



Isotopic Dependence of the Nuclear Caloric Curve

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The A/Z dependence of projectile fragmentation at relativistic energies has been studied with the ALADIN forward spectrometer at SIS. A stable beam of ^{124}Sn and radioactive beams of ^{124}La and ^{107}Sn at 600 MeV per nucleon have been used in order to explore a wide range of isotopic compositions. Chemical freeze-out temperatures are found to be nearly invariant with respect to the A/Z of the produced spectator sources, consistent with predictions for expanded systems. Small Coulomb effects ($\Delta T \approx 0.6$ MeV) appear for residue production near the onset of multifragmentation.

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The isotopic dependence of the nuclear caloric curve, the temperature-energy relation of excited nuclear systems [1,2], is of interest for several reasons. It is, at first, of practical importance for isotopic reaction studies, presently conducted in many laboratories and conceived under the assumption that the basic reaction processes remain unchanged if only the isotopic composition of the collision partners is varied. One expects that specific effects related to the isotopic dependence of the nuclear forces can be isolated in this way [3,4]. For example, in the statistical interpretation of isoscaling, analytic relations between the measured parameters and the symmetry term in the equation of state can be derived if the freeze-out temperatures can be assumed to be identical for the reactions one compares [3,5]. A significant isotopic dependence of the caloric curve would here present a complication.

From a theoretical point of view, the isotopic behavior of the caloric curve is useful for investigating its connection with limiting temperatures, i.e., the maximum temperatures nuclei can sustain before they become unbound [6,7]. These limiting temperatures have been found to be

correlated with the critical temperature of nuclear matter, in fact nearly linearly in mean-field calculations with Skyrme forces [8]. Experimental information on limiting temperatures will thus permit tests of microscopic calculations of the nuclear equation of state at finite temperature which cannot be easily obtained by other means [9,10].

In the calculations considering excited compound nuclei in equilibrium with their surrounding vapor, their stability was found to be strongly dependent on the Coulomb pressure generated by the protons they contain [6,7]. The limiting temperatures decrease along the valley of β stability because the effect of the increasing atomic number Z is stronger than that of the decreasing charge-to-mass ratio Z/A of heavy nuclei. A systematic mass dependence of measured breakup temperatures in multifragmentation reactions has, therefore, led to the suggestion that they may be identified with the predicted stability limits [11,12]. In this case, since Coulomb effects should be even more pronounced along chains of isotopes or isobars, one would expect a significant isotopic dependence of the caloric curve [2].

On the other hand, statistical models for multifragmentation, based on calculating the accessible phase space in expanded volumes [13,14], predict only small temperature differences for neutron-rich and neutron-poor systems [15]. To some extent, the isotopic behavior of the caloric curve thus turns into a test of the reaction mechanism, indicating whether the observed disintegrations are primarily caused by a Coulomb instability limiting the existence of compound nuclei or by the opening of the partition space.

Experiment S254, conducted at the SIS heavy-ion synchrotron at GSI Darmstadt, was devoted to the study of isotopic effects in projectile fragmentation at relativistic energies. Besides stable ^{124}Sn beams, neutron-poor secondary Sn and La beams were used in order to extend the range of isotopic compositions beyond that available with stable beams alone. The radioactive beams were produced at the fragment separator FRS [16] by fragmenting primary ^{142}Nd projectiles with energies near 900 MeV/nucleon in a thick beryllium target. The FRS was set to select ^{124}La and, subsequently, ^{107}Sn projectiles which were directed onto $^{\text{nat}}\text{Sn}$ targets of 500 mg/cm² areal density at the ALADIN setup. All three beams had a laboratory energy of 600 MeV/nucleon. At this energy, the acceptance of the ALADIN forward spectrometer is about 90% for projectile fragments with $Z = 3$, increases with Z , and exceeds 95% for $Z \geq 6$ [17].

In order to reach the necessary beam intensity of about 10^3 particles/s with the smallest possible mass-to-charge ratio A/Z , it was found necessary to accept a distribution of neighboring nuclides together with the requested ^{124}La or ^{107}Sn isotopes. The mean compositions of the nominal ^{124}La (^{107}Sn) beams were $\langle Z \rangle = 56.8$ (49.7) and $\langle A/Z \rangle = 2.19$ (2.16), respectively [18]. Model studies confirm that these $\langle A/Z \rangle$ values are also representative for the spectator systems emerging after the initial stages of the reaction [5,19].

The obtained mass resolution is about 7% (FWHM) for projectile fragments with $Z \leq 3$ and decreases to 3% for $Z \geq 6$. Masses are thus individually resolved for fragments with atomic number $Z \leq 10$. The elements are individually resolved over the full range of atomic numbers up to Z_{proj} with the resolution $\Delta Z \leq 0.6$ (FWHM) obtained with the TP-MUSIC IV detector [17].

