NUCLEAR BIG BANG*

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Possible existence of a new decay mode of highly excited nuclear matter is discussed. Experimental data are shown which suggest that a violent nuclear disassembly occurs at matter density considerably smaller than in normal nuclei. Several attempts to find signatures of instantaneous multifragmentation are evaluated. Prediction of various models ranging from statistical to quantum molecular dynamical ones are presented.

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1. Introduction

One of the most interesting features of the heavy ion induced reactions is the possibility to create various states of nuclear matter i.e. density, temperature, excitation energy. This opens a unique possibility to study nuclear equation of state, critical phenomena and other properties of nuclear matter.

It has been recently pointed out by Gross [1], Bondorf [2], Randrup [3], Friedman [4] and Bertsch [5] that the thermally equilibrated nuclear state at the density ρ equal $^1/_6$– $^1/_8$ of the normal ground state density will decay within few times 10^{-23} sec into clusters of masses intermediate between α particles and fission fragments. The fragments are moving outwards due to coulomb repulsion. I am calling this violent explosion nuclear big bang in analogy to the Big Bang which is believed to start the expanding Universe.

The existence of such a highly unstable nuclear state has been conjectured by several theorists [9, 10]. Many experimental results support this conjecture although no absolutely convincing evidence of multifragmentation from such peculiar excited low density state exists at the moment.

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In the present lecture I will discuss results of some experiments with the aim to prove experimentally the existence of nuclear instantaneous multifragment emission. Two basic theoretical models, *i.e.* the statistical model and the quantum molecular dynamical one, will be presented in more details.

2. Little and Big Bangs

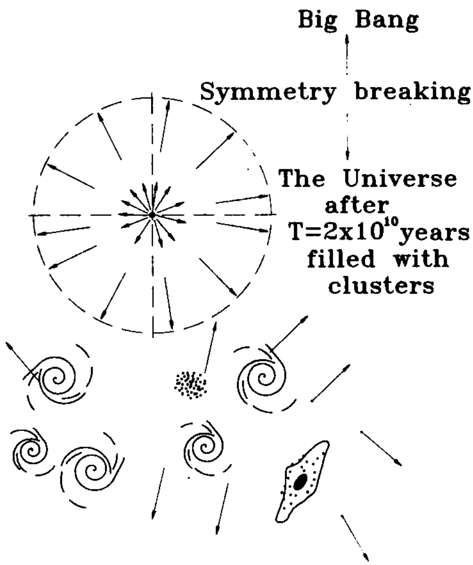

Fig. 1. The expanding and clusterized Universe.

Since the nucleus is a small object its explosion is sometimes called a Little Bang. Some fundamental similarities and differences between the Nuclear Little Bang and Universe Big Bang can be read from Figs 1 and 2. As a consequence of various fundamental interactions and symmetry breaking processes the expanding Universe at the age $T = 2 \times 10^{10}$ years is filled with matter in a form of clusters. We have stars, galaxies, clusters of stars, clusters and superclusters of galaxies. A highly excited nuclear system at the freeze-out density decays into clusters of nucleons within the characteristic time $\tau = 10^{-22}$ sec. We notice that the ratio of T/τ is to the order of magnitude equal to the ratio of the electromagnetic to the gravitational forces what is a nice illustration of the fundamental property of physical systems whose life times are proportional to the reverse of the strength of forces acting between its components.

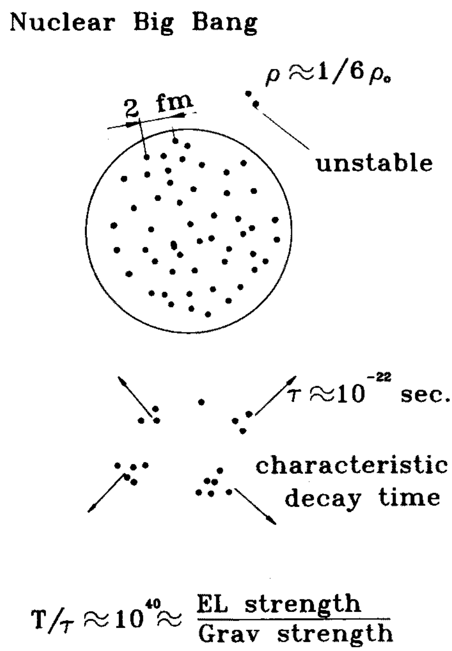

Fig. 2. The nucleus exploding into clusters.

