

Quest for the Quark-Gluon Plasma^{*)}

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arXiv:nuc1-th/0305096 v1 30 May 2003

Abstract

Present status and future prospect of the quest for the quark-gluon plasma, the primordial form of matter which once pervaded the early universe, with ultrarelativistic nuclear collisions are discussed.

^{*)} Invited talk given at Tokyo-Adelaide Joint Workshop on Quarks, Astrophysics and Space Physics, University of Tokyo, Jan. 6 -10, 2003.

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§1. Introduction

With the advent of the Relativistic Heavy-Ion Collider (RHIC) at Brookhaven we are now able to study nuclear collisions at extreme relativistic energies of up to $200A$ GeV with heavy ions as heavy as gold nuclei ($A = 197$). These energies far exceed the rest mass energy of the nucleon, $m_N c^2 = 0.94\text{GeV}$, hence the term "ultrarelativistic" applies. The primary physics motivation of studying nuclear collision at such ultrarelativistic energies is to recreate the physical conditions similar to those which once prevailed in the very early universe and study the primordial form of matter from which all the matter of the present universe was created. Indeed, such a nuclear collision typically results in production of more than few thousands of particles each having energies of 1 GeV; if these particles are in statistical equilibrium at a certain stage of the collision, then the temperature of the matter would be of the order of 10^{12} degree in Kelvin, the temperature of the universe as early as ten microsecond after the beginning of the Big Bang. What is the nature of the primordial form of matter under such extreme condition? How matter evolved from such primordial state to the present form of matter as we see it around us? It is the answers to these fascinating questions which we try to learn from the experiments of ultrarelativistic nuclear collisions.

In what follows, I discuss, after a brief introductory overview of our present theoretical understanding of the nature of matter under such extreme conditions and the space-time view of nuclear collisions at ultrarelativistic energies, what we had expected for the signals of new physics in ultrarelativistic nuclear collisions and what we have actually learned so far from the past experiments with some remarks on the coming experiments.

§2. Extreme states of matter

As we heat up matter around us, it experiences a series of drastic change in its state; from a solid, to a liquid, and then to a gas. These distinct states of matter are called *phases* of matter and the sudden change of phase at certain temperature is called *the phase transition*. As we heat up the matter further, all matter will be transformed eventually to a state called *plasma*, consisting of ions and electrons. This last transformation takes place gradually with increasing temperature by ionization of individual atom or molecule by collision; so it is not called the phase transition. Yet, the plasma, consisting of mobile charged particles, has distinct *collective* electromagnetic properties, such as *screening* and *plasma oscillation*; hence it is sometimes called the "*fourth phase of matter*". Plasma also glows by emitting photons which are created by collisions of charged particles; all living creatures on the glob, including ourselves, benefit very much from the flux of these photons emitted from Sun, a huge sphere

of hot plasma bound together by gravity, as their primary energy source.

Plasma is also formed when matter is compressed under high pressure; some of the electrons get freed from entrapments in an individual localized orbit and will form a *degenerate quantum plasma*. This change of state happens as a phase transition: the insulator-metal transition. The cold degenerate plasma do not glow itself, but still shines by reflecting light, or electromagnetic waves, at its surface.

More than 99.9% of the mass of each atom resides in the very tiny region at the heart of the atom: the atomic nucleus. The nucleus is a droplet of a *Fermi liquid* consisting of nucleons, protons and neutrons, with maximum size at $Z_{\text{Max}} \simeq 114$ constrained by the Coulomb repulsion between the protons and the saturation properties of nuclear force which holds the nucleons together. Nuclear matter also makes a transition to a gaseous state as its temperature is raised about a few tens of MeV^{*)} as can be achieved by low energy heavy ion collisions.

As the temperature of nuclear matter is raised further light mesons are created but there will be no ionization of quarks, the constituents of hadrons, nor emission of gluons, the quantum of color gauge field which holds together the quarks to form hadrons, due to their outstanding property referred to as *color confinement*. But with increasing temperature the density of these mesons will grow and since each meson is a composite system having a finite spatial extension, they would percolate into a network of zones, filled with quarks, antiquarks, and gluons, which will eventually pervade the entire space.¹⁾ If this naive expectation is realized, then nuclear matter should turn into a plasma of quarks and gluons at sufficient high temperatures.

