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Probing the Nuclear Liquid-Gas Phase Transition

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Abstract

Fragment distributions resulting from Au+Au collisions at an incident energy of E/A=600 MeV are studied. From the measured fragment and neutron distributions the mass and the excitation energy of the decaying pre-fragments were determined. A temperature scale was derived from observed yield ratios of He and Li isotopes. The relation between this isotope temperature and the excitation energy of the system exhibits a behavior which is expected for a phase transition. The nuclear vapor regime takes over at an excitation energy of 10 MeV per nucleon, a temperature of 5 MeV and may be characterized

by a density of 0.15-0.3 normal nuclear density.

Stimulated by the van der Waals behavior of the nucleon - nucleon force [1–3] and supported by the observation of a power law for the produced fragments in proton induced collisions [4] the idea of a liquid-gas phase transition in nuclear matter emerged [1,2,5–7] and even speculations on a second order phase transition at the critical point [8] were raised [9,10]. In the subsequent years interest in this phenomenon faded once the universality - and the corresponding 'theory-invariance' - of the observed power-law and the associated critical exponent τ emerged (see e.g. refs. [11,12]). In the meantime, renewed interest arouse just because of the similarities between very different phenomena [13] and - most recently - because of the attempt to extract critical exponents of fragmenting nuclear systems produced in the interaction of 1 AGeV Au nuclei with a carbon target [14,15].

Searching for signals of a nuclear phase transition we are confronted with at least four complications which are inherent – albeit not specific – for nuclear systems:

(1) Nuclei are composed of a limited number of constituents. For finite systems a broadening of a phase transition [16,17] and a reduction of the critical temperature from its bulk value of 15-20 MeV is expected [2,17–20].

(2) Nuclei are charged. The long-range Coulomb-repulsion between the constituent protons introduces instabilities [21] which may lead to a considerable shift of the critical temperature downwards to values around 5 MeV [3,22,23].

(3) Nuclei are transient systems without external field (e.g. pressure) and will, therefore, expand prior to their disassembly [7,24–28]. Furthermore, the aggregation into clusters gives rise to an effective equation-of-state [29].

(4) Nuclei are closed systems without a heat bath. Consequently the temperature of the system cannot be pre-determined but has to be reconstructed from observable quantities.

Generally phase transitions of rather small clusters ($\sim$10 constituents) are still well defined, distinguishable [17,30–32] and even detectable [33]. Excited nuclei, however, are generated in energetic nucleus-nucleus collisions whose complex dynamical evolution may obscure or even destroy possible signals of a phase-transition. In this respect, spectator matter seems to be ideally suited to investigate a thermally-driven phase transition. As indicated by the universality of the projectile fragment distributions in these reactions [34], the memory of the entrance channel dynamics is lost prior to the decay of the spectators and the radial flow dynamics which was shown to affect the fragmentation process [35] is small in these systems [35,36].

This letter reports a search for a signal of a phase transition in projectile spectators which are produced in Au+Au collisions at E/A=600 MeV. The experiment was performed with the ALADIN forward spectrometer system [37] of the GSI facility. Time-of-flight and charge information for charged fragments with $Z \geq 2$ were provided by the TOF-wall with an efficiency close to 100%. The TP-MUSIC detector, equipped with 48 anode stripes and 18 multiwire proportional counters, allowed the measurement of the charges, positions and angles of fragments with $Z \geq 2$. Complete tracking information was obtained for 32% (70%) of all detected Z=2 (Z=10) particles. Combining this information with the time-of-flight measurement the masses of light fragments were determined with a resolution of about $\Delta A_{FWHM}=0.3$ (0.5) for Z=2 (Z=10) particles, respectively. Charged particles emitted beyond the acceptance of the ALADIN spectrometer were detected and separated according to Z in a 84 element Si-CsI(Tl) hodoscope placed in front of the magnet. Neutrons emitted from the projectile spectator were detected in the LAND detector [38] within an angular region of [-2.2^o,$+11.0^o$] horizontally and $\pm 4.1^o$ vertically. Depending on the impact parameter, between 50% and 70% of all neutrons emitted from the projectile spectator were detected. In order to exclude the participant region an angular constraint of $\theta_{lab} \leq 7.3^o$ in the laboratory system and a rapidity cut corresponding to approximately 70% of the beam rapidity was applied to all detected charged fragments and neutrons.

