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PHASES OF NUCLEAR MATTER OBSERVED IN HEAVY ION COLLISIONS*

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This talk is a brief overview of strongly interacting matter phase transition studies. To begin with, I will discuss the phase transition of nuclear matter investigated in intermediate energy domain of heavy ion collisions. Then I will jump to the relativistic energies to review the fixed target experimental signatures of the quark–gluon plasma phase transition. The recent experiments at the ultrarelativistic collider energies will also be introduced. Finally, I will shortly mention a new project dedicated to investigate the novel states of dense baryonic matter.

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1. Introduction

Phase transitions in substances have been investigated for over a century. These studies were predominantly focused on macroscopic systems containing a large number of constituents. The substance in the atomic nucleus is called nuclear matter. It is generally believed that nuclear matter can exist in several phases. When trying to study the phases of nuclear matter one encounters problems. One of them is related to the size of the research object. The biggest "pieces" of nuclear matter available in laboratory contain a small number of nucleons and can be obtained from colliding the biggest nuclei giving the largest nuclear systems with less than 500 nucleons. On the other hand, nuclear matter in large quantities probably exists in the neutron stars which are the end of stellar evolution. However, the matter in neutron stars is only accessible by indirect observation of the pulsar radiations. The extended nuclear matter had been also present during a certain period of time after the Big Bang. The investigation of this form of nuclear matter can be done by studying the composition and distribution of matter in the present state of the Universe.

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A substance in statistical equilibrium can be characterized by a few thermodynamic variables and a non trivial relation between these variables is called an equation of state (EOS). Actually different relations are of interest in nuclear physics *e.g.* the relation between pressure p and baryon density ρ and temperature T, $p(\rho,T)$ or between p and chemical potential μ and T, $p(\mu,T)$ *etc.* Nuclear EOS plays a vital role because it affects different phases of the Universe evolution, namely the fate of the Universe at times of a few microseconds from the Big Bang, the supernova explosion and neutron star collisions.

There are three very important features of the EOS under investigation now:

- **Phase transition from nuclear liquid into coexistence phase of nuclear vapor (nucleons) and nuclear droplets (fragments).** This phenomenon is called nuclear liquid-gas phase transition. The forces between the individual nucleons in a nucleus vary with distance in a manner similar to those between molecules in an ordinary liquid. Thus it is expected that with increasing excitation energy the liquid-gas phase transition can take place in finite nuclei.

- **Phase transition from confined hadronic matter to deconfined partonic matter**. The idea of such transition has been around since the first models of the quark structure of hadrons. This deconfined chirally symmetric state of matter is called the quark–gluon plasma (QGP). In this new phase of matter the quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely. The QGP was the state of matter in the Universe a few microseconds after the Big Bang and prior to its condensation into hadrons.

- **Novel phases and structures of nuclear matter at a high density.** The nuclear density in the core of neutron stars exceeds that of nuclei by up to the factor of 10. In this condition, new structures of strongly interacting matter are predicted. The nuclear matter at large baryon densities is much less explored and the future facility at the GSI aims at detailed and comprehensive investigation of superdense baryonic matter.

Collisions of heavy atomic nuclei offer a unique possibility to create and investigate nuclear matter in a broad range of densities and temperatures. The kinetic energies of collisions discussed in this article spread from the intermediate ($\approx 100A$ MeV) to ultrarelativistic energies ($\approx 100A$ GeV).

2. Nuclear liquid-gas phase transition

There were two important experimental observations that caused very active theoretical and experimental studies of nuclear liquid-gas phase transition. The first experiment showed that nuclear fragment $(A_{\rm f}, Z_{\rm f}), 2 < Z_{\rm f} < 15$ mass yields produced by protons in the energy range $(80 < E < 350)$ GeV incident on krypton and xenon targets are described by a power-law dependence, *isobaric yield* $\propto A_{\rm f}^{-\tau}$ [1]. The particular value of $\tau \approx 2.6$ is significant for the fragment formation mechanism. Theoretical studies of liquid-gas phase transition indicate that near the critical point, the distribution of cluster sizes, *i.e.*, the number of constituents contained in a droplet, should obey a power-law with exponent is between 2 and 3 [2]. The second experiment was performed by the ALADIN collaboration [3]. The data for the ^{197}Au+^{197}Au reaction at 600 MeV were used to construct a nuclear caloric curve for fragmenting projectile like hot nuclei. The term "caloric curve" is commonly adopted for a relation between the system temperature T and excitation energy E.

