The nuclear liquid–gas phase transition within FMD

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A recent experimental attempt by the ALADIN group [1] to deduce an equation of state, which relates the excitation energy of a hot nucleus to its temperature, has stimulated both, theoretical and experimental efforts in this field. In the experiment excited projectile spectators were investigated in Au+Au collisions at a beam energy of E/A = 600 MeV. While the equation of state refers to a stationary system where liquid and vapour (evaporated nucleons) are in equilibrium, the experiment deals with an expanding source. This causes some uncertainties for the temperature, which is deduced from isotope ratios, because the system cools while it is expanding.

In molecular–dynamics calculations the finite system may be excited in a thermal manner, but similar problems arise when the phase transition sets in. Particles which escape from the nucleus cool down the residue and thermal equilibrium between liquid and vapour cannot be maintained. In order to avoid these difficulties, in the present simulations the excited nuclear system is confined by a wide container potential which is chosen to be a harmonic oscillator potential. Due to the containment evaporated nucleons cannot escape, but form a cloud of equilibrated vapour around the excited nucleus.

Thermodynamic relations are obtained by coupling the nuclear system to a reference system which serves as a thermometer. Both, the time–evolution of the nuclear system and of the thermometer are described by the Fermionic Molecular Dynamics (FMD) model [2]. Assuming thermal equilibrium in the sense of ergodicity [3] the temperature of the nuclear system is derived from the time–averaged energy of the thermometer and related to the time–averaged excitation energy of the nucleus [4].

The caloric curve shown in fig. 1 clearly exhibits three different parts. Beginning at small excitation energies the temperature rises steeply with increasing energy as expected for the shell model (full line). The nucleons remain bound in the excited nucleus which behaves like a liquid drop. At an excitation energy of 3 MeV per nucleon the curve flattens and stays almost constant up to about 11 MeV. This plateau at $T \approx 5$ MeV indicates the coexistence of liquid and vapour phases. At the beginning of the plateau the system contains only few evaporated nucleons which are in equilibrium with the residual excited liquid drop. Towards the end of the coexistence region the system contains small intermittent condensed fragments which may amalgamate or dissolve into vapour again. Around $E^*/A \approx 11$ MeV all nucleons are unbound and the system has reached the vapour phase. This is indicated by the steep rise of the caloric curve beyond this point. The "error bars" denote the fluctuations in temperature and excitation energy which arise from the energy exchange between thermometer and nucleons. Only the total energy of the system (nucleons & thermometer) is conserved.

In the excitation energy range between 3 and 11 MeV per particle the increasing number of nucleons in the vapour phase outside the liquid can be seen in the density plot fig. 2, where the radial dependence of the time–averaged density of the system of 24 nucleons is shown at three excitation energies in the coexistence region. For small excitations (E^*/A = 4.0 MeV) the nucleus, which due to recoil is bouncing around, is surrounded by very low density vapour (solid line). The dashed–dotted line (E^*/A = 7.4 MeV) and the dashed line (E^*/A = 11.2 MeV) show that with increasing energy the vapour contribution is growing and the amount of liquid decreasing. Above $E^*/A \approx 13$ MeV only vapour is observed.

The surprising close correspondence of this equilibrium caloric curve with the measured one [1] has to be investigated, in particular the role of the expansion and non-equilibrium effects.

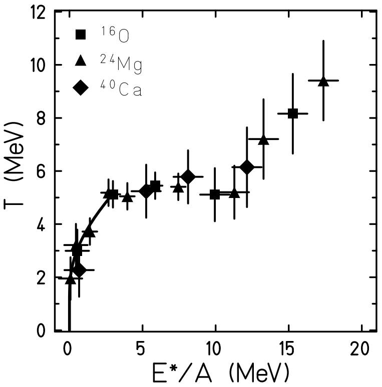

Figure 1: Caloric curve for ^{16}O–, ^{24}Mg– and ^{40}Ca–nuclei.

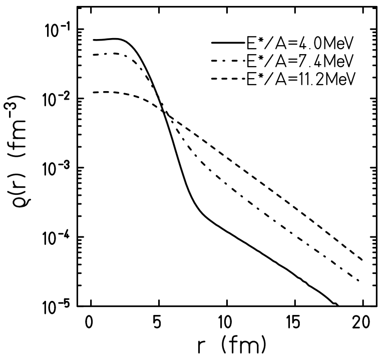

Figure 2: Radial density distribution of ^{24}Mg at various excitation energies in the coexistence region.

References

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[3] J.Schnack, H. Feldmeier, Nucl. Phys. **A601** (1996) 181
[4] J. Schnack, dissertation, TH Darmstadt (1996) (copy from `http://www.gsi.de/~schnack`)