows the results for $Z = 8$ as a function of the $N/Z$ value of the projectile. The lines represent the trend of the data (full line) and $<N>/Z = (N/Z)_{\text{proj}}$ (dashed).

The inclusive mean neutron-to-proton ratio $<N>/Z$ of light fragments in the range $3 \leq Z \leq 9$ is presented in Fig. 2. The values for $Z = 4$ have been corrected for the missing yield of unstable $^8\text{Be}$ by including an estimate for it obtained from a smooth interpolation over the identified yields of $^7,^9\text{Be}$-$^11\text{Be}$. This correction has a negligible effect for the case of $^{107}\text{Sn}$ because $<N>/Z$ of the detected beryllium isotopes is close to 1 already. For $^{124}\text{Sn}$ the value of $<N>/Z$ for $Z = 4$ is lowered from 1.24 to 1.18 which makes the systematic odd-even variation more clearly visible in the neutron rich case. The odd-even staggering is, however, much more pronounced in the case of the neutron-poor $^{107}\text{Sn}$. The strongly bound even-even nuclei attract a large fraction of the product yields during the secondary evaporation stage. This effect is, apparently, larger if the hot fragments are already close to symmetry, as it is expected for the fragmentation of $^{107}\text{Sn}$.

Inclusive data [16,18] obtained with the FRS fragment separator at GSI for $^{238}\text{U}$ and $^{56}\text{Fe}$ fragmentations on titanium targets at 1 A GeV bombarding energy confirm that the observed patterns are very systematic (Fig. 2 left panel). Nuclear structure effects characteristic for the isotopes produced combine with significant memory effects of the isotopic composition of the excited system by which they are emitted. This has the consequence that, because of its strong variation with $Z$, averaged neutron-to-proton ratios $<N>/Z$ for unspecified ranges of $Z$ are not very useful for studying nuclear matter properties. For this purpose, techniques will have to be used which cause the nuclear structure effects to cancel out. Selecting a particular element, e.g. $Z = 8$, is already sufficient to reveal the linear correlation of $<N>/Z$ with the $N/Z$ of the projectile (Fig. 2 right panel). According to the Statistical Fragmentation Model (SMM [19]), the correlation should be much stronger for the excited fragments at the breakup stage and, in fact, not deviate much from the
dashed $<N>/Z = (N/Z)_{\text{proj}}$ line in the figure. The reduction is due to sequential decay and its tendency of directing the isotope distributions closer to the valley of stability. For a quantitative analysis, a precise modeling of these secondary processes will, therefore, be required.

Fig. 3. Scaled isotopic ratios $S(N)$ for Li to O isotopes from the fragmentation of $^{124}\text{Sn}$ and $^{107}\text{Sn}$ projectiles at $600\text{ A}\text{MeV}$ (ALADIN, left panel) and for H to B isotopes from $^{12}\text{C} + ^{112,124}\text{Sn}$ at $E/A = 300$ and $600\text{ MeV}$ (INDRA, right panel, from ref. 25) as a function of the neutron number $N$. The centrality selection was obtained with $Z_{\text{bound}}$ (ALADIN, left panel, five bins as indicated) and according to charged particle multiplicity as measured with the full detector (INDRA, right panel, three bins with “central” indicating $b/b_{\text{max}} \leq 0.4$). The dashed lines in both panels are the results of exponential fits according to Eq. (1). Only statistical errors are displayed; note also the offset factors of multiples of three in the right panel.

4. Isoscaling

The phenomenon of isoscaling has been shown to be common to many different types of heavy-ion reactions.20–23 It is observed by comparing product yields $Y_i$ from reactions which differ only in the isotopic composition of the projectiles or targets or both. Isoscaling refers to an exponential dependence of the measured yield ratios $R_{21}(N, Z)$ on the neutron number $N$ and proton number $Z$ of the detected products. The scaling expression

