MULTIFRAGMENTATION AND THE SEARCH FOR THE LIQUID-GAS PHASE TRANSITION IN NUCLEAR MATTER

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] C. Groß,[1] G. Immé,[4] I. Iori,[2] U. Kleinevoß,[1] G. J. Kunde,[1†] 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*

The caloric curve of the highly excited projectile spectators emerging from peripheral collisions of two Au-nuclei at 600 A·MeV was determined by measuring fragments and neutrons of its decay. This analysis will be reviewed and preliminary results obtained from the decay also of the target spectator will be presented.

1 Introduction

An interesting aspect of highly excited nuclei is the prediction of a liquid-gas phase transition [1,2,3]. The decay channel which appears most promising for its verification is multifragmentation, a simultaneous break-up into several fragments of intermediate mass, where the coexistence of nuclear fragments and free nucleons can be seen as nuclear vapor.

In order to heat a nucleus up to the excitation energy where the phase transition is expected [4] - of the order of the total binding energy - two different classes of experiments are possible:
- central collisions of two equally sized nuclei at intermediate energies or
- peripheral collisions at much higher energies.

Whereas in the first case the overlap region is investigated, in the second case the spectator nuclei emerging from the primary collision will have the

†Present address: NSCL, Michigan State University, East Lansing, MI 48824
‡Present address: Nuclear Science Division, LBNL, Berkeley, CA 94720
§Present address: Max Planck Institut für Kernphysik, Heidelberg, Germany

excitation energies of interest.

Using the ALADIN spectrometer at GSI together with the Large Neutron Detector LAND we have investigated the reaction Au + Au at an incident energy of 600 A·MeV. From the measured fragments and neutrons the caloric curve [5] of the projectile spectator has been determined.
After a short review of the characteristic properties of spectator nuclei, I will discuss the determination of the caloric curve, including preliminary results from a new experiment, where also decay products of the target spectator have been measured.

2 Projectile Source

Projectile spectators from peripheral heavy ion collisions at high energies offer favorable conditions for the search for signatures of the predicted liquid-gas phase transition:

- At sufficiently high beam energies ($\geq 600A \cdot MeV$) the decay products are focussed into a narrow angular region around the beam axis. They maintain to a large extent the initial (beam) rapidity and thus are well separated from contributions from the interaction region. The primary projectile spectator emerging from the abrasion phase is therefore a well-defined source which can be reconstructed with high accuracy on an event-by-event basis.
- Because of the high source velocity heavy fragments can also be measured and detector thresholds are negligible. On the other hand the high velocities render a precise determination of the momenta in the decaying system difficult. This can be done better for the target spectator.
- The spectator source shows a high degree of equilibration (thermalization?). Without any selection criteria the transverse and longitudinal widths of fragments are found to be equal [6]. Only in the spectra of very light particles small preequilibrium contributions are found, which show up as a small enhancement towards lower rapidities, but still much closer to the projectile rapidity than to midrapidity. This distinction between preequilibrium contributions in the spectator decay and the interaction region is only possible at high incident energies where the different sources are well separated in rapidity.
- Depending on impact parameter very different excitation energies are transferred into the spectator nuclei. Therefore a whole excitation function can be measured simultaneously [7]. A disadvantage is, that in order to reach high excitation energies, rather central collisions have to be selected for which the mass of the remaining spectator contains as little as 25% of the

initial projectile [5].

- For a fixed impact parameter the excitation energy of the projectile spectator increases with increasing beam energy and/or target mass [8]. Despite of this, a universal behavior independent of beam energy or target mass is found if the events are selected according to the mass of the projectile spectator (more precisely according to Z_{bound} being defined as the charge sum of all projectile fragments excluding H-isotopes). This universality of the fragmentation process [9] is not only observed for the multiplicity of intermediate mass fragments (IMF, $3 \leq Z_{IMF} \leq Z_{proj}/3$) but also for the correlations between different fragments [10]. Obviously the process of fragment formation is independent of the details of the entrance channel dynamics, suggesting that the system passes through an equilibrated intermediate state for which the concept of temperature is meaningful.
- During the primary collision spectators undergo no or at most very little compression and the collective flow observed in the subsequent expansion is small (about 1 A·MeV) [11,12]. As a consequence up to excitation energies of about 8 A·MeV the expanding system may reach a turning point [13] leading to a long time span before the system breaks up and consequently a high degree of thermalization can be reached.
- Although the spectator decay as a function of Z_{bound} is independent of target mass, sufficiently heavy targets have the advantage that the cross section $d\sigma/dZ_{bound}$ is rather constant over nearly the whole range of Z_{bound}-values, whereas in case of light targets or low incident energies it drops steeply towards small Z_{bound}-values (see fig. 2). In this region fluctuations in the decay may reduce the sensitivity of the event characterizing variable Z_{bound} to the initial excitation energy.