3. Creation and decay of very hot nuclei

In this lecture we are dealing with nuclei excited to the energies close to the stability limit against total disintegration. There are two methods to produce such excitations. One method illustrated in Fig. 3 is the passage of fast light particle of the energy around few GeV per nucleon. The cascade which develops around the track of the projectile produces several low energy ejectiles (recoiled nucleons, pions) which excite the target. The target acts here as a spectator which stays practically at rest in the lab. system. The target is heated up without the compression phase and expands thermally reaching the freeze-out radius at which it decays suddenly into many intermediate mass fragments.

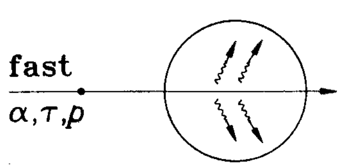

Fig. 3. Heating the nucleus by fast light particle.

The second method is a collision of two nuclei of comparable masses. In the central collisions we have a compression and the decompression phase

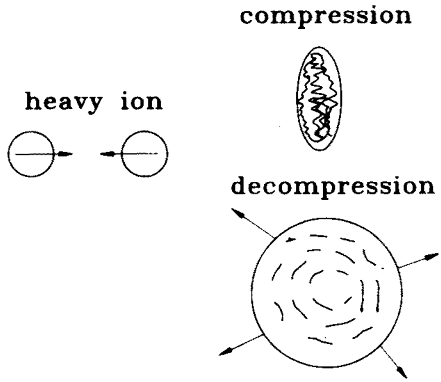

Fig. 4. Heating the fused nucleus in heavy ion collision.

(see Fig. 4). In the decompression phase the nucleus can reach the freeze-out instability radius and decays into many fragments. The statistical model can successfully describe the distribution of masses and angular correlations of fragments starting from the freeze-out radius. It cannot tell us, however, how this configuration was reached. The time development of the collision until the freeze-out configuration can only be described by the microscopic molecular dynamical model. In the past 10 years several versions of the quantum molecular models have appeared on the market. An example of the time dependence of the nucleon density distribution in the collision of $^{32}S + {}^{58}Ni$ at 30 MeV/n calculated by Lukasik [6] is shown in Fig. 5.

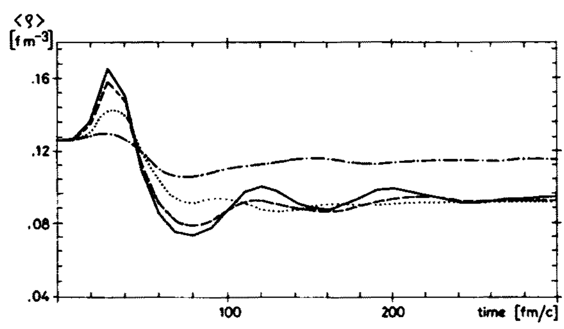

Fig. 5. Time dependence of the nucleon density in the $^{32}S + {}^{58}Ni$ collision at 30 MeV/n calculated by Lukasik in terms of the QMD model [6].

The decay of an excited nucleus can proceed through a chain of binary evaporation events or simultaneous emission of many intermediate mass fragments. We call the first mode of the decay a sequential one. The second one is called instantaneous one. Sometimes, names like binary and multi- or instantaneous fragmentation are used. Both decay modes are illustrated in Figs 6 and 7, respectively.

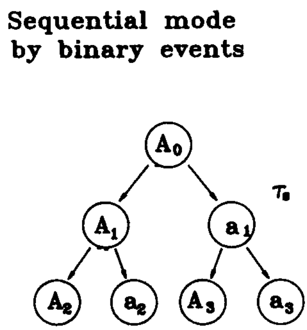

Fig. 6. Sequential decay mode of the hot nucleus.