Following the suggestion of Campi and co-workers [39] we determine the average excitation energy for a given event sample by a total energy balance:

$$\langle E_0 \rangle = (\langle \sum_i m_i \rangle + \langle \sum_i K_i \rangle) - (\langle m_0 \rangle + \langle K_0 \rangle) \qquad (1)$$

Here, the sum runs over all decay products i within an event where m_i is the mass and K_i the kinetic energy. m_0 and K_0 denote the mass and kinetic energy of the decaying pre-fragment with mass number $A_0 = \sum_i A_i$ and charge $Z_0 = \sum_i Z_i$. The mass numbers A_i of He and Li fragments were obtained by randomly sampling the observed mass distribution. For simplicity,the mass numbers of heavier fragments were randomly chosen from mass distributions given by the semi-empirical EPAX parameterization [40] which was adjusted to the data of a previous study of Au+Pb reactions at E/A=600 MeV [36,41]. This simplification is justified since isospin correlations between coincident fragments were found to be small [36].

Since in the present experiment hydrogen isotopes could not be detected quantitatively, the analysis requires an assumption on the hydrogen composition and the N/Z ratio of the pre-fragment. Systematic uncertainties due to this missing information were estimated by varying the p:d:t ratio between 1:0.3:0.1 and 1:0.6:0.4, which are representative values for more peripheral and central collisions, respectively [42], and - independently - the N/Z ratio of the pre-fragment between N_0/Z_0(Au)=1.5 and N_0/Z_0=1.3.

The average kinetic energies of the individual fragment charges were evaluated from the transverse width of the momentum distributions. This procedure assumes isotropic decay [34] and disregards the contribution from a directed transverse motion of the primary projectile spectator. This latter contribution (K_0 in eq. 1) was estimated and corrected for on the basis of earlier measurements of the transverse momentum of the decaying projectile spectators in Au+Pb reactions at E/A=600 MeV [36].

Figure 1 shows the size of the pre-fragment $\langle A_0 \rangle$ and its excitation energy per nucleon $\langle E_0 \rangle / \langle A_0 \rangle$ as a function of Z_{bound} - defined as the summed charge of all observed fragments with $Z \geq 2$ [34] - for several gates on the largest observed charge Z_{max}. The error bars reflect the maximum variation of the systematic uncertainties discussed before [43]. Consistent with the results of ref. [39], the excitation energy per nucleon is nearly linearly increasing with decreasing Z_{bound} though in the present study the maximum value of 16 MeV per nucleon is somewhat lower in the present analysis but still lies well above the binding energy of nuclei. Whereas the size of the pre-fragment depends only on Z_{bound} the present analysis reveals an additional dependence of the excitation energy on Z_{max}.

For a nuclear system at low density and in chemical and thermal equilibrium a measure of the temperature of the system may be obtained via double ratios of two isotope pairs differing by one neutron each [44]. Following this work we define a temperature T_{HeLi} in terms of the yield ratios ^{3}He/^{4}He and ^{6}Li/^{7}Li

$$T_{HeLi} := 16/ln(2.18 \cdot \frac{Y_{6Li}/Y_{7Li}}{Y_{3He}/Y_{4He}}). \qquad (2)$$

In order to test this definition we analyzed the results of several decay calculations. The quantum statistical model [45,46] predicts an almost linear dependence of T_{HeLi} on the actual temperature T of the system. The ratio T_{HeLi}/T varies between about 1.15±0.05 and 0.9±0.05 for breakup densities of $0.1\rho_0$ and $0.5\rho_0$, respectively. Results of sequential evaporation calculations with the code GEMINI [47] also confirm a nearly linear relation between T_{HeLi} and the *initial* temperature of the system $T = \sqrt{k \cdot \langle E_0 \rangle / \langle A_0 \rangle}$, where k denotes the inverse level density parameter. In line with QSM calculations for higher densities the ratio T_{HeLi}/T amounts to about 0.85. Finally, also the microcanonical multifragmentation model of Gross and co-workers [23] predicts a rather constant ratio of 0.85±0.05 between T_{HeLi} and the thermodynamic temperature of the system. Thus, T_{HeLi} provides within ±15% a common temperature scale in the evaporation, fragmentation and vapor regimes which are covered by the three models mentioned. Furthermore, these results justify our choice of the prefactor in Eq. 2 which was - motivated by the strong feeding of the α-particle yield via sequential decays of primary, excited fragments - increased a priori by 20% as compared to the ideal situation [44] where only fragments in their ground-states are considered.