Global fragmentation observables were found to depend only weakly on the isotopic composition. This is shown in Fig. 1 for the mean multiplicity of intermediate-mass fragments ($3 \leq Z \leq 20$) and for Z_{max} , both as a function of Z_{bound} . Here Z_{max} denotes the largest atomic number Z within a partition while the sorting variable $Z_{\text{bound}} = \sum Z_i$ with $Z_i \geq 2$ represents the Z of the spectator system, apart from emitted hydrogens.

The multiplicities exhibit the universal rise and fall of fragment production [17], and only a slightly steeper slope in the rise section ($Z_{\text{bound}} > 25$) distinguishes the neutron-

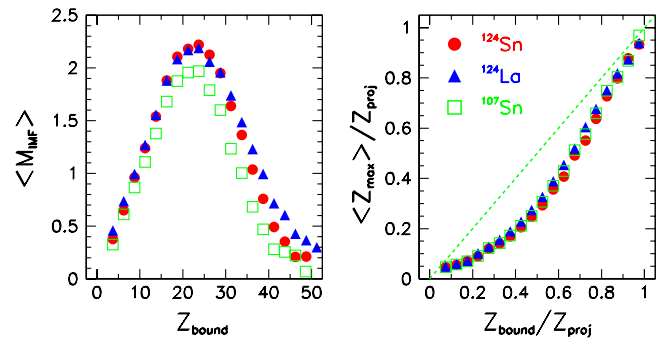


FIG. 1 (color online). Acceptance corrected mean multiplicity $\langle M_{\text{IMF}} \rangle$ of projectile fragments for ^{124}Sn (circles), ^{124}La (triangles), and ^{107}Sn (open squares) beams of 600 A MeV on $^{\text{nat}}\text{Sn}$ targets as a function of Z_{bound} (left panel) and correlations of $\langle Z_{\text{max}} \rangle$ with Z_{bound} (both normalized with respect to the atomic number Z_{proj} of the projectile, right panel).

rich ^{124}Sn from the two other cases. The difference can be related to the evaporation properties of excited heavy nuclei [20]. Neutron emission as the prevailing deexcitation mode of neutron-rich residue nuclei does not affect Z_{bound} . The emission of hydrogen isotopes reduces Z_{bound} since they are not counted therein. The same effect produces small differences in the correlation of $\langle Z_{\text{max}} \rangle$ with Z_{bound} (Fig. 1, right panel). There, the transition from predominantly residue production to multifragmentation appears as a reduction of $\langle Z_{\text{max}} \rangle$ with respect to Z_{bound} which occurs between $Z_{\text{bound}}/Z_{\text{proj}} = 0.6$ and 0.8.

The mean neutron-to-proton ratios $\langle N \rangle / Z$ of light fragments exhibit nuclear structure effects characteristic for the isotopes produced as well as a significant memory of the isotopic composition of the emitting system (Fig. 2). The mean neutron numbers are larger for the fragments of ^{124}Sn by, on average, $\Delta N = 0.4$. The values for $Z = 4$ have been corrected for the missing yields of unstable ^8Be fragments

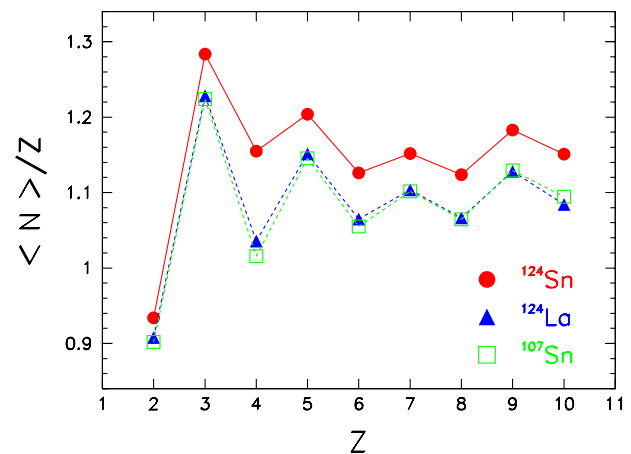


FIG. 2 (color online). Mean neutron-to-proton ratios $\langle N \rangle / Z$ of light fragments up to $Z = 10$ for $0.2 < Z_{\text{bound}} / Z_{\text{proj}} \leq 0.4$ as a function of the fragment Z .

by smoothly interpolating over the measured yields of $^{7,9-11}\text{Be}$. This has a negligible effect for ^{124}La and ^{107}Sn with $\langle N \rangle/Z \approx 1$ but lowers the value for ^{124}Sn from 1.23 to 1.16 which makes the systematic odd-even variations as a function of the fragment Z more clearly visible. Apparently, the strongly bound even-even $N = Z$ nuclei attract a large fraction of the product yields [21].

