Black Box QGP

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Abstract
As a heavy metal, lead is dangerous to health or to the environment and is not biodegradable and tend to accumulate in living organisms, therefore it is necessary to remove it from the polluted waters. In this research, thiol-functionalized Beta/MCM-41 nanocomposite (SH-Beta/MCM-41) was prepared by 3-mercaptopropyltrimethoxysilane (MPTMS) in the presence of aerosil-200 as silica source by two-step hydrothermal crystallization procedure. XRD, TG-DTG, N2 adsorption-desorption, SEM and FT-IR techniques were used to characterize the nanoparticles before and after functionalization. The functionalized hierarchical zeolite exhibited desirable adsorption capacity for lead, superior to either microporous zeolite or mesoporous silica, providing a valuable candidate for removing the heavy metal cation.

Keywords
Quark-Gluon Plasma, Lattice QCD Calculations, Relativistic Heavy-ion Nuclear Reactions

1. Introduction
The theory which describes the dynamics of the phase transition to the quark-gluon plasma (QGP) and back to the hadronic matter is still failed. In high-energy experiments, we can only measure produced particles in the final state, i.e. after the chemical and thermal freeze-outs. Consequently, the occurrence of equilibration processes while energy density decreases can not be confirmed experimentally. Same constrains are also valid for the degrees of freedom during the hadronization processes. It is known that the thermal models work well in the final state of particle production. They presume a charge-conserved hadronic phase. On the other hand, they have no access to the phase transition itself. In other words, the phenomenology of QGP and particularly the dynamics of the phase transition seems to represent a kind of black box.

This might explain why we used to assume that the deconfinement temperature $T_c$ at small chemical potential should be coincident with the chemical freeze-out temperature $T_{fo}$ [1, 2] at the same value of chemical potential. What are the consequences of this assumption? For example, which type of strongly interacting matter we are treating which has to undergo a phase transition back to confined hadrons, very much rapidly expands and finally freezes out through chemical processes without any change in its temperature? Is it possible to describe it by the quantum chromodynamics (QCD)?

Although the energy density available in the heavy-ion collisions at SPS@CERN [3], RHIC@BNL [4] and now at LHC@CERN [5] (14 GeV/fm$^3$ at a time of 1 fm/c after the collision) exceeds the critical value calculated in lattice QCD ($\varepsilon_c \approx 0.7$ GeV/fm$^3$), many physicists still debate about the QGP signatures under these laboratory conditions. If $T_c = T_{fo}$ should hold at small chemical potentials, phenomenological signals characterizing the phase transition should remain measurable in the final state. At least, QGP signatures which are not sensitive to a medium, such as color screening or $J/\Psi$ dissociation into two leptons have to survive at $T_c = T_{fo}$. On the basis of current experimental and theoretical progress, we can think of other solutions, like $T_c \gg T_{fo}$. If $T_c \gg T_{fo}$, then QGP signatures are very much contaminated (in-medium modified) so that the final state does not reflect the creation of QGP. Furthermore, we can assume that the production of QGP requires much higher temperature than the currently available temperature at RHIC [6].

The QCD predicts that matter under extreme conditions is simple (similar to the nature of the new state of matter). The idea that the matter at temperature larger than $\Lambda_{QCD}$, deconfined phase, forms an ideal gas is not originated in QCD. Therefore, only a good understanding of the dynamics of the phase transition would help us to characterize QGP.

2. Phase transitions to new state(s) of matter
The end of the hadron era was predicted about six decades ago [7]. No doubt that the hadrons will go into a new state of matter at sufficiently high temperatures and densities [8]. The wide acceptable framework to study the phase transition of strongly interacting matter is given by QCD. The QCD predicts that the hot hadronic matter becomes simple. This is not necessarily weakly interacting. The lattice QCD dates to thirty years ago; QCD Lagrangian has to be discretized and everything has to be put on a finite a space-time lattice. It has been shown that a change in the phase of matter undoubtedly exists at sufficiently high energy densities. The degrees of freedom markedly increase in a relative narrow region of temperatures. For a purely gluonic system, for which the equation of state can be computed without...
approximations, there is a deconfinement phase transition. It is of first order and the critical temperature is estimated as $T_c \sim 270$ MeV [9].

