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PROBING PHASE TRANSITIONS IN NUCLEI VIA CALORIMETRY *

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Heavy-ion reactions at relativistic energies offer the unique possibility for studying phase transitions in finite, hadronic systems. A general overview of this subject is given emphasizing the most recent results on the liquid-gas transition obtained via nuclear calorimetry.

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1. The essence of nuclei

Already two decades ago, the van der Waals behavior of the nucleon–nucleon force inspired the idea of a liquid-gas phase transition in nuclear matter [1–4]. What makes this nuclear liquid gas phase transition stand out from all other conceivable nuclear phase transitions, is the fact that both phases, cold nuclear Fermi liquids, on the one hand, and a nuclear gas consisting of free nucleons and a few light clusters, on the other hand, are known to exist in nature, and, what may perhaps be even more important, that both are experimentally accessible.

The first observation of a self-similar power law for the fragment mass distribution in proton induced reactions on Kr and Xe targets [5, 6] was — supported by the early predictions of nuclear multifragmentation [7, 8] — interpreted as an indication for a critical phenomenon [9, 3]. This observation has initiated an intensive search for signatures of criticality [10–12]. The systematic investigation of inclusive studies during the subsequent years showed that the power law exponent τ approaches a value of ≈ 2.5 at high bombarding energies [13]. This is consistent with the limits $2.0 \leq \tau \leq 3.0$ given [14] by the theory of critical phenomena. While the interpretation of inclusive mass spectra was criticized [15], it was shown in exclusive measurements that the mass or charge distributions may approach the pure

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power law for certain values of the chosen sorting variable. In this case, the sorting variable may serve as the parameter controlling the distance to the critical point or critical region. Indeed even minima of the exponent τ could be identified which were found to be close to the maximum fragment production [16–19]. Within Fisher's droplet model this minimum would allow to locate the critical point. It was, however, realized that in some cases the minimum value of τ was far below the expected value of about 2.2 [20, 17, 21]. Such low values may signal the influence of the large Coulomb fields of highly charged systems [21], the finite size of the system [22], the geometry of the source [23] and/or the dynamics of the nucleation process [24–26].

A further step was taken by the EOS collaboration who have reported values for critical-point exponents from the charge correlations measured for 1A GeV ^{197}Au on C reactions [27–29]. With the guidance provided by percolation studies on small lattices, recipes were developed on how to extract critical exponents from the data [30]. The reported results $\beta = 0.29 \pm 0.02$ and $\gamma = 1.4 \pm 0.1$ are close to those of a liquid–gas system and significantly different from those of percolation or mean-field theory [27]. This conclusion relies on the correct assessment of the systematic errors inherent to the procedure which, however, has been questioned by other authors [31–33]. Using the same experimental recipe, the results of the EOS collaboration could be reproduced in ^{208}Pb induced reactions on emulsions at 160A GeV [34], while an analysis of Au+emulsion reactions at 10.6A GeV gave significantly different critical exponents [35]. This illustrates that — despite enormous effort — the attempts to deduce critical parameters and critical point exponents remained elusive.

An alternative approach to explore the liquid–gas phase transition is possible via nuclear calorimetry. While this method is not restricted to second order phase transitions the interpretation of caloric information on nuclei has also to cope with several complications: Excited nuclei are transient systems which have to be generated in nuclear collisions. We are, therefore, facing the difficulty to produce isolated nuclear systems which have reached the highest possible degree of equilibration. Nuclei are composed of a limited number of constituents. In a finite system, fluctuations are limited. Singularities of phase transitions get, therefore, rounded and shifted with respect to their bulk values [36, 37]. Moreover, the long-range Coulomb-repulsion between the constituent protons introduces additional instabilities [38, 39] which may lead to a further downward shift of the apparent 'critical' temperature. Since no external fields (*e.g.* pressure) can be applied to excited nuclei in the laboratory, they may expand prior to their disassembly.