Precise natures of this transition is not known yet, including the existence of the phase transition or, if there is, the order of the transition, due to the difficulty of solving QCD in non-perturbative regime where this transition is expected. Currently prevailing prejudice, based on the results from Monte Carlo numerical simulations of discretized versions of QCD on finite size lattice²⁾, is that the transition is very rapid, at around $T \simeq 150\text{MeV}$, and is closely related to the restoration of the chiral symmetry of QCD which holds approximately for light quarks with small masses, but is broken spontaneously in the QCD vacuum. What we are more sure is that the relevant energy scale for the creation of the quark-gluon plasma is within the reach by ultrarelativistic nuclear collisions at RHIC, so we should seek for signals of the formation of the quark-gluon plasma.

Compressed form of nuclear matter may also exist in the core of compact stars, known as *neutron stars* which are created by the gravitational collapse of iron cores developed

^{*)} Hereafter we use the energy scale for the temperature. It can be translated to Kelvin scale by $1\text{MeV} = 10^{10}\text{K}$.

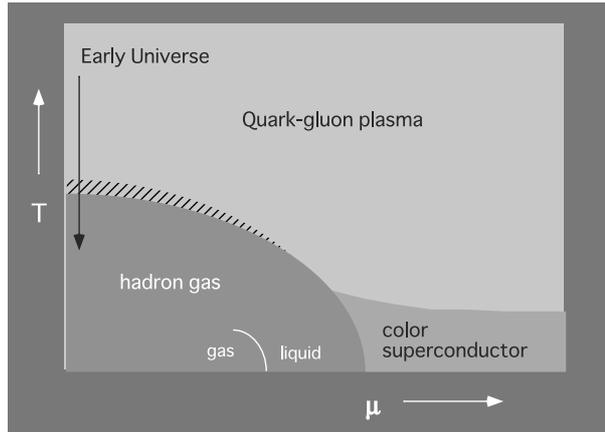


Fig. 1. Theoretical phase diagram of hot/dense matter

in massive stars, accompanying a spectacular event, *supernovae*, explosive outburst of the debris of the rest of the original star. Most of the gravitational energy, of order of 10^{53} erg, released by the formation of a neutron star, is emitted by neutrino burst, as first confirmed in 1987 by Kamiokande. The "neutron star" may be considered as a giant nuclei consisting of 10^{57} baryons (mostly neutrons) hold together by the gravitational attractive force against the repulsion due to the Pauli exclusion principle and nuclear force. It is covered by a thin layer (crust) of a metallic form of atoms, while the central density of the neutron core may exceed ten times the central density of ordinary nuclei. It is thus natural to speculate that matter at the heart of neutron star would have melted into a dense degenerate plasma of quarks. Such conjecture was entertained even long before the discovery of QCD.³⁾

It is known that in the presence of attractive two particle interaction, irrespective of the strength, Fermi surface of the degenerate Fermi gas is unstable with respect to the formation of two particle bound state, a *Cooper pair*, and the system turns into a coherent mixture of such bound states described by the BCS wave function. Similar situation may arise in the degenerate quark plasma if there is attractive quark-quark interaction at the Fermi surface; this happened to be the case for anti-triplet color channel of quark pair and this problem has been extensively studied in recent years.⁴⁾

Fig. 1 summarizes the present theoretical expectation of the phase diagram of hot and dense matter as plotted in the plane of the temperature T and the baryon chemical potential μ , the measure of the asymmetry of the baryon-antibaryon abundance in the system.

