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PHASE TRANSITIONS IN HIGHLY EXCITED NUCLEI[*]

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Phase transition in highly excited nucleus is treated in terms of thermodynamics of microensembles. The emission of intermediate mass fragments from pure thermally excited heavy nucleus ^{197}Au is an indication of the liquid to fog phase transition. Evidence of the spinodal decomposition of the heavy nuclear system is found and its relation to the multisaddle transition configuration and freeze-out state is presented.

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1. Why liquid to gas phase transition in nuclear physics?

During the 14 Gyr since the Big Bang the matter of the expanding Universe was subject to different phase transitions [1] from quark–gluon plasma to hadronic phase, nucleon gas phase to nuclear liquid phase, nucleon–electron plasma to atomic phase, condensed matter gas to liquid and liquid to solid state phase. Till present days it was impossible to create in the laboratory conditions to compress nucleon gas (protons and neutrons) to form nuclei. In thermonuclear explosions nuclei up to ^{4}He can be produced but the starting point would require nuclei like deuterium ^{2}H, lithium ^{6}Li

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or tritium ^{3}H. Light nuclei in the Universe can be of primordial origin from the Big Bang explosion or are produced in the interior of the stars. Stars are born around the inhomogeneities of the matter distribution in space due to the attractive gravitational force. Slow burning process regulated by the primary weak interaction reaction $p + p \to e^+ + d + \nu_e$ can be a source of nuclei up to ^{56}Fe. Heavier nuclei with N/Z ratio higher than one can be created only in phenomena like novae and supernovae explosions.

Thus in the laboratory as far as nuclei are concerned we can study only the liquid to gas phase transitions through the decay of highly excited nuclear states. The availability of various heavy ion beams allows us to create nuclei at various excitation energies, spins, izospins, compression and shape deformation. There is a great challenge to theorists to disentangle all these quantities and to find clear evidence of the phase transition and its order.

2. Microcanonical ensembles

The nucleus is an inhomogeneous non extensive object composed of a limited number of nucleons not exceeding 300. Non extensive means that $S \neq\ S_1 + S_2$, $E \neq\ E_1 + E_2$, where S and E indicate the total entropy and the total energy of the nucleus and S_1, S_2, E_1 and E_2 are entropies and energies of its parts. Forces between the constituent particles are of comparable or longer range (coulomb potential) than the size of the object. Good examples are the following objects: nuclei, stars, charged liquid droplets. Therefore, the microcanonical thermodynamics seems to be the proper one to describe the nuclei [2, 3]. There exists a hierarchy of ensembles: microcanonical ⇒ canonical ⇒ grand canonical in which the content of information about the system diminishes from the left to right. Conserved quantities are: total baryon number N, total energy E, total momentum $\boldsymbol{P}_{\rm tot}$, total angular momentum $\boldsymbol{J}_{\rm tot}$, total charge Z. Natural question arises: how to detect phase transitions and their order in the microcanonical ensemble? Extension of the conventional macroscopic and homogeneous thermodynamics to small object (*e.g.* 100 nucleons) is needed (although formally impossible).

The microcanonical partition sum (function) $W_f^{\rm mic}(E, T, A, Z, V)$ is defined as the sum of all multinucleonic (hadronic) quantum states localized in the volume V within a certain energy interval ϵ_0 keeping conserved quantities like energy E, baryon number A, charge number Z, total momentum $\boldsymbol{P}_{\rm tot}$, total angular momentum $\boldsymbol{J}_{\rm tot}$. In the microcanonical ensemble all partitions are equally probable. Knowing W we can calculate the entropy S, chemical potential μ, temperature T and pressure P:

$$S = k \ln\, W\,. \tag{1}$$

This famous formula forms an inscription on the grave stone of Boltzmann.