2. The making of boiling nuclei

In order to explore the liquid-gas phase transition in nuclei we have to deposit excitation energies which are of the order of the nuclear binding energy. In head on collisions between equally heavy nuclei the excitation is determined by the incident beam energy. The clear advantage of this method is that, for a given target–beam combination, systems with nearly constant mass number can be produced. However, a significant fraction of the energy is not converted into heat but in collective explosive motion [41– 48] (left part of figure 1), thus introducing an additional degree of freedom which unfortunately also depends on the incident energy. Spectator nuclei produced in more peripheral collisions do not show this collective motion in the *initial* stage, though some radial flow may arise during the thermally driven expansion and may contribute to the kinetic energies of the fragments [49] (see right part of figure 1 [40]). In contrast to central collisions, no apparent dependence on the entrance channel is observed in the charge partition of fragmenting spectator nuclei [50, 51, 16, 18, 19, 52]. This universality of the spectator decay suggest that a high degree of equilibrium is reached in the initial stages of the reaction.

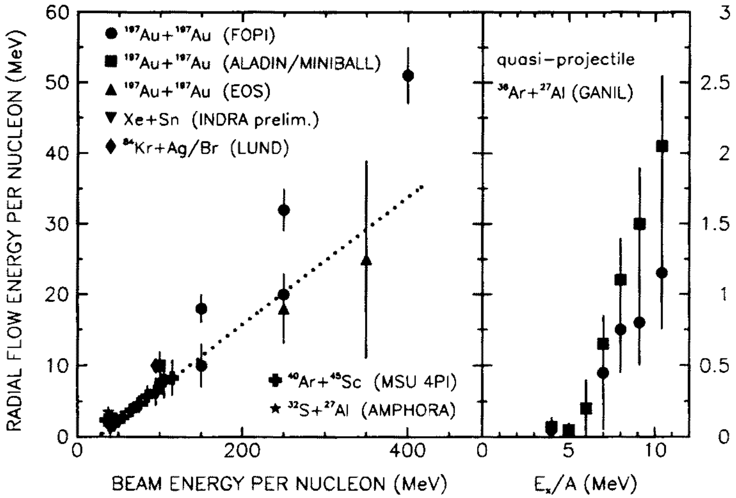

Fig. 1. Left part: systematics of radial flow energies in (nearly) symmetric nucleus-nucleus collisions as a function of the beam energy per nucleon. Right part: mean radial flow energy per nucleon versus the excitation energy per nucleon of quasi-projectiles in ^{36}Ar+^{27}Al reactions (from [40]; note the different vertical scale).

3. Hadronic thermometer

Nuclei are closed systems without an external heat bath. Consequently, the temperature of the system cannot be pre-determined but has to be reconstructed from observable quantities. For a microcanonical ensemble, the thermodynamic temperature of a system may be defined in terms of the total-energy state density. An experimental determination of the state density and its energy dependence is, however, hitherto impossible. Therefore, nuclear temperature determinations take recourse to 'simple' observables of specific degrees-of-freedom which constitute — at least for some ideal situations and generally within a canonical treatment — a good approximation to the true thermodynamic temperature.

At low excitation energies, the inverse slope parameters describing the kinetic energies or transverse mass distributions of the emitted particles are a good measure of the temperature. In intermediate energy and relativistic nucleus–nucleus interactions, however, these distributions suffer from possible collective flow effects, secondary decay processes, multiple Coulomb interaction and Fermi motion. While the spectral distributions are indispensable to disentangle thermal and collective phenomena, a more direct way to test whether locally thermal equilibrium is achieved and to determine a temperature is to study in detail the particle abundance [55]. Finally, from the relative population of two states of a given fragment, the so called emission temperature can be deduced. While the latter analysis requires a more demanding coincidence measurement of the decay products, isotope temperatures can be extracted from single particle yields.

For the following considerations we will assume a nuclear system at low density and in chemical and thermal equilibrium. For such a system a measure of the temperature T may be obtained via the double yield ratio of two isotope pairs, (Y_1/Y_2) and (Y_3/Y_4), differing by the same number of neutrons and/or protons [56]:

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

Here, B_i denotes the binding energy of particle species i and the constant a contains known spins and mass numbers of the fragments. Of course, a meaningful temperature scale can only be derived if the ratio R is sufficiently sensitive to the temperature of the system and if the yields of the considered fragments are measurable over a large range of excitation energy. A large sensitivity of this thermometer can be achieved if the binding energy difference $\Delta B = (B_1 - B_2) - (B_3 - B_4)$ is larger than the typical temperature to be measured. The analysis of more than 1000 possible 'thermometer' defined via equation 1 by Tsang *et al.* [57] supports this rule of thumb.