3 Determination of the Caloric Curve

In order to determine the caloric curve for the excited projectile spectator not only its temperature and excitation energy must be reconstructed, but also its mass.

3.1 Masses

The ALADIN-spectrometer is well suited for a complete reconstruction of the projectile spectator, because at sufficiently high energies ($\geq$ 600 A·MeV) nearly all IMF's are focussed into its acceptance and only a small number ($\leq$0.5 per event) is found in the surrounding Si-CsI hodoscope. The rapidity distributions observed in the ToF-wall are therefore the true distributions in case of fragments originating from the projectile spectator decay and distortions due to the angular and also the rigidity acceptance of the spectrometer would only show up for those of the fireball. Because of the high temperature of this source the latter yield is anyhow very small.

For He-fragments, and somewhat stronger for neutrons and H-isotopes, small preequilibrium contributions are seen [14] leading, however, even in the worst case of rather central collisions to an uncertainty in the projectile mass of at most 6 mass units.

Mass and charge of the primary projectile spectator were determined by summing up all fragments and nucleons assigned to this source. For fragments, where only the atomic charge has been measured, the corresponding masses were taken from an EPAX parametrization with parameters adjusted in a previous experiment [12]. For the first analysis [5] the multiplicity of H-isotopes had been deduced from the assumption that the N/Z-ratio of the projectile source (after abrasion) remained that of the initial projectile. This has now been confirmed by measuring protons from the target spectator.

3.2 Excitation Energies

The total excitation energy transferred to the projectile spectator can be determined by adding the kinetic energies of all particles transformed into the moving system to the Q-value of the reaction (the difference between the sum of the final masses and the mass of the primary fragment after the abrasion phase). For fragments and neutrons the energies were measured in the experiment. For H-isotopes those of neutrons (measured at 600 A·MeV) increased by the Coulomb energies had been assumed. At 1000 A·MeV considerably higher energies were measured for both species, the energies of fragments, however, remained constant. This difference is not yet understood.
A possible increase in the excitation energies will, however, partly be compensated if preequilibrium contributions and directed flow are taken into account.

3.3 Temperatures

Following the work of Albergo et al. [15] we have deduced the temperature of the primary projectile spectator from the yields of different light isotopes. For a thermally equilibrated system at low densities the temperature can be derived from a double ratio of the yields of two isotope pairs, differing by the same number of protons or neutrons:

$$R = \frac{Y_1/Y_2}{Y_3/Y_4} = \alpha \cdot e^{[(B_1-B_2)-(B_3-B_4)]/T} \tag{1}$$

B_i denotes the binding energies of the fragments and α can be calculated from their spins and masses. As can be seen the sensitivity increases with the difference between the binding energy differences of the two pairs. This makes ^3He and ^4He an ideal pair. A further requirement is that the fragments must be produced with sufficient yield over a wide range of excitation energies from the liquid to the gaseous phase. This excludes the use of much heavier fragments. For the projectile source H-isotopes had not been measured. Therefore ^3He and ^4He were combined with ^6Li and ^7Li and the resulting temperature was denoted as $T_{He,Li}$. For the target spectator we have also determined $T_{H,He}$ by measuring the d/t - ratio. Furthermore we have extracted $T_{Li,Be}$ from the ratio $\frac{^9Be/^8Li}{^7Be/^6Li}$.

Eq. 1 is valid as long as the measured yield ratios are not modified by contributions from either γ-decay of excited states or from feeding from heavier isotopes. Possible corrections were determined for each isotope thermometer individually by Quantum Statistical Model [16] calculations, a model which includes secondary decays. Over a wide range of densities (ρ/ρ_0 between 0.1 and 0.5) the reconstructed temperatures show a linear dependence with the initial ones. The same result was obtained when the temperatures were deduced from GEMINI-calculations for $\rho = \rho_0$. Since in all cases the temperatures deduced from the isotope yields were about 20% smaller than the initial ones, all isotopic temperatures have been scaled by a factor of 1.2.