These experimental observations of the finite nucleonic system breakup into several intermediate mass fragments has been associated with the nuclear liquid to nucleon vapor phase transition. Considering the complexity of nuclear collisions there is much uncertainty whether nucleonic system heated in collision process with its associated dynamic evolution leads to the critical state of nuclear matter. If so, another interesting question arises, whether the small system exhibit all features of the phase transition. The phase transitions are related to critical behaviors and are governed by the universal properties. Variety of signatures were employed in the identification of critical behavior of the finite nucleonic systems produced in nuclear collisions.

Over more than a decade, numerous experiments were dedicated to nuclear caloric curve measurement. The existing data contain the significant variation in the systems studied, in the collision dynamics involved, in the experimental and analysis techniques used, in the theoretical descriptions proposed and even in the manner the results were presented. Early attempts to draw a coherent conclusion from the information content in experimental caloric curves were rather unsuccessful [4, 5]. However, the recent review of caloric curve measurements indicates that the data provide direct measures of both the critical energy and the critical temperature for the phase change over a wide range of nuclear system masses [6]. The authors of Ref. [6] plotted the experimental correlated values of the temperatures and excitation energies per nucleon for five selected mass regions: $A = 30 \div 60$, $A = 60 \div 100$, $A = 100 \div 140$, $A = 140 \div 180$, $A = 180 \div 240$. The experimental data viewed in this way show that the obtained caloric curves are qualitatively similar in having a rising part at low excitation energies and then flatten into a plateau-like region at higher excitation energies. General rising of the caloric curves toward the curves corresponding to Fermi-gas model lines, $T = \sqrt{KE^*/A}$, for inverse level density parameters $K = 13$ in the low energies region and then leveling of the curve reflects a sudden increase of the heat capacity. On the other hand, the statistical models of multifragmentation predict flattening of the curve where the onset of multifragment production takes place.

The average temperature for the plateau region decreases with increasing system mass. This limiting temperatures which are observed in caloric curve measurements were previously associated with the system Coulomb instability temperature [7]. In the temperature-dependent Hartree–Fock model calculation [8], the instability temperature represents the limit of the equilibrium phase coexistence between liquid and vapor. Although in the absence of the Coulomb forces the coexistence is possible up to critical temperature of nuclear matter, the charged nuclear system becomes unstable at the limiting temperature which decreases with increasing system mass (charge). The departure from the rising part to flattening of experimental caloric curve in the $A \approx 160$ region was associated with critical point identified by the recent Fisher droplet model analysis [9]. This information was used to obtain apparent critical points from the experimental caloric curves for other mass regions. The values of these temperatures and excitation energies decrease with increasing nuclear system mass suggesting that disintegration of heavier systems occurs within the co-existence liquid-gas phase at temperature well bellow critical temperatures. Thus, the lightest nuclear systems are the most favorable to investigate the critical point in finite nuclei. Derived experimentally the limiting temperatures and excitation energies are in very good agreement with results of recent calculations employing either a chiral symmetry model or Gogny interaction [10, 11]. These calculations assume a soft equation of state with incompressibility of 194–228 MeV and critical temperature of 14.8–15.9 MeV for symmetric nuclear matter.

The combined results indicate that the condition of liquid-gas equilibrium phase similar to that assumed in the Coulomb instability calculations phase has been achieved.

Another approach to determine the critical point for the nuclear liquid-gas phase transition in finite nuclear matter is based on investigations of temperature and excitation energy region where maximum fluctuations in the disassembly of highly excited nuclear system are observed. Although a variety of observables have been used to identify this region, the recent theoretical analyses indicate that the apparent critical behavior may be observed far away from the actual critical point [12] and more experimental data are needed for precise identification of the excitation energy and temperature at the critical point.