Particularly large values for b are obtained if a ^{3}He/^{4}He ratio is involved. In order to acquire for the second yield ratio also a sufficient production yield we define in the following a temperature $T_{\mathrm{HeLi,0}}$ in terms of the yield ratios ^{3}He/^{4}He and ^{6}Li/^{7}Li according to Eq. (1).

To test the model dependence of the temperature definition via Eq. (1) and to investigate the influence of sequential decays and low lying γ-unstable states we analyzed the fragment distributions predicted by several decay models. Despite the strong feeding of the light particle yields through secondary decays these first calculations predict an almost linear dependence of $T_{\mathrm{HeLi,0}}$ on the actual temperature T of the system. However, in order to account pragmatically for a systematic underestimation of the temperature by the quantity $T_{\mathrm{HeLi,0}}$, we define the final isotope temperature via

$$T_{\mathrm{HeLi}} = 1.2 \cdot T_{\mathrm{HeLi,0}}. \tag{2}$$

For consistency reasons all values of T_{HeLi} presented hereafter include the factor $f_T = 1.2$. It is important to realize, though, that this calibration is model dependent and other decay models might predict different corrections [54, 58–62]. At present, there exists no consensus on the amount of sequential decay. While the proposed [54] correction factor of f_T=1.2 to $\mathrm{T}_{\mathrm{HeLi,0}}$ marks the mean value of the different calculations, it is clear that more experimental information on the decay of particle unstable resonances is required in order to solve this dilemma.

4. Nuclear calorimetry

The filled symbols in Figs. 2 and 3 show the isotope temperature as a function of the total excitation energy per nucleon [54]. This caloric curve can be divided into three distinctly different sections. In line with previous studies in the fusion evaporation regime the rise of $\mathrm{T}_{\mathrm{HeLi}}$ for excitation energies below 2 MeV per nucleon is compatible with the low-temperature approximation of a fermionic system. Within the range of $\langle E_0 \rangle / \langle A_0 \rangle$ from 3 MeV to 10 MeV an almost constant value for T_{HeLi} of about 4.5–5 MeV is observed. Finally, beyond a total excitation energy of 10 MeV per nucleon, a steady rise of T_{HeLi} with increasing $\langle E_0 \rangle / \langle A_0 \rangle$ is seen.

While in central collisions between equally heavy nuclei the slope parameters and the collective radial motion are strongly interlaced, the chemical temperatures deduced from the isotopic composition reflect a local property and are expected to be less affected by a radial flow. The filled stars in figure 2 show values for $\mathrm{T}_{\mathrm{HeLi}}$ for central Au+Au collisions at beam energies of 50, 100, 150 and 200 MeV per nucleon [64, 68] together with a point measured at 35 MeV per nucleon by the MINIBALL Collaboration. Central

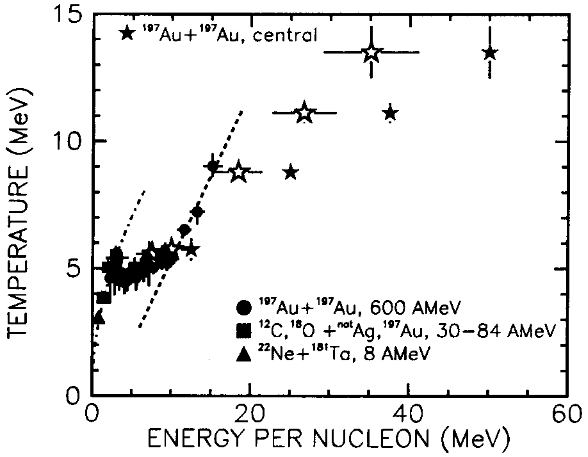

Fig. 2. Caloric curve of nuclei determined by the dependence of the isotope temperature T_{HeLi} on the excitation energy per nucleon. The stars indicate results for central Au+Au collisions at 35 (from [63]), 50, 100, 150 and 200 MeV per nucleon incident beam energy. For the filled stars the energy scale is given by the center-of-mass energy whereas in case of the open stars the radial flow energies (dashed line in figure 1) have been subtracted.

