Probing the Nuclear Liquid-Gas Phase Transition

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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 prefragments 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.

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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 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 arose 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*A* GeV 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 are 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 predetermined 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 (TOF) and charge information for 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

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with the time-of-flight measurement, the masses of light fragments were determined with a resolution of about $\Delta A_{\mathrm{FWHM}} = 0.3$ (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 an 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 $[-2.2°, +11.0°]$ horizontally and $\pm 4.1°$ 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 $\theta_{\mathrm{lab}} \leq 7.3°$ in the laboratory system and a rapidity cut corresponding to approximately 70% of the beam rapidity were applied to all detected charged fragments and neutrons.

Following the suggestion of Campi, Krivine, and Plagnol [39], we determine the average excitation energy for a given event sample by a total energy balance:

$$\langle E_0 \rangle = \left(\left\langle \sum_i m_i \right\rangle + \left\langle \sum_i K_i \right\rangle \right) - (\langle m_0 \rangle + \langle K_0 \rangle). \quad (1)$$

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 prefragment 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 semiempirical EPAX parametrization [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 prefragment. 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 prefragment between $N_0/Z_0(\mathrm{Au}) = 1.5$ 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. The mean kinetic energy of hydrogen fragments was calculated by adding a Coulomb energy of $1.44 Z_0/(2A_0^{1/3})$ to the mean neutron energies. This procedure assumes isotropic decay [34,43] 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 prefragment $\langle A_0 \rangle$ 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 [44]. Consistent with the results of Ref. [39], the excitation energy per nucleon is nearly linearly increasing with decreasing Z_{bound} though the maximum value of 16 MeV per nucleon is somewhat lower in the present analysis [39] but still lies well above the binding energy of nuclei.

For a nuclear system at low density and in chemical and thermal equilibriums a measure of the temperature of the system may be obtained via double ratios of two isotope pairs differing by one neutron each [45]. Following this work we define a temperature T_{HeLi} in terms of the yield ratios $^3\mathrm{He}/^4\mathrm{He}$ and $^6\mathrm{Li}/^7\mathrm{Li}$,

$$T_{\mathrm{HeLi}} := 16/\ln\left(2.18 \times \frac{Y_{6\mathrm{Li}}/Y_{7\mathrm{Li}}}{Y_{3\mathrm{He}}/Y_{4\mathrm{He}}}\right). \quad (2)$$

In order to test this definition we analyzed the results of several decay calculations. The quantum statistical model (QSM) [46,47] 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

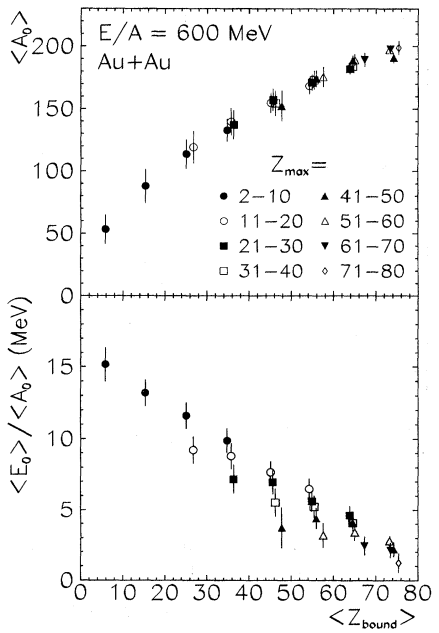

FIG. 1. Average prefragment size $\langle A_0 \rangle$ and its excitation energy per nucleon $\langle E_0 \rangle / \langle A_0 \rangle$ as a function of Z_{bound} and different bins in Z_{max}.

with the code GEMINI [48] also confirm a nearly linear relation between T_{HeLi} and the *initial* temperature of the system $T = \sqrt{k\langle E_0\rangle/\langle A_0\rangle}$, 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 [23] predicts a rather constant ratio of 0.85 $\pm$ 0.05 between T_{HeLi} and the thermodynamic temperature of the system. Thus T_{HeLi} provides within $\pm 15\%$ 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 [45], 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 [49], and T_{HeLi} was evaluated using the coincident light particle yields associated with emission from the target remnant [50]. The only value for T_{HeLi} in the evaporation regime below 2 MeV per nucleon excitation energy [51,52] is provided by the