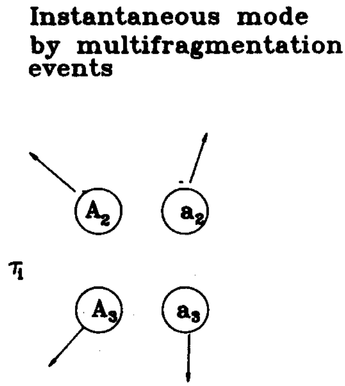

Fig. 7. Instantaneous decay mode of the hot nucleus.

Several attempts to distinguish between two decay modes mentioned above have been made. The difficulty lies in the fact that the decay times by both sequential τ_s and instantaneous τ_i fragmentation are comparable at high excitation energies.

The statistical model predicts the coexistence of three processes: evaporation (sequential decay), fission (two heavy fragments) and multifragmentation (many intermediate mass fragments). An example of the predicted relative contribution of those three processes in the decay of the ^{90}Ru nucleus at 600 MeV excitation by Gross and Massmann [7] is shown in Fig 8.

Various attempts to distinguish between the sequential and instantaneous fragmentation were made. A most comprehensive review of the tested and proposed signatures of instantaneous multifragmentation can be found in a work by Grotowski [8].

From the thermodynamic point of view, the instability of the decompressed nucleus against a decay into clusters of normal density can be a nice example of the so called spinodal region in the Van der Waals isotherms of nuclear matter. In this region, $(\partial\rho/\partial \mathrm{p})_{T=\mathrm{const}}$ is negative and the matter is

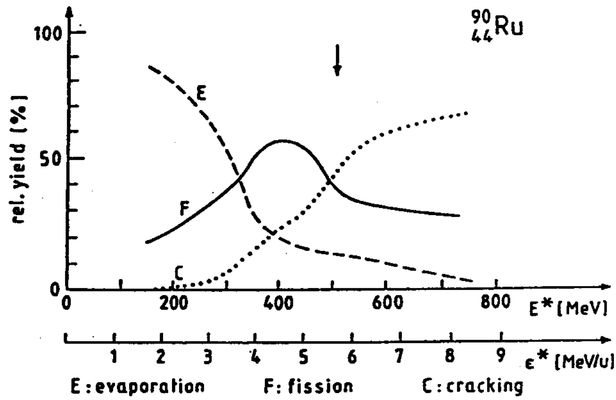

Fig. 8. Decay modes of the ^{90}Ru nucleus as a function of the excitation energy according to the prediction of statistical multifragmentation model of Gross and Massmann [7].

unstable against small fluctuation. This type of instabilities is called spinodal in analogy to the phase instabilities in two component metal alloys. A good example of the calculated Van der Waals isotherms of nuclear matter can be found in the paper of Sauer *et al.* [9] and thorough discussion of spinodal instabilities in a paper by Pethick and Ravenhall [10].

4. Phase transitions

A first order phase transition is characterized by the discontinuity of the first derivative $(\partial G/\partial/T)_{p=\mathrm{const}}$ of the Gibbs function. A good example is a liquid to gas transition. For example, if we heat up a jag of water, the temperature of water rises up until it reaches the boiling point and the absorbed energy is used for the conversion of liquid to gas (latent heat). Thus the temperature stays constant. This is illustrated in Fig. 9. For the nucleus the problem looks as follows. We have to measure the nuclear temperature independently of the excitation energy. For example, it is possible to measure the temperature using the Maxwellian shape of the evaporated light particle (p, n or α particles) and the excitation energy from the reaction kinematics. A plateau in the T(E^*) curve indicates the existence of a 1^{st} order phase transition. In many theoretical calculations a short plateau around $E^* = 5$ MeV·A and 6 MeV·A was found [11, 12].