Figure 2 shows the isotope temperature as a function of the total excitation energy per nucleon. Excitation energy - temperature pairs of this caloric curve extracted for projectile spectators of Au+Au collisions at E/A=600 MeV are marked by the solid points. Data for target residues produced at intermediate energies between E/A=30 and 84 MeV are shown by the open squares. In the latter case, the excitation energies were also deduced from an energy balance [51] and T_{HeLi} was evaluated using the coincident light particle yields associated with emission from the target remnant [52]. Because of the finite width of the excitation energy distribution and the exponentially decreasing production rate of ^{3}He towards low excitation energies temperatures can not be determined for excitation energies below approximately 2 MeV per nucleon in the present study. The only value for T_{HeLi} in the evaporation regime below 2 MeV per nucleon excitation energy [48,49] is provided by the $^{22}Ne+^{181}Ta$ fusion reactions at E/A=8.1 MeV [50] and is marked by the triangle in Fig.1.

The caloric curve shown in Fig. 2 can be divided in three distinctly different sections. In line with previous studies in the fusion evaporation regime [48,49] the rise of T_{HeLi} for excitation energies below 2 MeV per nucleon is compatible with the low-temperature approximation of a fermionic system

$$T = \sqrt{k \cdot \langle E_0 \rangle / \langle A_0 \rangle}. \tag{3}$$

For orientation the solid line depicts relation (3) for an inverse level density parameter of k=10 MeV. 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. This plateau may be related to the finding of rather constant emission temperatures over a broad range of incident energies which were deduced from the population of particle unstable levels in He and Li fragments [53]. We also note that the mean excitation energy of the plateau coincides with the limiting excitation energy for the fusion-evaporation process of about 4.5-6.4 MeV per nucleon [54]. 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 which may be described by a linear relation

$$T_{HeLi} = 2/3 \cdot (\langle E_0 \rangle / \langle A_0 \rangle - 2MeV) \tag{4}$$

where the slope of 2/3 alludes to a gas of classical, elementary particles.

The offset in eq. (4) probably signals a freeze out at a finite density. Assuming, for simplicity, a parabolic shape for the low density equation-of-state of the finite nuclear system [55]

$$(E/A)_{T=0} = K_c/18 \cdot (1 - \rho/\rho_0)^2 - 8MeV \tag{5}$$

and adding the excitation energy for a Fermi-Dirac gas at finite density the data in the vapor regime at $\langle E_0 \rangle / \langle A_0 \rangle > 10$ MeV can be explained with a constant freeze-out density between ρ/ρ_0= 0.15 and 0.3 if the compressibility K_c is varied between 144 and 300 MeV. While this interplay between the expansion dynamics and the density dependent properties of a Fermi gas might help to elucidate the gross features of the vapor branch one has to keep in mind that also in this regime typically 20% of the mass of the decaying system is contained in intermediate mass fragments. An internally consistent equation-of-state taking into account the clusterisation [29], the particle loss during the expansion [26,28] and the systematic variation of the source size (Fig. 1) is therefore required before more definite conclusions can be drawn.

In summary, we have studied fragment distributions resulting from Au+Au collisions at an incident energy of E/A=600 MeV. From the observed fragment and neutron distributions the masses and excitation energies of the decaying pre-fragments were determined. A temperature scale was derived from observed yield ratios of He and Li isotopes. Rising first strongly with increasing excitation energy, the isotope temperature stays rather constant at a value of about 5 MeV for excitation energies between 3 and 10 MeV per nucleon. For higher excitation energies, again an increasing temperature is found. Depending on the low density equation-of-state the freeze-out in this vapor regime may by characterized by a density between 0.15 and 0.3 of normal nuclear density. The observed caloric curve agrees qualitatively with predictions of the Copenhagen multifragmentation model [22] and is reminiscent of the paradigm of a phase transition, the first-order phase transition of bulk (and also finite [32]) H_2O - systems. Whether the present observation can be reconciled with a second-order phase transition - which is a prerequisite for the determination of critical exponents - will be an interesting task for future studies.