4 Caloric Curve

From the reconstructed excitation energies and masses together with the isotopic temperature the caloric curve of the projectile spectator shown in fig. 1 has been obtained [5]. It has a remarkable resemblence with e.g. that of water. Within the region from 3 to 10 MeV per nucleon a nearly constant value of about 5 MeV is observed, followed by an increase towards higher excitation energies which can be related to the transition from the vapour to the gas phase. The broad plateau at 5 MeV is in agreement with a series of experiments carried out over a wide range of incident energies where almost identical temperatures have been deduced from the population of excited states in He and Li. An often given explanation for this constancy of the emission temperatures is that fragment emission occurs when the initially hot nucleus has cooled down by the emission of lighter particles. In this case, however, the multiplicity of fragments should only depend on the size of the system at that time and not on the initial temperature. For the projectile spectator going from $Z_{bound} = 70$ to $Z_{bound} = 40$ the initial mass drops by 25% (the masses after light particle emission even more), but the fragment multiplicity increases

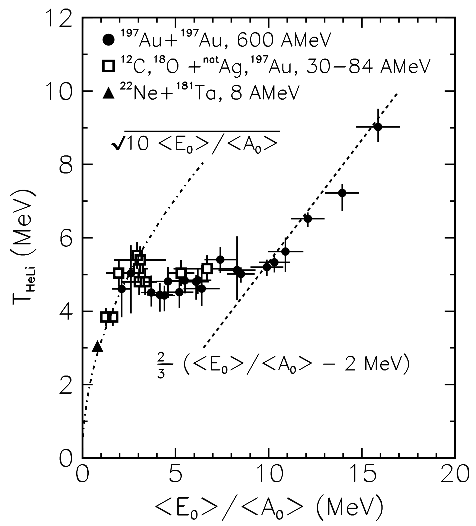

Figure 1: Caloric curve of excited spectator nuclei determined by the dependence of the isotopic temperature $T_{He,Li}$ on the excitation energy [5].

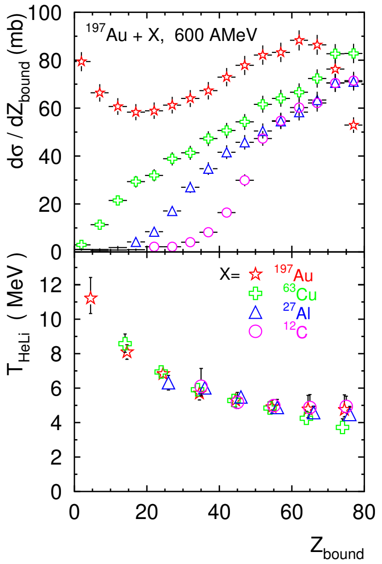

Figure 2: Top: Differential cross section as a function of Z_{bound} [17] for different targets. Bottom: $T_{He,Li}$ as a function of Z_{bound} for Au-interactions with different targets.

by a factor of three. This excludes the above explanation.

The final analysis of excitation energies (see the above discussion) is not yet finished. Therefore the temperatures obtained with different targets (see fig. 2) and those deduced from different isotope ratios (see fig. 3) will be presented as a function of Z_{bound}. Since large excitation energies correspond to small values of Z_{bound}, the temperature rise towards the gas phase in this presentation occurs towards the origin.

In fig. 2, bottom part, the dependence of $T_{He,Li}$ on Z_{bound} is shown for Au-interactions with different targets. Within the error bars all targets lead to identical distributions, confirming the universality of spectator decay. With the light targets ^{12}C and ^{27}Al this comparison is, however, limited to Z_{bound} values larger than 35 and 25, respectively, because for lower values of Z_{bound} the cross sections (see fig. 2, upper part) are vanishing.
A similar agreement is found for the different isotopic temperatures $T_{H,He}$, $T_{He,Li}$ and $T_{Li,Be}$ shown in fig. 3. Although this cannot be seen as a general proof for the validity of temperatures deduced from isotope yields, the agree-

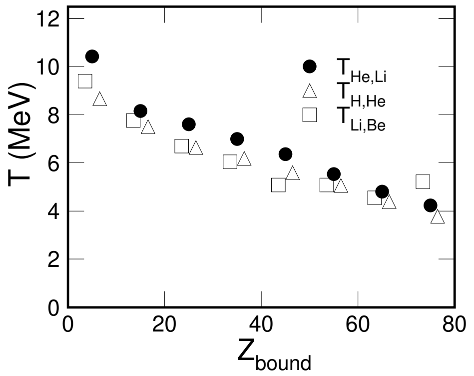

Figure 3: Temperatures determined from different isotope combinations for the reaction Au+Au at 600 A·MeV as a function of Z_{bound} [17].