Recently, some indication of the existence of a sort of plateau has been found in the T versus E^* function studied experimentally by the HMI Berlin — IFJ Cracow collaboration [13]. The reaction studied was ^{32}S + ^{58}Ni at 30 MeV·A. A phoswich crystal ball Argus 4π was used for charged particle detection. At forward angles, evaporation residua were measured by semiconductor telescopes. Their velocities and masses were determined by the

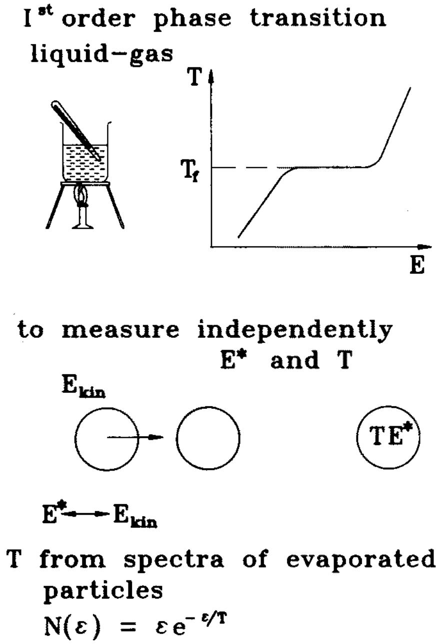

Fig. 9. Liquid to gas phase transition.

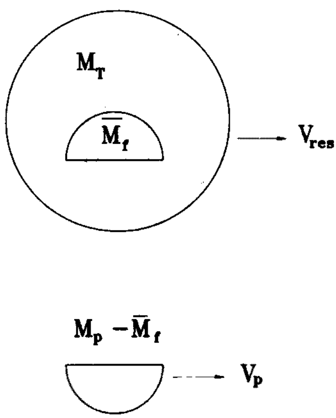

Fig. 10. Kinematics of the incomplete fusion reaction.

time of flight technique. Since the velocity of the evaporation residuum is practically equal to the velocity of the initial hot fragment, from the simple incomplete fusion model and energy momentum conservation it was possible to infer about the excitation energy of the primary fragment (see Fig. 10). The evaporation spectrum of light ejectiles, α-particles and protons were measured by the crystal ball in coincidence with evaporation residua. The shape of the spectra fitted with Maxwellian curves allowed to determine the

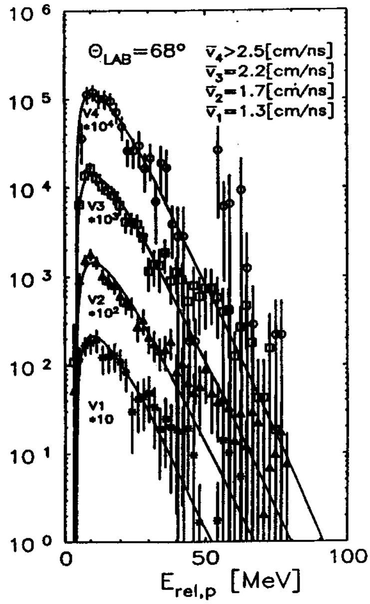

Fig. 11. Spectra of protons from the ^{32}S + ^{58}Ni reaction at 960 MeV gated by various velocity groups of the evaporation residua.

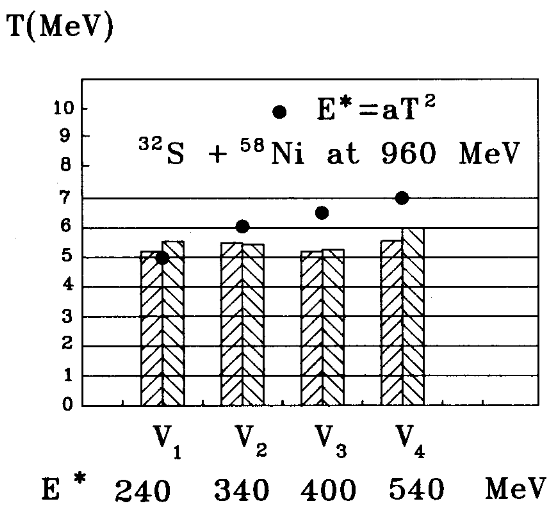

Fig. 12. Temperature versus excitation energy of heavy fragments produced in the ^{32}S + ^{58}Ni reaction at 960 MeV. Left and right slabs indicate temperatures determined from proton and α spectra, respectively. After A. Sourell [13].

