# Present Status of the Caloric Curve of Nuclei

U. Lynen[1] for the ALADIN collaboration:
R. Bassini[2], M. Begemann-Blaich[1], Th. Blaich[3], H. Emling[1], A. Ferrero[2], S. Fritz[1], S.J. Gaff[8], C. Groß[1], G. Immé[4], I. Iori[2], U. Kleinevoß[1], G. J. Kunde[8], W. D. Kunze[5], V. Lindenstruth[1],[‡] M. Mahi[1], A. Moroni[2], T. Möhlenkamp[6], W. F. J. Müller[1], B. Ocker[1], T. Odeh[1], J. Pochodzalla[1],[§] G. Raciti[4], Th. Rubehn[1‡], H. Sann[1], M. Schnittker[1], A. Schüttauf[5], C. Schwarz[1], W. Seidel[6], V. Serfling[1], J. Stroth[1], W. Trautmann[1], A. Trzcinski[7], G. Verde[4], A. Wörner[1], H. Xi[1†], E. Zude[1], B. Zwieglinski[7]

[1] Gesellschaft für Schwerionenforschung, D-64291 Darmstadt, Germany
[2] Dipartimento di Fisica, Università di Milano and I.N.F.N., I-20133 Milano, Italy
[3] Institut für Kernchemie, Universität Mainz, D-55099 Mainz, Germany
[4] Dipartimento di Fisica dell' Università and I.N.F.N., I-95129 Catania, Italy
[5] Institut für Kernphysik, Universität Frankfurt, D-60486 Frankfurt, Germany
[6] Forschungszentrum Rossendorf, D-01314 Dresden, Germany
[7] Soltan Institute for Nuclear Studies, 00-681 Warsaw, Hoza 69, Poland
[8] NSCL, Michigan State University, East Lansing, MI 48824, USA

Spectator decay was studied for the system Au + Au at an energy of 1000 A·MeV and the decay of the interaction region at energies between 50 and 200 A·MeV. In both cases temparatures were derived from several double-ratios of neighboring isotopes and from the population of excited states in $^{5}$Li and $^{4}$He. Agreement was found among the different isotope temperatures and also among the two excited state temperatures. The comparison of isotope and excited state temperatures, however, reveales large differences, which cannot be explained by feeding corrections.

At incident energies between 600 and 1000 A·MeV the energy spectra of fragments and also neutrons of the decaying projectile spectator were measured. Whereas the slope parameters of the energy spectra and mean energies for fragments with $Z \geq 2$ are independent of the incident energy, a strong dependence is found for the lightest particles, so that preequilibrium contributions to the spectator decay should be taken into account.

## 1. Introduction

The similarity of the N-N interaction with a van-der-Waals force has led to the prediction of a liquid-gas phase transition in nuclear matter [1–3] which, in case of a finite nucleus, is expected in the vicinity of the total binding energy [4]. It is thus accessible in

[‡]Present address: Nuclear Science Division, LBNL, Berkeley, CA 94720
[§]Present address: Max Planck Institut für Kernphysik, Heidelberg, Germany

heavy ion collisions already at intermediate energies. Although many experiments have been performed in the past, it turned out to be difficult to find an unambigious signature. This results partly from the fact that nuclei are finite and with respect to the number of constituents rather small systems and, more important, that the systems are transient and all observables depend on time.

The measurement of the caloric curve of excited projectile spectators emerging from the reaction Au + Au at 600 A·MeV [5], which resembled to an astonishing degree that of ordinary liquids, has initiated intense discussions. The main point of criticism was the use of the hitherto seldomly employed 'isotope thermometer', where the temperature $T_{HeLi}$ was deduced from the double ratio of the isotopes $^3$He, $^4$He and $^6$Li, $^7$Li [6]. Since the yield of $^4$He results to a large extent from secondary decays this temperature is expected to depend considerably on the applied feeding corrections [7,8]. A further point of criticism [9] was that the sizes of spectator nuclei emerging from peripheral collisions vary strongly with impact parameter resp. the excitation energy.