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FIGURES

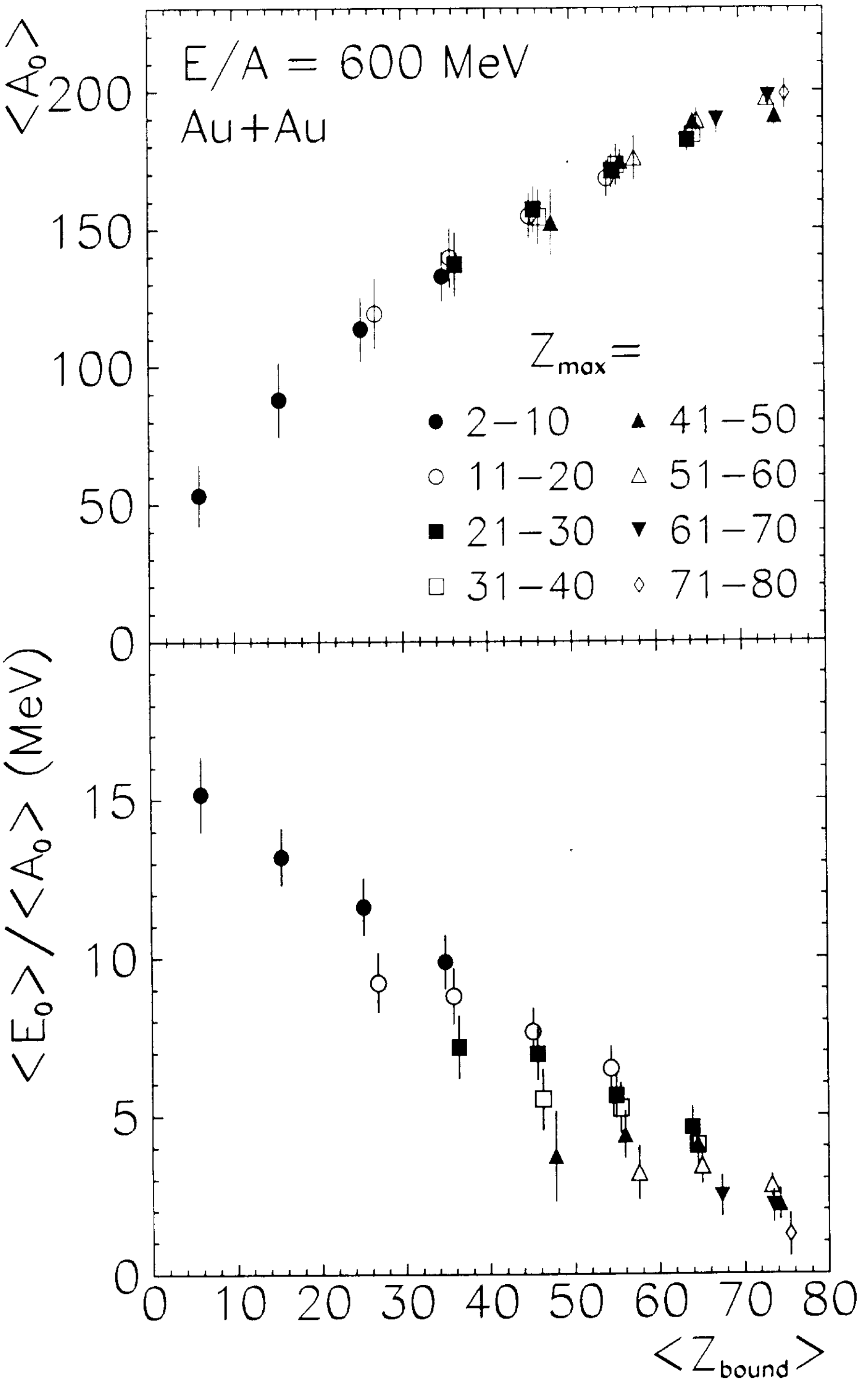

FIG. 1. Average prefragment size $\langle A_0 \rangle$ and its excitation energy per nucleon $\langle E_0 \rangle / \langle A_0 \rangle$ as a function of Z_{bound} and different bins in Z_{max}.