$$R_{21}(N, Z) = Y_2(N, Z)/Y_1(N, Z) = C \cdot \exp(\alpha N + \beta Z)$$

(1)
describes rather well the measured ratios over a wide range of complex particles and light fragments.24 The accuracy with which the isoscaling relation is
obeyed is conveniently judged by regarding the scaled isotopic ratios $S(N) = R_{21}(N, Z)/\exp(\beta Z)$, obtained by dividing out the common $Z$ dependence after fitting according to eq. (1). Isoscaling means that all the scaled yield ratios will follow the same exponential dependence on the neutron number $N$. The results for the pair of reactions with $^{124}$Sn and $^{107}$Sn projectiles, sorted into five bins of $Z_{\text{bound}}$ are shown in Fig. 3, left panel. Alternatively, one may also regard the behavior of the exponential slopes $\alpha(Z)$ of the yield ratios for individual elements or $\beta(N)$ for individual chains of isotones. As demonstrated in Fig. 4 for the inclusive yields from the same pair of reactions, the deviations from the common mean value are impressively small. Besides the precision with which isoscaling is observed in the range of fragments from Li to Ne, also the monotonic decrease of the slope of $S(N)$ with centrality represents a remarkable observation. Qualitatively, it resembles that observed for the reactions $^{12}$C + $^{112,124}$Sn at 300 and 600 MeV per nucleon, studied with INDRA at GSI (ref.\cite{25}, right panels of Fig. 3).

The statistical model offers a simple physical explanation for the appearance of isoscaling in finite systems. Charge distributions of fragments with fixed mass numbers $A$, as well as mass distributions for fixed $Z$, are approximately Gaussian with average values and variances which are connected with the temperature, the symmetry-term coefficient, and other parameters. (Here the symmetry-energy term, $E_{\text{sym}} = \gamma(A - 2Z)^2/A$ with the coefficient $\gamma$, is that of the liquid-drop description of the nascent fragments at freeze-out and $\gamma = 25$ MeV is normally used\cite{19}) The mean values of the fragment distributions depend on the total mass and charge of the systems, e.g. via the chemical potentials in the grand-canonical approximation, while the variances depend mainly on the physical conditions reached, the temper-
nature, the density and possibly other variables. For example, the charge variance \( \sigma_Z \approx \sqrt{AT/8\gamma} \) obtained for fragments with a given mass number \( A \) is only a function of the temperature and of the symmetry-term coefficient since the Coulomb contribution is very small. This relation of isoscaling with the symmetry energy has attracted considerable interest recently [21, 22, 25, 27, 28]. In the grand-canonical approximation, assuming that the temperature \( T \) is about the same (see below), the scaling parameters \( \alpha \) and \( \beta \) are given by the differences of the neutron and proton chemical potentials for the two systems divided by the temperature, \( \alpha = \Delta \mu_n/T \) and \( \beta = \Delta \mu_p/T \). The proportionality of \( \Delta \mu_n \) and thus of the isoscaling parameters with the coefficient \( \gamma \) of the symmetry-energy term has been obtained from the statistical interpretation of isoscaling within the SMM [21] and Expanding-Emitting-Source Model [24] and confirmed by an analysis of reaction dynamics [27]. The relation is

\[
\Delta \mu_n = \mu_{n,2} - \mu_{n,1} \approx 4\gamma \left( \frac{Z_1^2}{A_1^2} - \frac{Z_2^2}{A_2^2} \right) = 4\gamma \Delta (Z^2/A^2) \tag{2}
\]

where \( Z_1, A_1 \) and \( Z_2, A_2 \) are the charges and mass numbers of the neutron-poor and neutron-rich systems, respectively, at breakup. The difference of the chemical potentials depends essentially only on the coefficient \( \gamma \) of the symmetry term and on the isotopic compositions. A proportionality of \( \alpha \) and \( 1/T \), with \( T \) derived from double isotope ratios, has been observed for light-ion (p, d, \( \alpha \)) induced reactions at bombarding energies in the GeV range [21]. Also the symmetry-term coefficient \( \gamma \approx 22.5 \) MeV, deduced according to eq. (2), supported the statistical approach. These data were inclusive and a value close to the standard value was to be expected because the fragment multiplicities are small in this case [29].