In order to check our results we have performed two new experiments in which the temperatures were deduced not only from the yield of different stable isotopes (isotope temperatures) but simultaneously from the population of excited states (excited state temperatures [10,11]). In addition to a comparison of the two thermometers, the problem of preequilibrium contributions to the excitation energies determined via calorimetry for spectator decay will be discussed in this report.

## 2. Experiment

The symmetric Au - Au system was studied with beams of the SIS-accelerator at GSI. For the planned comparison of isotope and excited state temperatures the following detectors were used. Seven telescopes, each consisting of 3 Si-detectors (50, 300 and 1000 $\mu$ thickness) followed by a 4 cm CsI crystal, allowed isotope identification of fragments up to Z=5. Three large area Si-CsI hodoscopes with fine granularity allowed to reconstruct the yield of particle unstable states from the correlation functions of their decay products. With this set-up experiments in two different energy regions were performed:

- At 1000 A·MeV the target spectators were investigated. To reduce contributions from the fireball the hodoscopes were placed at $135^0$ with respect to the beam axis.
- At energies between 50 and 200 A·MeV the interaction region in central collisions was studied. In this case the hodoscopes covered the region around $90^0$ in the cm-system where contributions from possible remnants of the projectile and target should be minimal.

In both cases a similar range of excitation energies is covered, although most other parameters of the reactions, e.g. flow or source size are very different [12]. It should, therefore, be possible to investigate the influence of these parameters on the measured temperatures.

In case of spectator decay a good determination of the impact parameter is necessary, since it controls the transferred excitation energies [13]. As in previous experiments the impact parameter was deduced from $Z_{bound}$ [14], where $Z_{bound}$ is defined as the sum of charges of projectile fragments with $Z \geq 2$. For the investigation of the interaction region already a coarse determination of the impact parameter is sufficient, since the degree of centrality affects mainly the size of this source whereas the excitation energy per nucleon is determined by the incident energy.

As will be discussed later, in peripheral collisions a significant part of the energy carried away by neutrons and protons cannot be attributed to a thermalized spectator source. The results for this source will, therefore, be presented as a function of $Z_{bound}$. Results obtained for the interaction region will be shown as a function of the incident energy.

## 3. Model calculations

Calculations were performed within the statistical multifragmentation model SMM [15], where the distribution of primary excitation energies as a function of impact parameter was chosen such that the measured correlations of the mean fragment multiplicity $\langle M_{IMF} \rangle$ and of the mean charge asymmetry between the two largest fragments $\langle a_{12} \rangle$ with $Z_{bound}$ were best reproduced. It turned out that for $Z_{bound} \geq 30$ the fragment multiplicity alone allows to determine the mean excitation energies, while for the lowest values of $Z_{bound}$ even both together yield no strong constraint. The fact that the excitation energies in this work are somewhat larger than those from previous analyses [16] of the earlier $^{197}$Au on Cu data [17] at 600 A·MeV reflect the small increase in fragment multiplicity observed in the more recent experiments due to an improved acceptance [18].

## 4. Excitation Energies of Projectile Spectators

Due to the large acceptance of the ALADIN-spectrometer and the strong forward focussing of fragments from the projectile spectator nearly all of its decay products have been detected event-by-event, so that the primary mass after the abrasion phase could be reconstructed. In case of fragments where only the charge was measured the corresponding mass was taken from an EPAX parametrization [19]. In order to determine the initial excitation energy by calorimetry the kinetic energies of the decay products were trans-