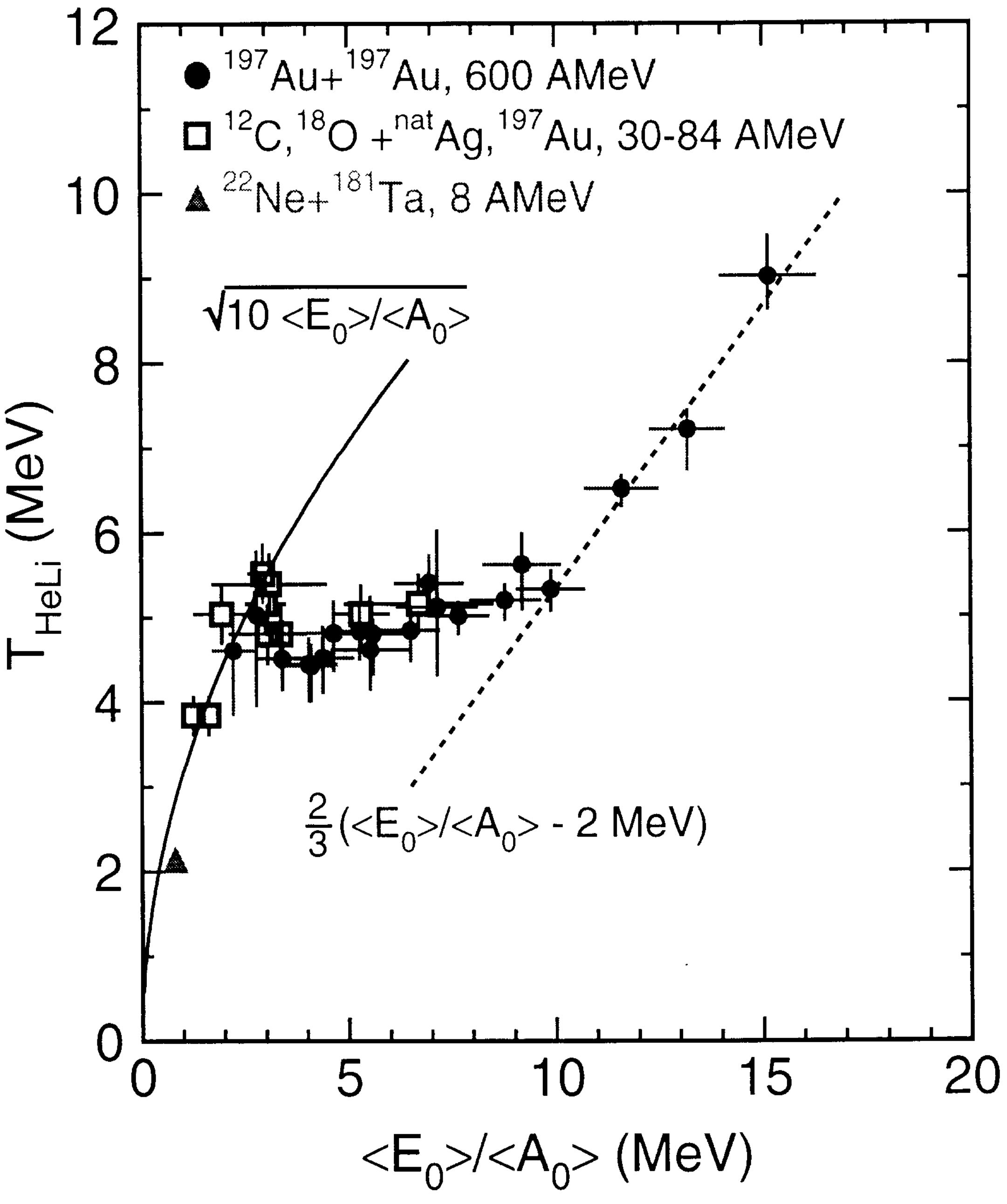

FIG. 2. Caloric curve of nuclei determined by the dependence of the isotope temperature T_{HeLi} on the excitation energy per nucleon. The lines are explained in the text.