The following formulae hold:

$$
\begin{aligned}
\frac{1}{T} &= \frac{\partial S}{\partial E}\,, && (2)\\
\mu &= -T\,\frac{\partial S}{\partial N}\,, && (3)\\
P &= T\,\frac{\partial S}{\partial V}\,, && (4)\\
W_f^{\rm mic} &\sim \exp\bigl[S_F(E,V,A,Z,\boldsymbol{J}_{\rm tot},\boldsymbol{P}_{\rm tot})\bigr] && (5)
\end{aligned}
$$

in micro thermodynamical ensemble all partions $W_f^{\rm mic}$ are equally probable. If H_N indicates the N body Hamiltonian, ϵ_0 is small energy interval, p and q are generalized coordinates, then:

$$
\begin{aligned}
W(E,N,V,\ldots) &= \epsilon_0\,{\rm Tr}\,\delta(E-H_N)\,, && (6)\\
{\rm Tr}\,\delta(E-H_N) &= \int d^{3N}p\,d^{3N}q\,\frac{1}{(2\pi\hbar)^{3N}N!}\,\delta\bigl[E-H_N(q,p)\bigr]\,. && (7)
\end{aligned}
$$

3. Multifragmentation of highly excited nuclei

At the excitation energies of 3–10 AMeV a copious emission of intermediate mass fragments *i.e.* light nuclei with $2 < Z \leq 20$ is observed. This emission may be a sign of a liquid to gas phase transition and can be treated in terms of the microcanonical thermodynamics. The main characteristics of this process are listed below:

1. It occurs nearly simultaneously, within the short time interval from 50 fm/c to 100 fm/c.
2. Fragments are accelerated by the Coulomb field from what is called freeze-out radius.
3. Fragments are emitted symmetrically in the source coordinate system.
4. Flattening of the caloric curve is observed.
5. Fluctuation $\sigma_{\rm K}^2 = \langle K^2\rangle - \langle K\rangle^2$ of the measured kinetic energy release K is observed from event to event.
6. Charge dependence of emitted IMF's has an exponential character $Z^{-\tau}$ with the value of $\tau \approx 2$.
7. Negative specific heat capacity indicates a phase transition of the first order. Let us consider

$$E_{\rm t} = E_{\rm K} + E_{\rm P}\,, \qquad (8)$$

where E_{t} is the total energy, E_{K} total kinetic energy of constituents and E_{P} indicates total potential energy. Total heat capacity is:

$$\frac{1}{C_{\mathrm{t}}} = -T^2 \frac{\partial^2 S}{\partial E_{\mathrm{t}}^2} \,. \tag{9}$$

Then, according to D'Agostino *et al.* [4],

$$\frac{C_{\mathrm{t}}}{A} = C_{\mathrm{K}} + C_{\mathrm{P}} = \frac{C_{\mathrm{K}}^2 T^2}{C_{\mathrm{K}} T^2 - \sigma_{\mathrm{K}}^2} \,, \tag{10}$$

where

$$\sigma_{\mathrm{K}}^2 = \langle K^2 \rangle - \langle K \rangle^2 \,. \tag{11}$$

8. Anticorrelation between thermal protons bremsstrahlung and emitted IMF's is observed.
9. Disappearance of the gamma quanta of the giant dipole resonance was also noticed.
10. Influence of the centrifugal flow in case of noncentral collisions is noticed. An example of the proof of the existence of the phase transition of the first order can be found in the paper of Chomaz [5].

4. Pure thermally excited nucleus

Pure thermal excitation of heavy nuclei with fast relativistic projectiles has been proposed by Karnaukhov *et al.* [6]. The principle of this method is shown in Fig. 1 Relativistic light projectile passes through the heavy nucleus starting an intranuclear cascade [7]. The recoiled nucleons, clusters with energies higher then their binding energy in the heavy nucleus are ejected out of the nucleus. Part of the recoiled nucleons or clusters of lower energies are left inside the nucleus. A substantial fraction of particles can still be emitted as preequilibrium ejectiles. The final energy left in the target nucleus has a form of pure thermal energy. There is no rotation, compression