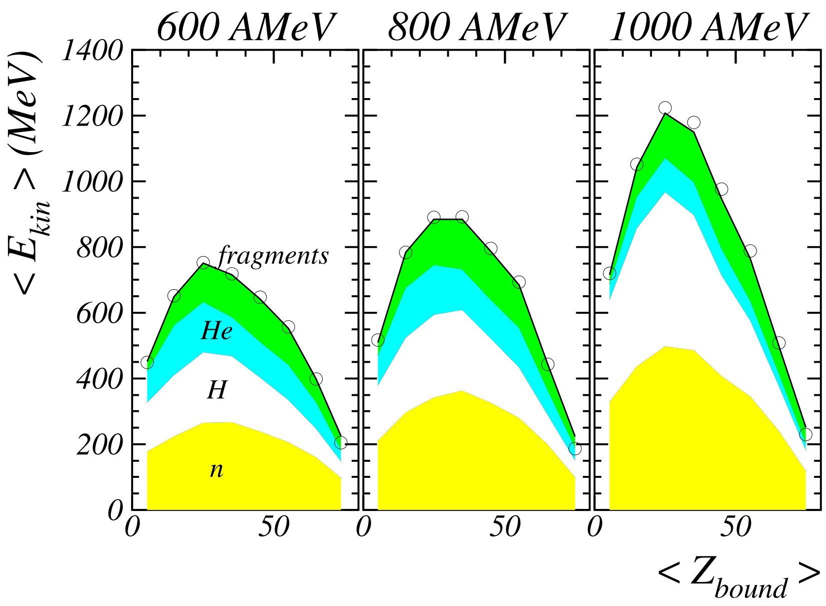


Figure 1.
Summed kinetic energies of the different decay products of the projectile spectator as a function of $Z_{bound}$ [20].

formed into the projectile system. In fig. 1 the energies carried away by different particle species are shown. Whereas the energies found in fragments with Z $\geq$ 2 are independent of the incident energy and confirm the universality of spectator decay [14], the energy carried away by neutrons increases significantly when the beam energy is raised from 600 to 1000 A·MeV. H-nuclei from the target spectator have been measured only at 1000 A·MeV where their mean energies agreed with those of the neutrons, if the additional Coulomb energy was taken into account. The energies shown in fig. 1 for 600 and 800 A·MeV, where only neutrons have been measured, are based on the assumption that the same relation is valid. Since the neutron multiplicities remain unchanged, the dependence on incident energy results from an increase of their mean kinetic energies.

In fig. 2 the resulting excitation energies per nucleon are shown for the three beam energies together with the input values of the SMM calculations. Whereas for the lowest energy of 600 A·MeV the experimental values are rather close to those with which SMM can reproduce the measured fragment distributions, at 1000 A·MeV they are nearly a factor of 2 higher. In fig. 3 the energy spectra of protons measured at $150^0$ in the lab at 1000 A·MeV are shown for different regions of $Z_{bound}$. For peripheral collisions two components with slope parameters of about 6 and 25 MeV can clearly be distinguished.

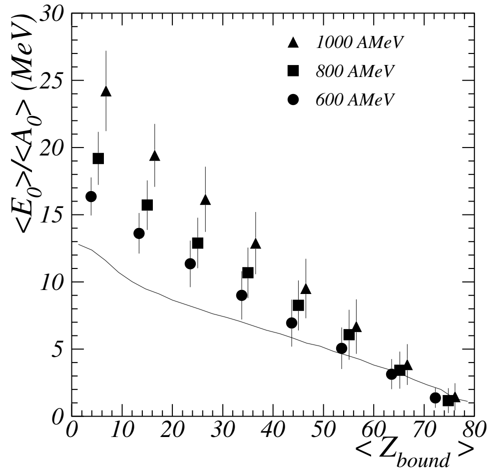


Figure 2. Excitation energy per nucleon of the spectator nucleus. The circles, squares and triangles show the results for incident energies of 600, 800 and 1000 A·MeV. The line denotes the energy at breakup of the SMM calculation.