The present reactions studied with ALADIN cover the full rise and fall of fragment production while the \( ^{12}\text{C} \) induced reactions studied with INDRA cover mainly the rise up to \( Z_{\text{bound}} \approx Z_{\text{proj}}/2 \) with multiple fragment production being dominant in central collisions [13]. In both cases, the measured temperatures rise slightly with increasing centrality but not sufficiently fast in order to compensate for the decrease of the isoscaling parameter \( \alpha \). The product \( \Delta \mu_n = \alpha \cdot T \), therefore, decreases. With the assumption that the isotopic compositions remain close to those of the original \( ^{112,124}\text{Sn} \) targets, the evolution of the apparent symmetry-term coefficient \( \gamma_{\text{app}} \), i.e. without corrections for the effects of sequential decay, was followed into the regime of multifragmentation with the \( ^{12}\text{C} \) induced data measured with INDRA [25]. It was again found to be close to the normal-density coefficient \( \gamma \approx 25 \) MeV for peripheral collisions, associated with small fragment multiplicities, but dropped to lower values of 15 to 17 MeV for the central impact parameters leading to multifragmentation. This result is confirmed by the preliminary analysis of the new data for projectile fragmentation measured with ALADIN. The product \( \alpha \cdot T \) drops by about 20% through the rise of fragment production but then remains fairly constant once the regime of multifragmentation has been reached \( (Z_{\text{bound}}/Z_{\text{proj}} \leq 0.5) \).
5. \(N/Z\) dependence of the nuclear caloric curve

Two examples of double-isotope temperatures deduced from the measured isotope yields are shown in Fig. 5 as a function of \(Z_{\text{bound}}\). Besides the frequently used \(T_{\text{HeLi}}\) (left panel), determined from \(^3\)He and \(^6\)Li yields also the results for \(T_{\text{BeLi}}\) are displayed (right panel). For \(T_{\text{BeLi}}\) the isotope pairs of \(^7\)Be and \(^6\)Li are used which each differ by two neutrons. The double difference of their binding energies amounts to 11.3 MeV and is nearly as large as the 13.3 MeV in the \(T_{\text{HeLi}}\) case. The apparent temperatures are displayed, i.e. no corrections for secondary decays feeding the ground states of these nuclei are applied.

Both temperature observables show the same smooth rise with increasing centrality that was observed earlier in a study of \(^{197}\)Au fragmentations.\(^{30}\) According to \(T_{\text{BeLi}}\), the temperatures at the chemical freeze-out are identical for all three reaction systems and have the same dependence on \(Z_{\text{bound}}\). This is not equally visible in \(T_{\text{HeLi}}\) which exhibits slightly larger values for the neutron rich case of \(^{124}\)Sn. Inspection of the single isotope ratios shows, however, that the \(^3\)He ratio represents an exception in that it varies much less than the other ratios with the neutron-richness of the system. A possible explanation is offered by the observations shown in Fig. 2. The strong population of even-\(N\)-even-\(Z\) nuclei, evident from the behavior of \(<N>/Z\), suggests that also \(^4\)He nuclei are abundantly produced. The effect is stronger in the neutron-poor cases for which the apparent \(T_{\text{HeLi}}\) will be accordingly lower. Taking this nuclear-structure effect into account is likely to reduce the differences between systems also for this thermometer.

The observed invariance of the breakup temperature with the isotopic composition of the system is of interest because it is opposite to what is expected according
to the finite-temperature Hartree-Fock calculations of Besprosvany and Levit. The limiting temperatures obtained for the stability of excited nuclei are strongly dependent on the Coulomb pressure generated by the protons they contain. Along isobars, the limiting temperatures decrease rapidly toward the proton rich side and, along the valley of stability, they decrease with increasing mass because the effect of the increasing $Z$ dominates over that of the decreasing $Z/A$. For the nuclei studied here, a difference of about 2 MeV is predicted between the limiting temperature of $^{124}$Sn and those for the proton rich $^{107}$Sn and $^{124}$La or for the heavier $^{197}$Au. A difference of this magnitude is clearly not seen in the data (Fig. 5). Neither does a comparison with the apparent temperatures measured for $^{197}$Au fragmentations (Fig. 7 in ref. 30) provide evidence for the predicted mass dependence. The temperatures are the same, within errors, when regarded as a function of the scaled quantity $Z_{\text{bound}}/Z_{\text{proj}}$. This, however, is suggested by the $Z_{\text{bound}}$ scaling of fragmentation observables if a comparison of sources of different mass but equal excitation is intended to be made.