Two temperature observables, deduced from the resolved isotope yields, are shown in Fig. 3 as a function of the normalized Z_{bound} . Besides the frequently used

$$T_{\text{HeLi}} = 13.3 \text{ MeV} / \ln\left(2.2 \frac{Y_{6\text{Li}}/Y_{7\text{Li}}}{Y_{3\text{He}}/Y_{4\text{He}}}\right) \quad (1)$$

(left panel, Ref. [1]), also

$$T_{\text{BeLi}} = 11.3 \text{ MeV} / \ln\left(1.8 \frac{Y_{9\text{Be}}/Y_{8\text{Li}}}{Y_{7\text{Be}}/Y_{6\text{Li}}}\right) \quad (2)$$

deduced from Li and Be fragment yields is displayed (right panel, Ref. [22]). The apparent temperatures, as given by the formulas, are shown, i.e., without corrections for secondary decays feeding the ground states of these nuclei. Including such corrections will raise the temperature values by 10 to 20% [1,22]. The dependence of the secondary-decay corrections on A/Z has been quantitatively studied with two models, the SMM [14] and the quantum statistical model of Hahn and Stöcker [23] but significant effects (>300 keV) were not found.

Both temperature observables show the same smooth rise with increasing centrality that is familiar from earlier studies of ^{197}Au fragmentations [22,24]. The dependence on the isotopic composition is rather weak. The mean temperature differences between the neutron-rich and neutron-poor systems amount to $\Delta T_{\text{HeLi}} = 0.5 \pm 0.1$ MeV and $\Delta T_{\text{BeLi}} = 0.1 \pm 0.1$ MeV in the bin of maximum fragment production, $Z_{\text{bound}}/Z_{\text{proj}} \approx 0.5$, and become

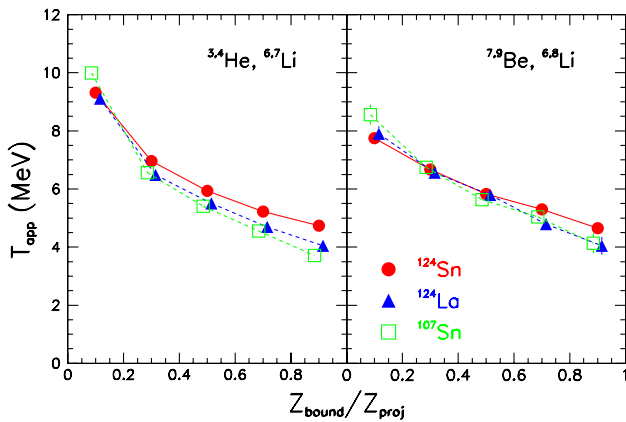


FIG. 3 (color online). Apparent temperatures T_{HeLi} (left panel) and T_{BeLi} (right panel) as a function of $Z_{\text{bound}}/Z_{\text{proj}}$ for the three reaction systems. For clarity, two of the three data sets are slightly shifted horizontally, only statistical errors are displayed.

negligible at smaller Z_{bound} . This translates into a similar invariance for the nuclear caloric curve as Z_{bound} may serve as a measure of the deposited energy E_x . The latter is expected on the basis of the participant-spectator geometry but also confirmed by the observation that the degree of fragmentation, known to depend on E_x [25], is strongly related to Z_{bound} (Fig. 1). At larger Z_{bound} , in the regime of predominantly residue production ($Z_{\text{bound}}/Z_{\text{proj}} \approx 0.7$ and above), the temperatures of ^{124}Sn decays exceed those for the neutron-poor systems by about 0.6 MeV.

Within these limits, and particularly in the regime of multifragmentation, the deduced temperatures are consistent with the overall observation that the reaction processes are not strongly affected by a variation of the system A/Z . Only the fragment mass distributions react sensitively to this parameter (Fig. 2). Comparing to the theoretical predictions, we find that the global behavior of the breakup temperatures is in good agreement with the SMM calculations for ^{124}Sn and ^{124}La nuclei of Ogul and Botvina [15]. The differences obtained for these cases are negligible in the multifragmentation regime and reach a maximum $\Delta T \approx 0.4$ MeV in the transition region where the equilibrium temperature for the more proton-rich ^{124}La system is slightly lower.