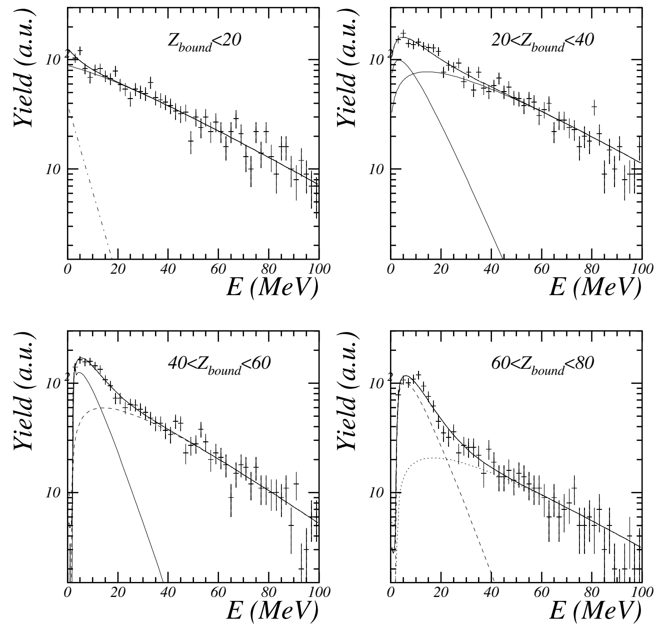


Figure 3. Energy spectra of protons measured at $150^0$ at an incident energy of 1000 A·MeV for different values of $Z_{bound}$. Two sources of Maxwellian shape were fitted to the spectra [21].

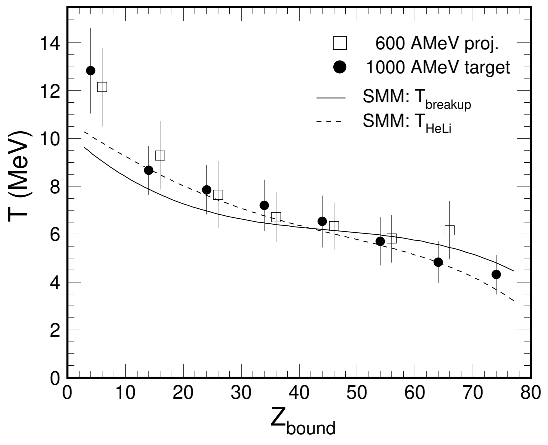


Figure 4. $T_{HeLi}$ derived from the projectile spectator at 600 A·MeV and the target spectator at 1000 A·MeV. The two lines are explained in the text.

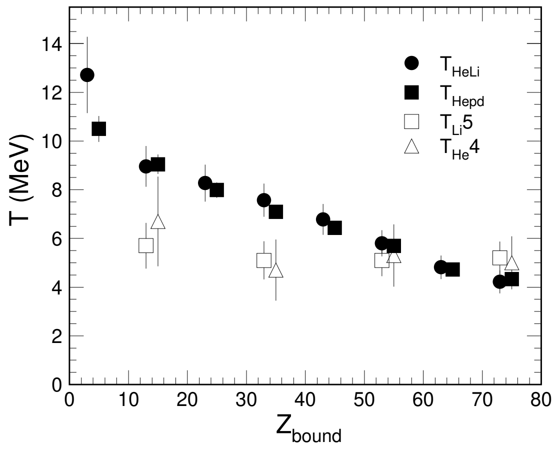


Figure 5. Comparison of $T_{HeLi}$ with temperatures derived from the population of different excited levels in $^5$Li and $^4$He for the target spectator of Au-Au collisions at 1000 A·MeV [22].

For smaller impact parameters the relative intensity of the second component is increasing and the slope parameter remains nearly unchanged. This behavior is difficult to explain by thermal emission from the spectator. Therefore, a nonnegligible fraction of the observed protons - and most likely also of the neutrons - should be excluded when the thermalized part of the excitation energy of the spectator is reconstructed.

## 5. Temperatures from Spectator Nuclei

In fig. 4 the isotope temperatures determined for projectile spectators at 600 A·MeV and target spectators at 1000 A·MeV are shown as a function of $Z_{bound}$. The good agreement between the two measurements is an indication that the detection efficiencies, which in case of projectile and target fragments are very different, are well under control. In both cases feeding has been taken into account by multiplying the result of the original Albergo formula by a factor 1.2. This factor was obtained from QSM [23,24] calculations for spectator decay. The two lines in fig. 4 show results of the above described SMM calculations. The solid line is the initial temperature at breakup. The agreement with the data is surprisingly good, especially if one takes into account that the two constraints used for the determination of the initial excitation energies in SMM are not very selective for the smallest $Z_{bound}$-values and an equally good fit could be obtained if higher excitation energies were assumed for these impact parameters. The dashed line shows the isotope temperature calculated from the yield of He and Li fragments predicted by the SMM calculations. This temperature has also been multiplied by a factor 1.2. The good agreement between the two lines shows that also in SMM the feeding corrections can be approximated quite well by a factor 1.2.