temperature. The spectra of protons are shown in Fig. 11. The determined temperatures versus excitation energy are shown in Fig. 12. As can be seen, in the range of excitation energy 300 – 540 MeV the temperature stays practically constant. For comparison, in Fig. 12, the solid points indicate the temperature calculated using the formula of the Fermi gas, $E^* = aT^2$, where a is the level density parameter of the nuclear gas.

5. Towards higher energies

There is a lack of systematic measurements of E* versus T where both intensive and extensive parameters were measured independently in a broad energy range from low to high energies reaching the stability limit of the nucleus. Thus the evidence of the first order phase transition is still rather poor. There are, however, many indications of the existence of the limiting temperature and limited energy which can be stored in the excited nucleus.

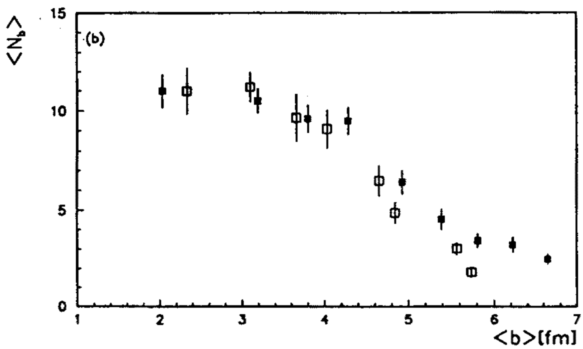

Fig. 13. Number of evaporated intermediate mass fragments versus impact parameter for the ^{32}S + emulsion nuclei reaction at 200 GeC/A. After A. Dąbrowska *et al.* [14].

Some evidence came from the studies of ultrarelativistic collisions. In Fig. 13, results of the Louisiana, Minnesota, Cracow collaboration are shown [14]. The number of intermediate mass fragments evaporated from the excited target like fragment originated in ^{32}S + emulsion nuclei collision at 200 GeV·A is shown as a function of the impact parameter *b*. The parameter *b* was estimated from the number of pions emitted in the collision and/or the number of fast projectile-like fragments. As can be seen, from certain *b* value down to central collision the number of intermediate mass fragments is constant which indicates that the nucleus can carry on a certain limiting energy only in spite of the possibility of transferring more energy to the spectator part of the target in the strictly central collision. The importance of the existence of the spectator part of the target in the central collision was recently shown by Cherry *et al.* [15] in the collision of ^{197}Au at 10 GeV· A with emulsion nuclei. With decreasing b the number of evaporated intermediate mass fragments decreases (see Fig. 14). This, at first sight unexpected result, indicates a simple fact that in central collision of a heavy nucleus with a light target no spectator target part exists.

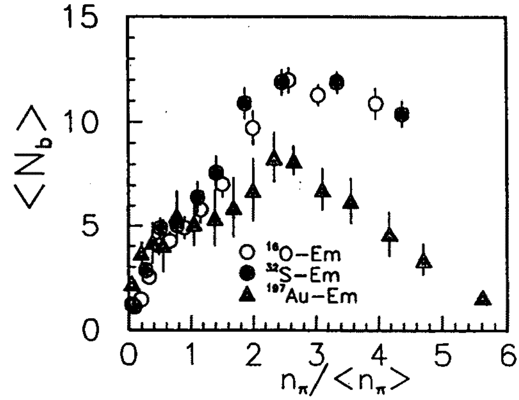

Fig. 14. Number of evaporated intermediate mass fragments versus impact parameter for the ^{16}O, ^{32}S and ^{107}Au collisions with emulsion nuclei at 10 GeVA. The impact parameter was estimated from the number of emitted fast pions n_π. Taken from [15].