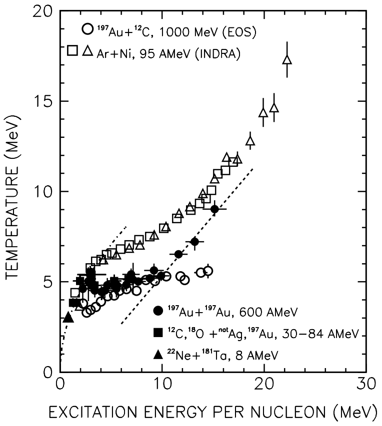

Figure 4: Comparison of caloric curves obtained by the ALADIN-, the EOS- [18] and the INDRA [19]-collaboration.

ment between $T_{H,He}$ and $T_{Li,Be}$ gives another indication that light particles and fragments see the same source temperatures, resp. have similar emission times. A further conclusion is that the $^3He/^4He$-ratio can be used for temperature determination, despite of the modification of the α-yield by evaporation.

5 Comparison with other Experiments and Conclusion

In fig. 4 the caloric curve measured by ALADIN [5] is compared to preliminary results from the INDRA [19]- and the EOS [18]-collaboration, for which $T_{He,Li}$ has also been determined.
The EOS-result was obtained for Au-interactions with a C-target at 1000 A·MeV and therefore should be directly comparable with our measurement. The agreement in the plateau is very good, but the second rise towards vaporisation is not seen, as in our result with a C-target. The vanishing cross sections observed for small Z_{bound} values indicate that at 1000 A·MeV even in central collisions C is too light in order to vaporize the Au-projectile completely. The fact that the plateau in the two experiments extends to different energies may be related to the different bombarding energies as discussed above.
The *preliminary* result of the INDRA-collaboration was obtained for the Ar+Ni system at 95 A·MeV, where only that half of projectile fragments emitted in forward direction has been analyzed. While the deduced temperatures are about 2 MeV higher, the qualitative shape of the ALADIN-result is repro-

duced. A possible explanation for the difference could be the N/Z-ratio or the small system size.

The determination of the caloric curve of highly excited spectators opens up a new way to investigate the expected liquid-gas phase transition in nuclear matter. The close resemblance between the caloric curves of nuclei and that of water is surprising, since nuclei are closed systems and neither the pressure nor the volume remains constant when the energy is increased. Although we believe that spectator decays are in so far optimal as nearly no flow is observed during expansion, it is not clear whether the dynamics of the decay can be completely neglected [13]. This will certainly be the focus for further experiments in the future.

Acknowledgments

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**, 1623 (1978)
2. H.Jaqaman *et al.*, *Phys. Rev.* C **27**, 2782 (1983)
3. P.J.Siemens, *Nature* **305**, 410 (1983)
4. J.Bondorf *et al.*, *Nucl. Phys.* A **444**, 460 (1985)
5. J.Pochodzalla *et al.*, *Phys. Rev. Lett.* **75**, 1040 (1995)
6. U.Lynen *et al.* in *11th Winter Workshop on Nuclear Dynamics* (1994).
7. J.Hubele *et al.*, *Z. Phys.* **340**, 263 (1991)
8. W.D.Kunze, *PhD-thesis, University Frankfurt* (1996)
9. C.A.Ogilvie *et al.*,*Phys. Rev. Lett.* **67**, 1214 (1991)
10. P.Kreutz *et al.*, *Nucl. Phys.* A **556**, 672 (1993)
11. G.J.Kunde *et al.* *Phys. Rev. Lett.* **74**, 38 (1995)
12. V.Lindenstruth, *PhD-thesis, University Frankfurt* (1993)
13. G.Papp and W.Nörenberg, *22nd Winter Workshop, Hirschegg* (1994).
14. A.Schüttauf, *PhD-thesis, University Frankfurt* (1996)
15. S.Albergo *et al.*, *Nuovo Cimento* A **89**, 1 (1985)
16. D.Hahn and H.Stöcker, *Nucl. Phys.* A **476**, 718 (1988)
17. T.Moehlenkamp *PhD-thesis, Dresden* (1996)
18. M.L.Tincknell *et al.*, *12th Winter Workshop on Nuclear Dynamics* (1996)
19. G.Auger *et al.*, *1st Catania Rel. Ion Studies, Acicastello* (1996)