Fig. 5 shows the comparison between several isotope and excited state temperatures obtained for the target spectator at 1000 A·MeV. For the two isotope temperatures, $T_{HeLi}$ and $T_{Hepd}$, nearly identical values are obtained and the same is true, if the two temperatures deduced from excited states in $^5$Li and $^4$He are compared, although their error bars are rather large. For very peripheral collisions all temperatures agree with each other. The isotope temperatures, however, increase towards smaller impact parameters, whereas the excited state temperatures remain constant.

## 6. Temperatures from the Interaction Region

In fig. 6 isotope and excited state temperatures obtained for the interaction region at incident energies between 50 and 200 A·MeV are shown. The differences between the two thermometers which were found for the spectator decay, now show up even more pronounced. With increasing beam energy the isotope temperatures are rising, whereas the temperatures derived from the population of excited levels remain constant. At 200 A·MeV the differences are large: whereas the isotope temperatures are around 12 MeV those derived from excited states are below 5 MeV. Sequential decay calculations which reproduce the observed mass distributions cannot explain this difference between the two thermometers and other explanations have to be found.

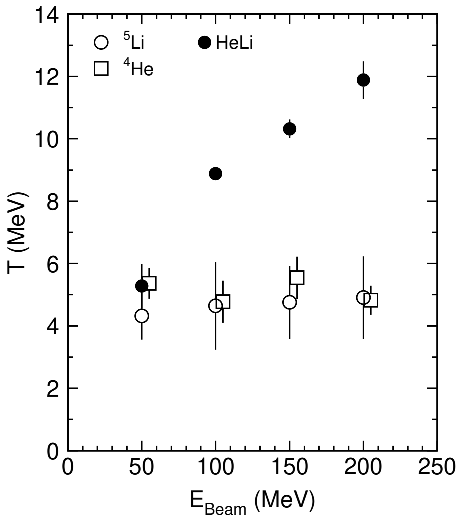


Figure 6. Comparison of $T_{HeLi}$ with temperatures derived from the population of excited levels in $^5$Li and $^4$He for the interaction region at incident energies between 50 and 200 A·MeV [25]. $T_{HeLi}$ is again multiplied by a factor of 1.2.

## 7. Conclusions

The aim of the present investigation was to check the excitation energies and the temperatures which had been used for the determination of the caloric curve.

The excitation energies determined in [5] from calorimetry had not been corrected for preequilibrium emission. The present analysis [20] has shown that in peripheral collisions the energies of neutrons depend strongly on the incident beam energy and the slope parameters of protons were found to be independent of impact parameter. Both effects are indicative of non-negligible preequilibrium contributions. Therefore the experimental excitation energies shown in fig. 2 are an upper limit. On the other hand the values with which SMM can reproduce the fragment distributions (solid line in fig. 2) should be considered as lower limit and the true excitation energies will probably lie between these two limits.

The isotope temperature $T_{HeLi}$ has been confirmed by remeasuring it for the target spectator and good agreement was found with other isotope temperatures. This confirms that the experimental inefficiencies are under control. The values found for $T_{HeLi}$ agree very well with those temperatures, with which SMM calculations can reproduce the observed fragment distributions. A direct comparison of the temperatures determined for the decay of the spectator resp. that of the interaction region the is difficult as long as the excitation energies per nucleon are not well determined. The only place where a comparison without too many assumptions seems possible is for that incident energy resp. that impact parameter where the fragment multiplicity has its maximum. In case of central Au-Au collisions this corresponds to an incident energy of 100 A·MeV and for spectator decay to $Z_{bound}$-values of about 40. The corresponding $T_{HeLi}$-temperatures are 8.6 and 8 MeV, close to the total binding energy. The good agreement between both values can be considered as an indication that flow (in central collisions) or a decreasing source size (for spectator decay) has no strong influence on $T_{HeLi}$.