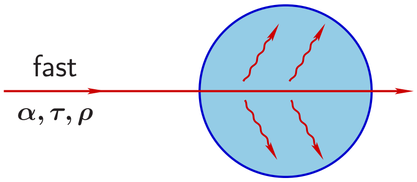

Fig. 1. Heating the nucleus by fast light particle.

or shape distortion causing additional difficulties in the calculation of the decay of the formed excited system. After the time of a few tens of fm/c the excited nucleus expands and subsequently explodes into preformed IMF's at the so-called freeze-out radius. The freeze-out radius studied by many experimental and theoretical groups is about 1.4–1.8 R_0, where R_0 indicates the radius of the nucleus in its ground state. Nucleus is a small nonextensive system of nucleons interacting beside short range nuclear forces also by long range coulomb fields. So the analysis of the experimental data on the Z distribution of IMF's and energy spectra was performed in the frame of the microthermodynamical model. We have used the SMM (statistical multifragmentation) model of Bondorf *et al.* [8]. The following method of analysis was accepted. First the excited nucleus during the slow thermal expansion process has to reach the point at which it decides how it will decay. We call it the transition point or multisaddle configuration. We did a series of calculations of the Z distribution for different values of the volume V of the system and determined V_t (transition volume) at which the best fit was obtained. SMM gave us also the value of temperature T_t of the transition state. Next we have calculated the energy distribution for selected IMF's (carbions) in coincidence with the signal from the multiplicity detector for different values of the freeze-out volume V_f. The calculations were performed for spectra measured inclusively or in coincidence with the multiplicity signal. The results are shown in Table I and Figs 2, 3, 4, and 5. As can be seen, the determined freeze-out volume is notably larger then the transition volume. There is also a big difference (factor of two) between the values of V_f based on inclusive and exclusive data in coincidence with IMF's multiplicities. It is then possible to study the multifragmentation decay of one slowly moving single source. The excitation energy of this source remnants of ^{197}Au is of the order of 900 MeV and the mean mass number $\sim$ 173 amu. This leads to the estimation of the excitation energy of 5 AMeV, well in the region of multiple intermediate mass fragments emission. According to

TABLE I

Values of the ratios of the transition volume V_t and freeze-out volume V_f to the values of the ground state volume V_0.

Volume	V_t/V_0	V_f/V_0
Inclusive data	2.9 ± 0.2	11 ± 3
Exclusive data	2.6 ± 0.3	5 ± 1

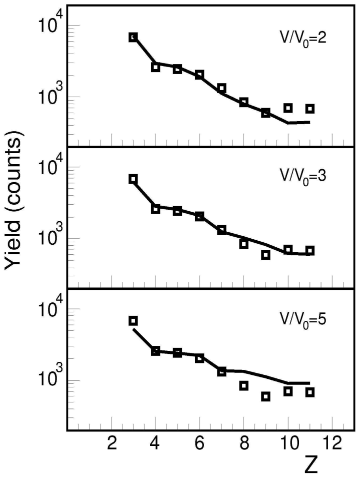

Fig. 2. Z distribution for different values of the ratio of the volume V to the ground-state volume V_0.

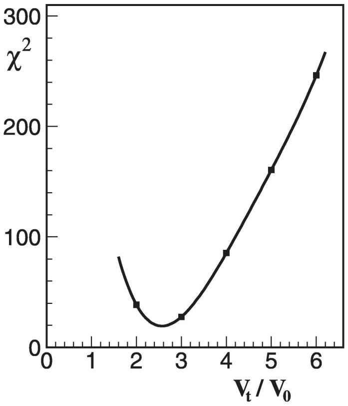

Fig. 3. The value of χ^2 as a function of V_t/V_0.