It is natural to ask what happens if we perform central collision at the highest available ultrarelativistic energy of the nuclei of comparable masses. The energy release would be the highest for the case of a collider experiment. We might then create condition close to the next phase transition, namely the quark gluon plasma phase. It is at present the next important problem of nuclear physics which we are going to study at RHIC in Brookhaven and LHC at CERN. Again, we may recall at this point the analogy with the Big Bang of the Universe. The crucial information about the condition existing in the Big Bang was obtained from the spectra of the thermal relict radiation which has at present temperature of 2.7 K. Why not look then on the lowest energy radiation emitted in the highest energy central collision. It may consist of protons, pions, K, η, ρ, ω, and ϕ mesons. The measured transversal momentum range should be around 40 MeV/c which will require detection threshold as low as possible. Such experiment has been suggested recently by the Phobos collaboration of physicist from MIT, Brookhaven, Copenhagen and Cracow [16]. In Fig. 15, the schematic view of the Phobos experiment at RHIC in Brookhaven is shown. Two arm spectrometer filled with arrays of semiconductor detectors placed between the pole pieces of an electromagnet will allow to distinguish between various types of ejectiles and determine their angle of emission and the energy. Correlation experiments of the Hanbury Brown Twiss type will be possible. Strong fluctuation in particle emission and anomalies in the strange ejectiles production are expected close to the threshold of the quark gluon plasma

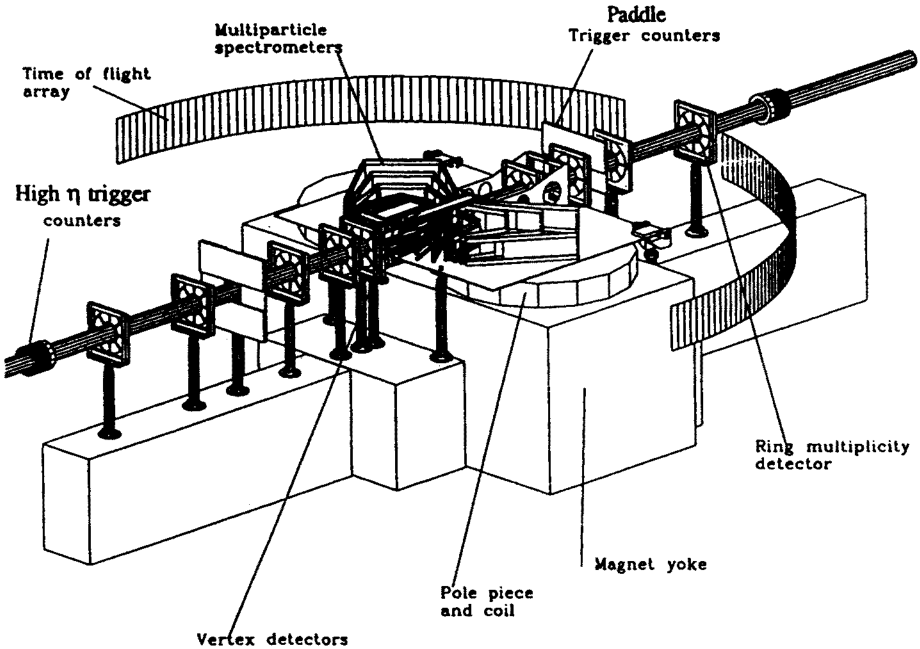

Fig. 15. Schematic view of the Phobos detector [16].

phase transition. Of particular interest is the observation of ϕ mesons which have a short life time of the order of 45 fm/c. Its decay may be strongly affected by the properties of surrounding nuclear matter in the deconfined state. The total energy release in the ^{197}Au + ^{197}Au collision would be 40 TeV. Still higher energies around 1000 TeV are expected to be accessible after year 2000 with LHC at CERN. We might hope that new properties of highly excited nuclear matter will be discovered in those experiments.

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