§3. Nuclear collisions at ultrarelativistic energies

The only method at our disposal, although very crude and not ideal, to create and study hot dense matter in laboratory experiments is to collide two nuclei at extreme relativistic

Table I. Relativistic heavy-ion accelerators

	E_{Lab} [GeV]	E_{cm} [GeV]	Δy	γ_{cm}
AGS (BNL)	$30Z/A$	$6Z/A$	3.5	7
SPS (CERN)	$400Z/A$	$20Z/A$	6	10
RHIC (BNL)	–	$250Z/A$	11	100
LHC (CERN)	–	$8000Z/A$	17	2500

energies. Such high energy nuclear collisions have been observed since more than a half century ago in high energy cosmic ray events as a special cases of multiparticle production phenomena which have been described in terms of phenomenological thermodynamic or hydrodynamic models incorporating space-time picture as imposed by the special relativity.⁵⁾ The interests in high energy nucleus-nucleus collisions revived in 80's from the prospect of creating and studying a quark-gluon plasma and this led to the initiation of the experimental programs at Brookhaven and CERN in mid 80's using existing hadron accelerators (AGS at Brookhaven and SPS at CERN), while a dedicated relativistic heavy-ion collider (RHIC) was built at Brookhaven. The energy per nucleon of ion beams accelerated by these machines are shown in table 1. In the table, the center of mass collision energies per nucleon $E_{cm} = \sqrt{m_N E_{Lab}/2}$ of AGS and SPS fixed target experiments are given together with the rapidity difference of target and projectile nucleons ($\Delta y = y_p - y_t$). The table also contains the parameters of LHC which is now under construction at CERN.

At untrarelativistic energies, a head-on collision of two nuclei mass number A may be view as a collision of two highly contracted nuclei of a disk shape. The Lorentz contraction factor in the center of mass frame, $\gamma_{cm} = E_{cm}/m$, is $\gamma_{cm} \simeq 100$ at the RHIC energy and the longitudinal thickness of the nuclear disk becomes $2R/\gamma_{cm} \simeq 0.015\text{fm}$ even for heavy nuclei, which is smaller than the hadron size. Under such conditions, it may be more natural to view the collision process as a collision of two inter-penetrating beams of partons, the constituents of nucleons, instead of collisions of individual nucleon as a whole. After the collision, two "wounded nuclei" consisting of these "primary" partons would continue to fly along essentially the same paths as the free particles, but the space-time region sandwiched by them will be excited and filled up with excitations of quarks and gluons.⁶⁾ The net baryon number will be carried away with the primary partons and hence we may expect the formation of quark-gluon plasma with vanishing baryon chemical potential as in the very early universe. Matter created in between two receding nuclei will expand and cool down, and it will eventually disassemble into ordinary hadrons, and a few leptons, filling the mid-rapidity region of particle distribution in the rapidity space. A space-time view of matter

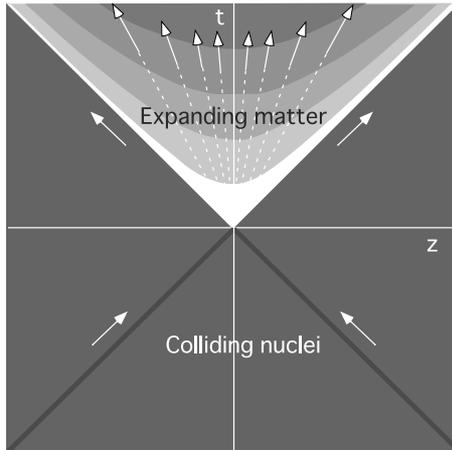


Fig. 2. Space-time view of a nuclear collision

evolution seen in the center of mass frame is depicted in Fig. 2.

This dense gas of (secondary) partons may, or may not, quickly achieve a local thermodynamic equilibrium by their mutual interaction. If it does, as first assumed by Landau, then the subsequent evolution of the system will be described entirely by the conservation laws provided that the equation of state of equilibrium matter is known; then an adiabatic hydrodynamic expansion of the system will follow.