Gross [2] massive IMF's emission is an indication of the liquid to droplets (fog) transition. Experiment was performed with the 8.1 GeV proton beam from the JINR synchrophasotron at Dubna. Spectra of emitted particles from the ^{197}Au were measured with the FASA detector [9]. Multiplicity of IMF's were measured with 64 thin CsJ(Tl) scintillator counters which served as multiplicity detector. Spectra of emitted IMF's were recorded with 5 silicon telescopes. Since the analysis with SMM allowed us to determine the transition volume V_t or transition density ρ_t, the freeze-out volume V_f or freeze-out density ρ_t as well as the temperatures of the corresponding points T_t, T_f we have put forward a conjecture that in this case we have to deal

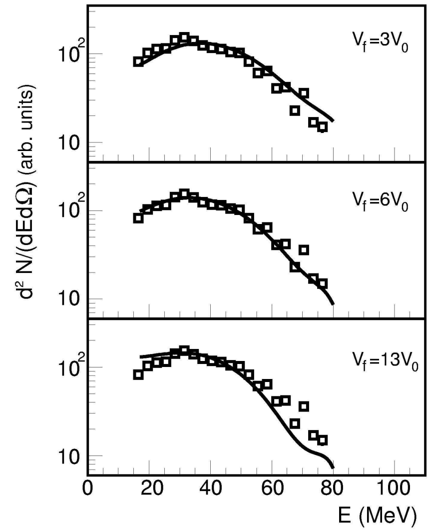

Fig. 4. Kinetic-energy spectrum of carbon ions emitted from pure thermally excited target spectator nucleus, calculated for different $V_{\rm f}$ volumes.

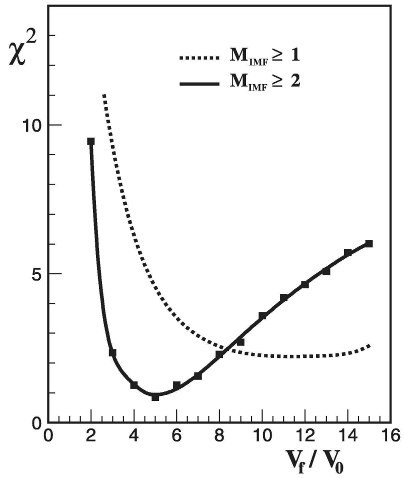

Fig. 5. The value of χ^2 as a function of the ratio $V_{\rm f}/V_0$, for the inclusive $M_{\rm IMF} \geq 1$ and exclusive $M_{\rm IMF} \geq 2$ data.

with a spinodal decomposition of the system. In Fig. 6, the path from the ground state liquid at normal density and zero temperature to the excited states lying in the region of spinodal instability in the (T, ρ) graph is shown. We have indicated also the value of the critical temperature of nuclear liquid taken from Karnaukhov *et al.* [10].

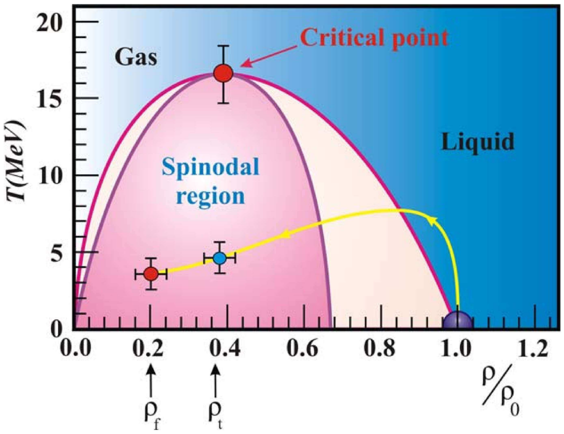

Fig. 6. Proposed spinodal path of the fragmentation of thermally excited ^{197}Au.

The obtained results seem to solve the existing differences in the determination of the critical temperature for the liquid to fog or liquid to gas phase transition between the different groups of authors of experimental or theoretical papers on this subject [10–16]. Our conclusion is that values of T around 5–10 MeV are spinodal decomposition break-up temperatures T_b and values around 18–20 MeV are critical temperatures above which nuclear liquid cannot exist.

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