6. Discussion

It is one of the basic assumptions of isotopic reaction studies that the mechanism as such remains unchanged and that effects related to the asymmetry dependence of the nuclear forces can be isolated by changing nothing but the isotopic composition of the system. This view is supported by the observed invariance of the chemical breakup temperatures, here for the case of spectator fragmentation. The interpretation of the breakup temperatures as a manifestation of the limiting temperatures predicted by the Hartree-Fock model, on the other hand, is not equally supported. This interpretation was derived from the $Z_{\text{bound}}$ dependence of the temperature which suggested a mass dependence because of the changing mass of the spectator system. Later on, the predicted mass dependence was found to be confirmed in a compilation of chemical break-up temperatures from several experiments including the earlier ALADIN data, which led to their use as a general reference for testing predictions of nuclear stability with respect to temperature (see ref. 31 for references). The new data for the $A \approx 120$ region and their comparison with $^{197}$Au fragmentations suggest that the observed variation with decreasing $Z_{\text{bound}}$ is more related to the increasing excitation energy than to the decreasing mass of the produced spectator system. Breakup temperatures fairly independent of the isotopic composition or mass of the system are, e.g., predicted by the statistical fragmentation models which are based on the concept of a phase-space driven instability.

The discussion of the isoscaling results has focussed on mainly three topics, among them primarily the effects of sequential decay for the isoscaling parameters and for the symmetry term, as well as the role of the surface term in the symmetry energy. Surface terms gain in importance as the mean mass of the produced fragments decreases in multi-fragment decays. Thirdly, also a possible modification of the source $N/Z$ due to preequilibrium emissions prior to breakup will affect and
most probably reduce the isoscaling parameters. So far, however, none of these mechanisms has been identified as providing an obvious explanation for the large drop that is observed. Calculations with the microcanonical Markov-chain version of the SMM even show that sequential decay will cause the isoscaling coefficients to increase if the symmetry term governing the mass distributions of the hot fragments is reduced. Transport models predict that the isotopic composition at breakup should not deviate by more than a few percent from the original value. New experimental results, furthermore, indicate that the isotopic dependence of the surface term is reduced, with respect to that needed to describe ground-state masses, as the excitation of the system increases. This is also expected theoretically.

A decrease of the isoscaling parameter $\alpha$ with increasing violence of the collision, beyond that expected from the simultaneous increase of the temperature, has also been observed for reactions at intermediate energy (refs. 28, 39, and references therein) and a systematics is emerging. A very recent interpretation of these results arrives at the conclusion that the reduced density, rather than the elevated temperature, causes the symmetry term to be smaller than the standard value. This analysis uses a temperature independent potential part of the symmetry term and a kinetic part in the form of a Fermi gas, and it is argued that the isoscaling phenomenon itself is evidence for the fact that properties of the considered homogeneous nuclear matter are observable in fragmentation reactions.

In the Statistical Multifragmentation Model normal-density fragments statistically distributed within an expanded volume are considered. Here a reduction of the symmetry term in their liquid-drop description can be imagined to be caused by fragment modifications in the hot environment, including deformations or the effects of nuclear interactions between them. The neglect of such effects in the actual codes should probably be regarded as an idealization as the assumption of equilibrium at the final freeze-out stage requires nuclear interactions in order to achieve it. The consequences of a reduced symmetry term for predicted global fragment observables, as e.g., multiplicity, are rather small for this class of models. The partitioning is predominantly driven by the surface term in the fragment description while a variation of the symmetry term affects mainly the isotopic distributions.

Further studies will be needed in order to put some of the assumptions on a firmer basis and to quantitatively establish the reduction of the symmetry term in multi-fragment breakups. The sequential decay corrections are obviously important but also the evolution of the isotopic compositions during the reaction process deserves attention. It will have to be explored whether an experimental reconstruction of the neutron-to-proton ratio of the detected spectator systems will be feasible using the coincident neutron data measured with the LAND detector.

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