The first stage of the adiabatic expansion is of one-dimensional character since the expansion is predominantly in the longitudinal direction and the cooling of the system will take place as the conserved entropy of the system will be diluted by being spread over an expanding volume as the matter expands. This adiabatic cooling is determined by solving the hydrodynamic equations, but if we adopt the Lorentz boost invariant expansion, along with Bjorken⁷⁾, which ensures the Ansatz $v_z = z/t$ for the longitudinal flow velocity and $\tau = \sqrt{t^2 - z^2}$ for the proper time, then we find that the entropy density decreases inversely proportional to τ . This results in $T \propto \tau^{1/3}$ if we use the ultrarelativistic ideal gas relation between the entropy density s and the temperature T : $s = aT^3$ where $a = 2N_{eff}\pi^2/45$ and the effective degrees of freedom is given by $N_{eff} = 16 + 21n_f/2$ for an ideal gas of color octet gluons and massless n_f flavor quarks. During this stage the transverse expansion of the system sets in from the outer edge of the system where the pressure gradients generate a transverse acceleration of matter. The inward edge of the transverse rarefaction wave propagate through the longitudinally expanding matter with the velocity of sound and an element of matter will be set in transverse motion after the wave passes by as illustrated in Fig. 2.

As the rarefaction wave reach the center of the matter, the whole matter will be set in full three dimensional expansion and it will disintegrate into a free stream of hadrons

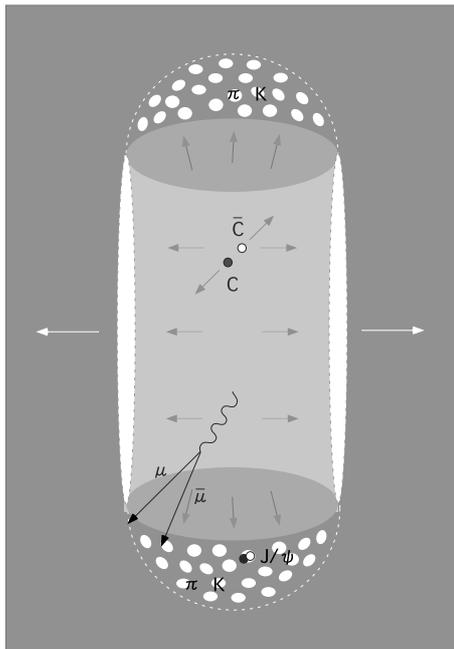


Fig. 3. A snapshot of expanding matter created by nuclear collision

quickly. This time scale is given in terms of nuclear radius R and the sound velocity c_s as $\tau_{exp} = R/c_s \simeq (1-2)R \text{ fm}/c$. The lifetime of the plasma is determined by this expansion time scale, although detail of its evolution is influenced by other factors like the kinetic properties of the plasma and its hadronization mechanism which are still unknown and remain as the challenging problems of theoretical research.

§4. Probes of the quark-gluon plasma

As we have discussed in the previous section, even if a quark-gluon plasma is produced in high energy nuclear collision it will cool down very rapidly and will disassemble into thousands of ordinary hadrons on a very short time scale of $10^{-21} - 10^{-20}$ seconds. This makes it extremely difficult to identify the signal of the quark-gluon plasma formation. Many ideas have been proposed and some of the important ones will be discussed now in the light of experimental data taken after the proposal.

Flavor composition: In a quark-gluon plasma, quarks and anti-quarks are populated according to the statistical rule. In equilibrium, it is determined only by the mass of the excitations and there is a good reason to assume that three light flavor quarks (up, down, strange quarks) are almost equally abundant in the plasma with zero net baryon number. The time scale for the approach to flavor equilibrium was computed by perturbative QCD and was found to be shorter than the lifetime of the system⁸⁾. It was soon realized⁹⁾,

however, that this initial symmetry in flavor abundance may not be reflected directly in the final hadron abundance as an enhancement of the production of strange hadrons (K , Λ , $\bar{\Lambda}$, ...); contrary to this naive expectation, if a quark-gluon plasma is formed and adiabatically evolved into hadron gas, its entropy content should be preserved and most likely this will lead to a dilution of the K/π ratio because pions are most easily produced to compensate the entropy of gluons. The final relative abundance of various hadrons may only reflect the freeze-out stage of the matter.

Enhancement of strange particle production was observed both in AGS¹⁰⁾ and SPS¹¹⁾ experiments. Most part of these data are fitted very well to a simple statistical abundance of ideal gas with two fitting parameters T and μ .¹²⁾ It remains an interesting question whether an anomalous yield of some very exotic hadrons such as Ω^- which consists of three strange quarks and therefore is very difficult to be produced in hadron-hadron collision may be enhanced anomalously in a nuclear collision was indeed observed at SPS experiments.