A completely different dependence seems to exist for the temperatures deduced from excited states. Good agreement is again found among temperatures deduced from different excited states, but the general trend that these temperatures depend neither on the impact parameter nor the incident energy is difficult to understand. Unfortunately the experimental errors are still so large that no final conclusion can be drawn, but it appears very likely that the temperatures derived from excited states do not reflect the temperature of the system at the time when the fragments are produced.

The freeze-out time of a nuclear state is correlated with the cross section, with which it is populated or destroyed in collisions with other hadrons during the expansion phase. Since excited states can be destroyed by almost any inelastic collision, they will freeze-out very late and reflect the temperature of the system at a late time. The situation may be similar to the differences found for the absorption of $J/\Psi$ and $\Psi'$ in a hot hadronic gas [26] formed in ultrarelativistic heavy ion collisions, where the stronger bound $J/\Psi$ is less affected by collisions with other hadrons than the more loosely bound $\Psi'$.

Although the differences found for the isotope and excited state temperatures will complicate the situation as far as the liquid-gas phase transition is concerned it could turn out to be a valuable tool for a better understanding of fragment formation at low densities.

## 8. Acknowledgements

This work was supported in part by the European Community under contract ERBCHGE-CT92-0003 and ERBCIPD. J.P. and M.B. acknowledge the financial support of the Deutsche Forschungsgemeinschaft under contract Po256/2-1 and Be1634/1-1.

## REFERENCES


1. D.Q.Lamb *et al.*, Phys. Rev. Lett. 41 (1978) 1623
2. H.Jaqaman *et al.*, Phys. Rev. C 27 (1983) 2782
3. P.J.Siemens, Nature 305 (1983) 410
4. J.Bondorf *et al.*, Nucl. Phys. A 444 (1985) 460
5. J.Pochodzalla *et al.*, Phys. Rev. Lett. 75 (1995) 1040
6. S.Albergo *et al.*, Nuovo Cimento A 89 (1985) 1
7. H.Xi *et al.*, Phys. Rev. C 54 (1996) R2163
8. F.Gulminelli and D.Durand, Nucl. Phys. A 615 (1997) 117
9. J.B.Natowitz *et al.*, Phys. Rev. C 52 (1995) 2322
10. D.J.Morissey *et al.*, Phys. Lett. 148B (1984) 423
11. J.Pochodzalla *et al.*, Phys. Rev. Lett. 55 (1985) 177
12. U.Lynen *et al.*, Proc. Int. Conf. on Nuclear Physics, Wilderness, South Africa, editors H.Stöcker, A.Gallmann, J.H.Hamilton, World Scientific 1997, p.200
13. J.Hubele *et al.*, Z.Phys. A 340 (1991) 263
14. C.A.Ogilvie *et al.*, Phys. Rev. Lett. 67 (1991) 1214
15. J.P.Bondorf *et al.*, Phys. Rep. 257 (1995) 133
16. A.S.Botvina *et al.*, Nucl. Phys. A 584 (1995) 737
17. P.Kreutz *et al.*, Nucl. Phys. A 556 (1993) 672
18. A.Schüttauf *et al.*, Nucl. Phys. A 607 (1996) 457
19. K.Sümmerer *et al.*, Phys. Rev. C 42 (1990) 2546
20. C.Gross *et al.*, Thesis, Frankfurt/Main 1997
21. T.Odeh *et al.*, Thesis, Frankfurt/Main 1997
22. S.Fritz *et al.*, Thesis, Frankfurt/Main 1997
23. D.Hahn and H.Stöcker, Nucl. Phys. A 476 (1988) 718
24. J.Konopka *et al.*, Phys. Rev. C 50 (1994) 2085
25. V.Serfling *et al.*, Thesis, Frankfurt/Main 1997
26. M.C.Abreu *et al.*, Nucl. Phys. A 610 (1996) 404c