reactions were selected by the number of light particles detected in the forward hemisphere in the center-of-mass. Isotope ratios measured close to 90° in the cm-system were used to evaluate the isotope temperatures. For these data points, the *total* available center-of-mass energy per nucleon has been chosen as the horizontal axis. However, as discussed in Section 2, only part of this energy is available for heating. For a proper comparison with the caloric curve determined by the spectator nuclei, one had to determine the thermal excitation energy *at normal density*. A lower limit for this energy can be obtained by subtracting the measured flow energies (figure 1) from the available center-of-mass energy. The corresponding data points are indicated by the open stars in figure 2. Even considering the fact that the flow energy generated during the expansion from normal nuclear density towards the freeze-out density should — for consistency — be included in the energy scale, the similarity between the caloric curves in central and peripheral collisions is quite impressive and may be viewed as a signal of common underlying physics in both types of reactions. Of course, a more quantitative understanding of the expansion dynamics will be required before the question can be answered whether and to what extent radial flow modifies the properties of the caloric curve.

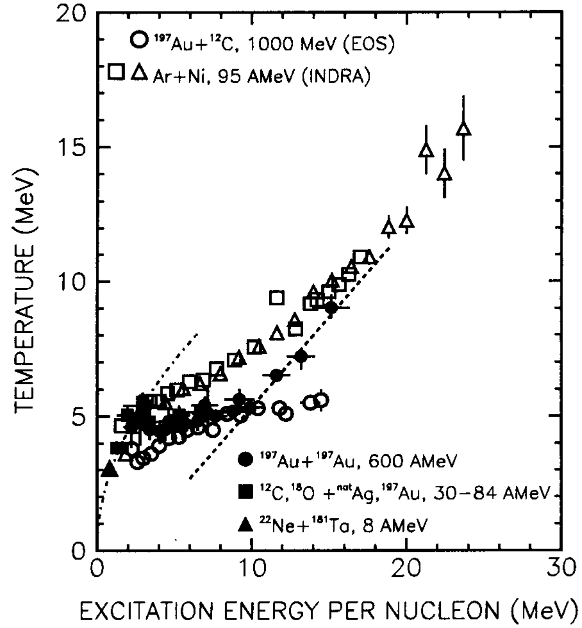

Fig. 3. Comparison of ALADIN's caloric curve (solid points) to results obtained by the EOS collaboration for spectators produced in Au+C reactions at 1000 AMeV [28] (open circles) and by the INDRA collaboration for quasi-projectiles produced in 95 AMeV Ar+Ni reactions [65] (open triangles and squares).

Figure 3 summarizes the presently available caloric curves measured via T_{HeLi} as defined in Eq. (2). A recent result of the EOS collaboration for ^{197}Au+^{12}C reactions at 1000 AMeV beam energy is shown by the open circles [28]. These data nicely confirm the plateau-like behaviour at intermediate excitation energies between 5 and 10 MeV per nucleon, though the rise at high excitation energies is not observed in that experiment. This is in line with a similar observation by the ALADIN collaboration at 600 MeV per nucleon Au induced reactions on light targets [66]. Though it is important to note that for the light carbon target the cross section strongly drops for Z_{bound} values below about 40. At small Z_{bound}, fluctuations in the decay as well as in the detection process might diminish the sensitivity of the event characterizing observable (here Z_{bound}) to the actual initial excitation energy for the central reactions in asymmetric systems. As a consequence, no reliable temperature values can be extracted from the ALADIN data for Z_{bound} values less than 30. If also for the excitation energy the Z_{bound} universality holds this means that only the 'plateau' region can be probed by C+Au reactions.

The different reaction geometry represents a further possible source for the deviation between Au+Au and Au+C reactions: in Au+C reactions the participant and spectator regions have a larger overlap in momentum space. In addition, spectator nuclei produced in Au+Au reactions might be more compact compared to more rarified spectators in the most central Au+C collisions.

A recent result of the INDRA collaboration for the Ar+Ni system at 95 AMeV [65] is indicated by the open triangles and squares in figure 3. In this reaction, the half of the projectile-like source pointing into the beam direction has been analyzed. While the caloric curve of this quasi-projectile exhibits the qualitative behaviour of the ALADIN caloric curve, the temperature appears to be systematically higher by about 1–2 MeV. Clearly, more systematic studies are needed in order to clarify whether this discrepancy is for example due to the definition of the decaying source (which in the Fermi-energy regime is not well separated from the fireball), the small size of the system in the Ar+Ni reaction ($\approx$ 32 nucleons [65]) or the different neutron-to-proton contents of the source.