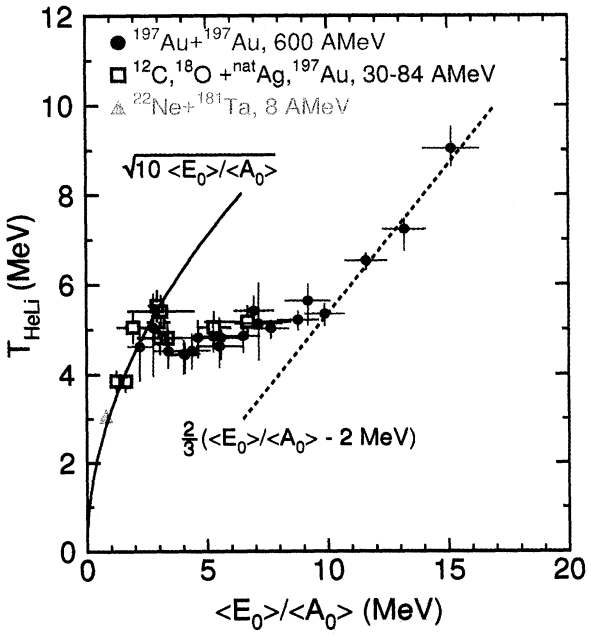

FIG. 2. Caloric curve of nuclei determined by the dependence of the isotope temperature T_{HeLi} on the excitation energy per nucleon. The lines are explained in the text.

^{22}Ne + ^{181}Ta fusion reactions at $E/A = 8.1$ MeV [53] and is marked by the triangle in Fig. 2.

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 [51,52] the rise of T_{HeLi} for excitation energies below 2 MeV per nucleon is compatible with the low-temperature approximation of a fermionic system

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

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 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 [54], though a quantitative calibration of the two thermometers remains an interesting task for future experiments. 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 [55]. 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

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

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 a parabolic shape for the low-density equation of state of the finite nuclear system [56]

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

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 $\rho/\rho_0 = 0.15$ and 0.3, if the compressibility K_c is varied between 144 and 300 MeV. Of course, more quantitative conclusions will require an internally consistent equation of state taking into account the clusterization [29], the particle loss during the expansion [26,28], and the systematic variation of the source size (Fig. 1).

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 prefragments 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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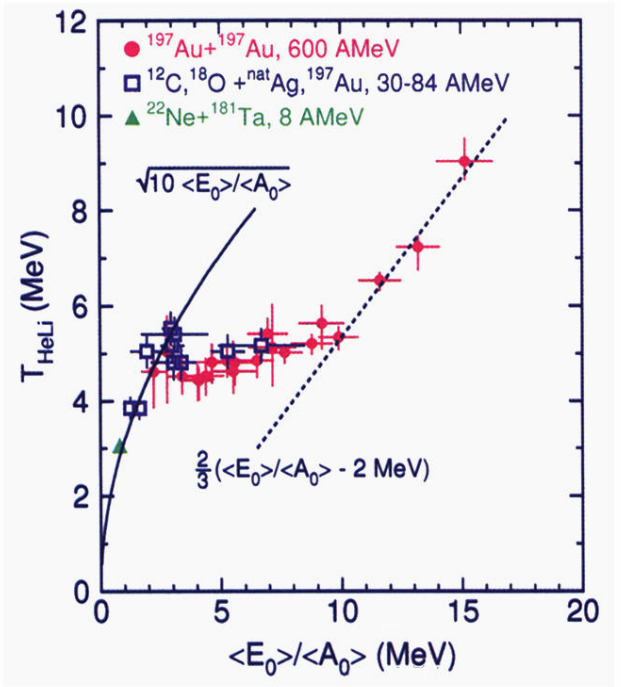

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