Rather small isotopic variations of the caloric curve have also been predicted with Thomas-Fermi-type calculations in which expansion [26–28] and shape degrees of freedom [29] have been considered. The obtained temperatures of 5 to 8 MeV are within the present range but it is not obvious that the experimental temperatures of fragmented systems at chemical freeze-out can be considered as representative for uniform spherical nuclei, even after expansion.

For a quantitative comparison with the expectations for limiting temperatures of compound nuclei, the region of transition from residue production to multifragmentation ($Z_{\text{bound}}/Z_{\text{proj}} \approx 0.7$) seems best suited. The residue channels associated with the highest temperatures are found here. They may be separated from the fragmentation events in the same bin by applying an additional condition on $Z_{\text{max}}/Z_{\text{proj}}$. Furthermore, in order to account for the above-mentioned effects of evaporation and to select equivalent degrees of fragmentation, slightly lower Z_{bound} limits were chosen for the neutron-poor projectiles (by 0.05 on the reduced scale, cf. Fig. 1).

In Table I, a summary of the experimental values for these event classes is given together with the Hartree-Fock results of Besprosvany and Levit [7]. Besides the predictions for the nominal projectiles, also those for nuclei with the same A/Z but only 75% of the projectile mass are included. These are the spectator systems most likely populating this bin [1]. Their limiting temperatures are higher than those of the nominal nuclei while their difference is slightly smaller.

The displayed experimental temperatures contain a 20% side-feeding correction. The additional condition on Z_{max}

TABLE I. Limiting temperatures T_{lim} from Ref. [7] for the nominal isotopes ^{124}Sn , ^{124}La , and ^{107}Sn and $T_{\text{lim},0.75 A}$ for the corresponding nuclei with 75% of the nominal mass and the same A/Z in comparison with the experimental double-isotope temperatures T_{HeLi} and $T_{\text{HeLi,res}}$, taken as 120% of the apparent values at $Z_{\text{bound}}/Z_{\text{proj}}$ intervals [0.6,0.8] for ^{124}Sn and [0.55,0.75] for the neutron-poor cases. For $T_{\text{HeLi,res}}$, the additional condition $Z_{\text{max}}/Z_{\text{proj}} \geq 0.6$ (0.55 in the neutron-poor cases) was applied. All values are given in MeV, the errors are purely statistical.

Projectile	T_{lim}	$T_{\text{lim},0.75 A}$	T_{HeLi}	$T_{\text{HeLi,res}}$
^{124}Sn	8.2	9.2	6.27 ± 0.04	5.96 ± 0.08
^{124}La	6.3	7.6	5.89 ± 0.05	5.59 ± 0.11
^{107}Sn	6.6	8.2	5.79 ± 0.05	5.22 ± 0.09

reduces the mean experimental temperature by $\Delta T = 0.4 \pm 0.1$ MeV (last column of Table I). Less violent processes associated with smaller energy deposits are selected [1]. With the same condition, also the difference between the neutron-rich and neutron-poor spectator systems changes, rising by a small amount from $\Delta T = 0.40 \pm 0.05$ to 0.6 ± 0.1 MeV (statistical errors).

It is obvious that Coulomb effects on the scale of MeV as exhibited by the Hartree-Fock limiting temperatures are not observed. On the other hand, the large difference in average magnitude of the predicted and measured temperatures is not as crucial as it may appear at first sight. As noted already by Natowitz *et al.* [11], the predictions depend sensitively on the type of force used in the calculations [9]. The experimental average $T_{\text{HeLi,res}} \approx 5.6$ MeV for $A \approx 90$ nuclei is close to the results obtained with the SkM* force by Song and Su [8] who, however, have not studied the dependence on A/Z . If these low values, including the corresponding critical temperature $T_c \approx 14$ MeV for infinite nuclear matter [8], can be shown to be realistic a link may be established between the limits of dynamic compound stability and the onset of multifragmentation. Otherwise, and as suggested by the SMM results [15], also the transition to multifragmentation is predominantly governed by the properties of the fragmentation phase space.

In summary, the study of projectile fragmentation over wide ranges of A/Z , up to presently available limits for proton-rich beams, has shown that the overall isotopic dependence is weak. In particular, the breakup temperatures entering the nuclear caloric curve were found to be identical within a few hundreds of keV, compatible with the assumption of identical reaction trajectories usually made in isotopic reaction studies, and in good agreement with the SMM predictions for a statistical population of the asymptotic phase space including the partition degree of freedom. The temperature differences reach a value of about 0.6 MeV in selected channels of residue production. The temperature $T \approx 5.6$ MeV measured for these pro-

cesses represents a lower bound for the limiting temperature of compound nuclei in the $A \approx 90$ region.

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