3. Quark–gluon plasma phase

The computer simulation of lattice-regularized quantum chromodynamics (QCD) at finite temperature is the most reliable approach to study the thermodynamics of equilibrated system of quarks and gluons. Such simulations strongly support the expectation that hadronic matter undergoes a phase transition into deconfined quarks and gluons phase in which chiral symmetry is restored. Although both phenomena, namely chiral symmetry breaking and confiment, are related to different aspects of non-perturbative QCD vacuum, the calculations show that both critical temperatures coincide.

The standard Monte Carlo sampling techniques limit the QCD lattice simulation to the systems of vanishing baryon density (baryo-chemical potential $\mu_{\mathrm{B}} = 0$). Recent theoretical progress allows to conduct the lattice simulation of the QCD phase transition for the baryo-chemical potential up to $\mu_{\mathrm{B}} = 800$ MeV. The lattice simulations for the realistic quark mass spectrum predict:

- The critical temperature of the phase transition between the hadronic and quark–gluon phase is $T_{\mathrm{c}} = 175 \pm 15$ MeV. This transition is most likely sudden and takes place in a narrow range of about 20 MeV temperature. The critical temperature decreases slowly with increasing baryo-chemical potential.

- The change of energy density which may be interpreted as latent heat of the transition is $\Delta\varepsilon/T_{\mathrm{c}}^4 \approx 8$.

Experimental study of ultrarelativistic nucleus–nucleus collisions is a new and rapidly evolving field. First experiments started in 1986 with light ions ($A \approx 30$) almost simultaneously in Brookhaven at the AGS ($E_{\mathrm{beam}} \approx 15$ GeV/nucleon) and at CERN at the SPS ($E_{\mathrm{beam}} = 200$ GeV/nucleon). Heavy ions ($A \approx 200$) have been available at the AGS since 1992 and at the SPS since 1994. In these experiments collisions occur with a target fixed in the laboratory frame. The Relativistic Heavy Ion Collider (RHIC) started its operation in June 2000 at Brookhaven National Laboratory. RHIC has two beams circulating in opposite directions around 3.8 km ring with six interaction regions. The accelerator has a design luminosity of $2 \times 10^{26}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for Au+Au beams at $\sqrt{s_{NN}} = 200$ GeV and produces collisions at a rate up to $1,000$ Hz. Four of the interaction regions are instrumented with the experimental setups of BRAHMS, PHENIX, PHOBOS and STAR [13]. Each of these experiments will contribute uniquely to the exploration of the high temperature and high/low baryon density region of the phase diagram of strongly interacting matter. The Broad RAnge Hadron Spectrometer

(BRAHMS) experiment [14] has been designed to gather basic information on momentum spectra and yields for various emitted hadrons as a function of transverse momenta, $p_{\rm t}$, and rapidity, y.

After 16 years of data collection at CERN, it is now clear at least for the CERN heavy ion physicists, that the experimental results from seven large experiments namely, NA44, NA45, NA49, NA50, NA52, WA97 and WA98 [15] give "compelling evidence for production of the new state of matter" plasma of quark and gluons [16]. Quoted statement from the CERN press release is based on several exciting observations:

- The initial energy density reached in central Pb+Pb collisions at 160 GeV/nucleon was estimated to about 3 GeV/fm^3. Such conditions are well above the critical value of 1GeV/fm^3 predicted by the lattice calculations for the production of the deconfined phase.

- A significant thermal photons emission for central Pb+Pb collisions was reported. In contrary, the data for peripheral collisions showed no evidence for any photon excess above the expected background. Emission of thermal photon is a positive identification of the deconfined phase.

- The suppression of charmonia bound states in heavy ion collisions was found. It is expected that the quarkonia cannot survive in the quark–gluon plasma in equilibrium due to the strong color screening effects. On the other hand, the charmed quarks cannot be produced below the critical energy density and temperatures higher than the critical temperature are required in order to screen in the plasma high mass quarkonia interactions.

- A very large enhancement factor of multi-strange baryons was observed in Pb+Pb collisions with respect to $p+p$ results. This observation indicates a fast strangeness production during the hadronization phase. However, additional effects such as re-scattering of the hadrons in the final state might play a role.

- The azimuthal distribution of the hadrons in the final state is another observable which indicates the deconfined phase production.

In summary, the results of the CERN heavy ion experimental program provided convincing evidence for the formation of the quark–gluon plasma.