Leptons and photons: Leptons and photons are called *penetrating probes* since they are free from strong final state interaction and thus expected to carry information of the interior of the matter produced.¹³⁾ In contrast, hadrons are created only at the surface (hyperspace in $3 + 1$ dimensional Minkowski space) of the plasma and may suffer more final state interaction before they freeze out into free streaming particles. In particular, dileptons (a pair of lepton and its anti-particle) couple to local thermal fluctuation of electromagnetic current in the hot matter and their invariant mass spectrum may reveal the nature of the matter from which they are emitted. The high mass tail of the dilepton invariant mass spectrum $M > 3$ GeV is known to be dominated by the "Drell-Yan" pairs which are produced at the earliest stage of the nuclear collision by annihilation of primary partons (quark and anti-quark) into a virtual photon. Dilepton created in the interior of the quark-gluon plasma by the annihilation of thermally excited quark and anti-quark pair are expected to dominate in the intermediate mass range $2 \text{ GeV} < M < 3 \text{ GeV}$,¹⁴⁾ while many of the low mass dileptons are produced by the electromagnetic decay of hadrons and hence interesting as a probe of properties of individual hadron in the dense medium as expected from some theoretical models.¹⁵⁾

The data taken at SPS indeed shows some enhancement and change in the shape of low mass dilepton spectrum in e^+e^- channel¹⁶⁾, however the effect is seen in light-ion induced reactions and no more prominent in heavy-ion induced reactions. Also it can be understood in terms of many-body correlations in the medium¹⁷⁾ without invoking the change of hadronic properties.

Quarkonium: A pair of heavy quark and its anti-particle ($c\bar{c}$, $b\bar{b}$) are occasionally produced at the initial stage of collision by primary parton interaction and some of them can evolve into a bound state called quarkonium. Hadronic production of vector quarkonium

can be observed by the high mass resonances in the dilepton invariant mass spectrum. In particular, J/ψ (3S_1 $c\bar{c}$ state) forms a prominent peak at $M = 3.1\text{GeV}$ which stands out of Drell-Yan continuum. If a pair is produced in the event which also results in formation of a quark-gluon plasma, then the subsequent evolution of the pair to bound state will be prohibited by the plasma screening of the mutual interaction of the pair. Since the continuum Drell-Yan pair will not be much affected by the plasma formation, this should result in a strong suppression of the peak/continuum ratio in the dilepton spectrum: J/ψ suppression.¹⁸⁾ So we proposed that the signature is an absence of a signature. Mass shift of the J/ψ peak was also proposed¹⁹⁾ as a signal of precursory effect of deconfinement, but unfortunately the long time scale for the decay of J/ψ prohibits to observe this effect.

Suppression of the J/ψ peak relative to the Drell-Yan continuum was observed in the early experiments with light ions at SPS.²⁰⁾ However, it was soon found²¹⁾ that the observed suppression can be interpreted in terms of a "nuclear absorption" model which parameterizes the collisional loss of charmonium on the way out of nuclei, the effect already seen in pA collisions.²²⁾ A new surprise came with the data from the lead beam experiments which exhibit anomalous suppression in the events at small impact parameters²³⁾ which cannot be fitted by extrapolation by simple nuclear absorption model and requires additional exotic mechanism such as plasma suppression.^{24) - 26)} This conclusion was challenged by the claim²⁷⁾ that the observed yields of J/ψ as compared to other lighter hadrons are very close to the statistical equilibrium value which would mean that most of J/ψ 's are produced by the recombination of $c\bar{c}$ from a thermal bath. Although thermal origin of J/ψ at SPS energies is not consistent with other data²⁸⁾, it was pointed out that there would be an enhancement at higher collider energies.^{28), 29)} A preliminary RHIC data seem to exclude this possibility.³⁰⁾