5. Emission temperatures at high excitation energies

A first cross comparison of the T_{HeLi} thermometer with emission temperatures deduced from relative population of excited states gave compatible results for the ^{36}Ar+^{197}Au reaction at 35A MeV [67]. A similar agreement was also found in central Au+Au collisions at 35A MeV [63]. For a cross calibration of the two thermometer over a larger excitation energy region and in order to quantify the amount of sequential decay, the relative population of excited states in light fragments produced in Au+Au reactions at various beam energies was determined [64]. For this purpose the ALADIN spectrometer was supplemented by three hodoscopes consisting of 216 Si–CsI(Tl) telescopes.

In figure 4 we compare the isotope temperature T_{HeLi} (closed symbols) with apparent emission temperatures deduced from the relative population of states in ^{5}Li (open symbols). Here, the estimated random part of the available excitation energy is used as the horizontal axis. Note, however, that the energy scale is not of prime relevance for this comparison. In central collisions at beam energies between 50 and 200 MeV we observe a clear discrepancy between the isotope temperature (closed crosses) and the emission temperature (open crosses) which is increasing with rising beam energy. Besides the very low value for the emission temperatures of only 4 MeV, their constancy – despite an increase of the beam energy by a factor of four – is particularly striking. A similar divergence of the two thermometers is seen for the three uppermost central bins in spectator fragmentation at

600 resp. 1000 MeV per nucleon incident beam energy. Also there the emission temperatures (open circles) show a rather constant value, even though at a slightly higher level of about 5 MeV.

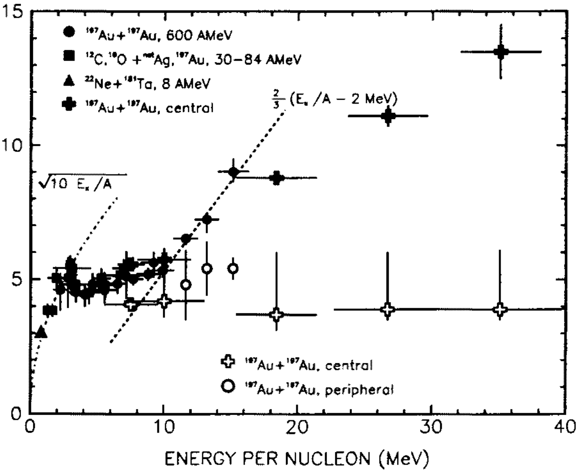

Fig. 4. Comparison of the caloric curve measured via the isotope temperature T_{HeLi} (closed symbols) with apparent emission temperatures deduced from the relative population of states in ^{5}Li (open symbols; the data point at E/A $\approx$ 7 MeV is from Ref. [63]; all other data from [64]).

If the population of excited states is indeed as small and constant as the emission temperatures suggest, sequential decays will only moderately disturb the isotope temperatures and, moreover, the relative correction will not change significantly with increasing excitation or beam energy. Surely this corroborates the isotope ratios as a robust thermometer. But it also implies that — although sequential decays undoubtfully affect the difference between the emission and isotope temperatures — sequential feeding alone can probably not account for the observed discrepancy between the two thermometers.

Lacking at the moment a quantitative explanation of this surprising observation, it might be instructive to recall a similar phenomenon during the cosmic big-bang. Also there different degrees-of-freedom freeze out at various stages of the big-bang evolution, hence signaling different temperatures. Of course, this cooling is intimately related to the existence of collective radial flow. It may, therefore, not be to surprising that the discrepancy between the two thermometer emerges as soon as collective flow starts to represent a significant part of the available energy. While such a scenario may help to explain the low values for the emission temperatures, it does not account for their surprising constancy. Especially in view of this observation a word of caution should be added. Microscopic calculations suggest, that the internal excitation of produced fragments may not only be influenced by the local momentum distribution of the surrounding nucleons but may also reflect correlations within the initial projectile [72, 53, 70, 73, 69] Furthermore, a detailed treatment of the quantum nature of the produced fragments warrants more attention in future studies (see for example [74, 75]). Finally, it remains to be seen whether an equilibrium approach is justified at all to describe a fast expanding nucleus decaying into quantum clusters.

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