There is a great hope that the first heavy ion collider RHIC will supply more information on the properties of the quark–gluon phase of strongly interacting matter. The early results from all four experiments have been recently published. Let me summarize here the first results which were obtained by the BRAHMS collaboration in which our group from the Jagiellonian University participates.

The BRAHMS experiments have measured pseudo-rapidity densities of charged particles and anti-particle to particle ratios from ^{197}Au + ^{197}Au collisions at $\sqrt{s_{NN}} = 130$ GeV and $\sqrt{s_{NN}} = 200$ GeV. The data were collected over a large range of pseudo-rapidity as a function of collision centrality. Although the full understanding of ultra-relativistic heavy ion collisions requires more detailed analyses, the current investigation leads to several conclusions:

- The charged particle production scales smoothly from $\sqrt{s_{NN}} = 130$ GeV to $\sqrt{s_{NN}} = 200$ GeV in a wide region around midrapidity.
- The charged particle multiplicities in the interval of approximately -0.5 to -1.5 units below the beam rapidity are largely independent of the collision centrality and collision energy, supporting a limiting fragmentation picture. In contrast, around the center of mass rapidity, an increase in the reaction energy is utilized for increased particle production.
- The estimated value of the Bjorken energy density at $\sqrt{s_{NN}} = 200$ GeV is several times higher than the critical value predicted for the quark–gluon plasma phase transition.
- The ratio of negative to positive pions is close to unity as would be expected at these bombarding energies where about 5000 charged particles (predominantly pions) are produced per central collision. The anti-proton to proton ratio at midrapidity increases from 0.64 for $\sqrt{s_{NN}} = 130$ GeV to 0.75 for $\sqrt{s_{NN}} = 200$ GeV. These values are the highest observed so far in heavy ion collisions. However, the full transparency is not reached.

4. Phase of dense baryon matter

The highest net baryon densities are expected for heavy ion collisions in the beam energy range between 10 and 40 GeV/nucleon. The proposed accelerator facility at the GSI will open up the possibility to study the region of dense baryonic matter at moderately high temperatures. There are three major reasons to study nuclear matter at high density:

- **Investigation of the nuclear EOS**. Compressibility of nuclear matter is an important bulk property of the nuclear matter and was predominately studied for nuclei in close vicinity of their ground states.

Such studies allowed to determine the curvature of the nuclear EOS for a small range of nuclear density. An extrapolation of the nuclear EOS into the region of higher densities is strongly dependent on the modification of the baryon and meson properties in dense and hot nuclear medium. The compressibility determines a resistance of nuclear matter to the gravitational pressure and also defines the maximum mass of neutron star before its collapsing into the black hole.

- **Investigation of the dense medium modification of hadron properties**. Spontaneous chiral symmetry breaking in the QCD vacuum leads to a non-zero values of quark–antiquark and gluon condensates. It was postulated that these chiral condensates are responsible for the observed masses of the hadrons which are relatively large as compared to the current masses of the quarks. Moreover the values of the condensates decrease with increasing baryon density or temperature. Thus, there is a tendency to restore chiral symmetry in dense hadronic matter.
- **Exploration of possible new phases of nuclear matter at ultra high density.** Novel phases of strongly interacting matter are expected to occur at the baryon density which exceeds the baryon density of ordinary nuclei by up to the factor of 10. In this case, variety of competing form of matter are predicted [17]. In particular, condensates of kaons, a large abundance of hyperons or a plasma of quarks and gluons.

5. Summary

The quantitative understanding of the rich phenomena of strongly interacting matter is a fascinating challenge for modern fundamental research. Energetic collisions between heavy nuclei provide the most powerful tool for this study. A lot of work has been done during recent years to verify different signatures of phase transitions in strongly interacting matter. We showed that each signal has its own weak point and cannot be used as a final proof. In order to reach rather strong evidence for liquid-gas phase transition in finite nuclei the combined results from many experiments were utilized. Also an observation of the quark–gluon plasma formation in heavy ion collision was declared after collecting of many experimental signatures provided by different experiments.

Looking further ahead, the large hadron collider (LHC) currently constructed at CERN will open up for exploration an entirely new territory. The initial temperatures up to 1000 MeV for Pb+Pb collisions have been predicted and much longer plasma lifetimes are expected.

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