Jets: Hard scatterings of primary partons generates a pair of energetic partons carrying large transverse momenta which will fragment into back-to-back hadron jets in the free space. Such jets have been well identified in $p\bar{p}$ collisions at Tevatron.³¹⁾ In nucleus-nucleus collision each member of the pair scattered in deep interior of the collision volume will travel through the matter on its way out before fragmenting into hadrons and thus will change its energy-momentum by interaction with the medium. The distances that two members of the pair travel depend on the location where the primary parton scattering took place in the collision volume and therefore they are not the same in most cases. This may lead to an imbalance in the two jets or even extinction of one of the jets or both.³²⁾ Significance of this effect depends crucially on the parton energy loss in the dense matter which depends on the nature of matter the high energy partons traverse. It was pointed out that the gluon radiation is a dominant mechanism of the parton energy loss in the quark-gluon plasma³³⁾ and it leads to thermalization of mini-jets components which otherwise dominate the high

momentum tail of the hadron spectrum.³⁴⁾

The inclusive hadron spectrum observed in SPS experiments shows enhancement at high momentum and this has been interpreted as a multiple scattering effect ("Cronin effect" in pA collision) or hydrodynamic flow effect. The data taken at RHIC however have qualitatively different feature from these SPS data, showing systematic suppression of the high momentum tail at $E > 5$ GeV which is suggestive of a manifestation of jet quenching.³⁵⁾

§5. Outlook

We have learned so many things from the fixed target experiments at AGS and SPS, and some of the data strongly suggest a picture that a quark-gluon plasma is formed at SPS at least for a short while. It is, however, still very important to confirm these results by on-going RHIC experiments and future experiments at LHC more systematically and to look for new effects which become manifest only at high energies. As we increase the energy of collisions, hard scattering of primary partons plays more and more important role. It has been anticipated³⁶⁾ that "mini-jet" components will eventually dominate the energy deposition which at lower energies is mainly due to the "soft" interactions as modelled by string formation and decay. It has also been emphasized that the rescatterings of these hard partons in dense partonic medium (quark-gluon plasma) are crucial to assess the utility of various probes of the quark-gluon plasma.³⁷⁾ Increase of the collision energy is generally favorable to create a denser (hotter) matter with a longer lifetime.

We should also keep in mind that the physical conditions achieved by these new collider experiments are very different from those of fixed target experiments, and some of the assumptions implicitly used for the analysis of SPS data may not be applicable for interpretation of new data. For example, we have recently pointed out that the nuclear absorption of charmonium will change qualitatively at high energies due to quantum coherence in multiple scatterings.^{38), 39)} Increase of charm production rate may become a serious problem to use the charmonium suppression as a probe of the quark-gluon plasma at LHC. This needs to be checked experimentally, but if this turns out to be the case we may resort to bottomonium ($b\bar{b}$ bound states like Υ) as a new probe of the very high temperature plasma.

In closing, I like to quote a very famous phrase from Chinese translation of a sutra of Mahayana Buddhism:

色 (shiki/se) : Color,
即 (soku/ji) : That
是 (ze/shi) : is
空 (kuh/gong) : empty.

A word-to-word translation of the phrase is indicated on the right of each word together with Japanese/Chinese pronunciation. It would imply: "Thing which has color does not exist." One may be surprized at finding that the ancient Buddhist teaching contains such a modern statement on the quark confinement!⁴⁰⁾ The true meaning of this phrase is said to be that "Everything around us, which has color so that we can see, does not stay unchanged eternally. Things exist only in a state of flux. " This statement is considered as an essence of the Buddhist view of the world which may look somewhat pessimistic from the point of view of scientific endeavor. In science, we are always looking for knowledge of lasting significance. I may still conclude this talk happily in accord with this phrase as follows: Our Universe was created in the Big Bang and its matter content has evolved from the primeval plasma to the present state of matter, as we see it. The quark-gluon plasma may still be formed in a state of flux in nuclear collision and we may have already seen a flash of it!

Acknowledgements

The author thanks the organizer of the workshop, Tetsuo Hatsuda, for his kind invitation and my colleague in Komaba, Hirotsugu Fujii, for collaboration and helpful conversations on the most recent results from RHIC experiments.

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- 39) H. Fujii, contribution to this volume.
- 40) The opposite statement: 空即是色 (kuh-soku-ze-shiki) which is also written in the sutra can find another interesting modern interpretation in QCD physics: "the vacuum is a (non-trivial) state of color (fluctuation)!" .