The difficulties in the lattice calculations start when the fermion sector is switched on. Nevertheless, it has also been observed that the chiral symmetry is restored at the same critical temperature $T_c \approx 154 - 174$ MeV (depending of quark flavors) as that of deconfinement transition. The restoration of chiral symmetry means that the effective mass of quarks forming the hadron states becomes zero. Another important consequence of chiral symmetry breaking restoration is the disappearance of the mass degeneracy of hadronic states with the same spin but different parity quantum numbers. Dynamical quarks can only be included in lattice QCD in certain approximations. The order of the phase transition in full QCD is not yet completely known. We merely see a rapid change in bulk thermodynamic quantities. Consequently, the transition is known as cross-over. The behavior of the QCD phase transition at a finite chemical potential is not yet known from first principle of QCD. Nevertheless, if we look at the lattice results at a zero chemical potential, Fig. 1, we find that the system at temperatures of $4 - 5T_c$ remains below the Boltzmann limit [10]; $\varepsilon_{SB} \approx g n_f^2 T^4 / 30$. It seems that $\varepsilon / T^4$ would remain constant at much higher temperatures. This means that the deconfined system would remain strongly correlated. This is also valid at finite chemical potentials.

![Figure 1](image-url)  

**Figure 1.** Energy density in lattice QCD calculated for different quark flavors. It is clear that the energy density at the temperature $1.2 T_c < T > 4 T_c$ is smaller than the energy density in the Stefan-Boltzmann limit.

Apart from the known properties of the lattice QCD calculations, like heavy quark masses and finite lattice size and spacing, we have from this figure an evidence that the hadrons undergo a phase transition to a strongly correlated phase. Another important finding is the nature of phase transition. It is not a real phase transition but a rapid change in the degrees of freedom. Characterizing the nature of matter above $T_c$ is essential for the particle physics. Understanding the evolution of the Universe in early stages would be based on a clear characterizing of the phase transition(s).

## 3. Results and discussion

### 3.1 RHIC results and lattice response

Using elliptic flow, it was possible to conclude that RHIC has produced thermalized matter at a very high energy density\(^1\). For the first time, the hydrodynamics with a zero viscosity can describe the heavy-ion reactions. In relativistic hydrodynamics, under the assumption of local thermalization, the number density, current and energy-momentum tensors are

\[
\begin{align*}
\delta n_i^\mu &= 0, \\
\delta \mu J^\mu &= 0, \\
\delta n T^\mu v &= 0, \\
J^\mu &= n_i u^\mu, \\
T^\mu v &= (\varepsilon + P) u^\nu - P g^\mu\nu - \eta (\delta^\mu u^\nu + \delta^\nu u^\mu + \text{Tr}) - \zeta (\xi),
\end{align*}
\]

where $\eta$ and $\zeta$ are shear and bulk viscosities, respectively. The number density and entropy density are conserved. In strongly interacting quantum fields, the lower bound of the ratio of shear viscosity to entropy density is as [11]

\[
\frac{\eta}{s} \approx \frac{1}{4\pi^3}
\]

As mentioned above, it was possible to describe RHIC results by hydrodynamics, even if the last two terms in Eq. 2 are entirely removed. This means that matter above $T_c$ should also have zero viscosity. It is a fluid rather than a free plasma. In other words, the correlations do not completely vanish.

The pioneering quenched lattice calculations performed by Nakamura for the transport coefficients of gluonic plasma [12, 13] seem to confirm the above results. The lattice calculations are performed in the framework of the linear response model.

\[
\langle T_{12}(x,t) T_{12}(x',t') \rangle_{\text{ret}} = \int d^3x' \int_{-\infty}^{t} dt_1 e^{\xi(t_1-t)} \int_{-\infty}^{t_1} dt' < T_{12}(x,t) T_{12}(x',t') >_{\text{ret}},
\]

where $< T_{12}(x,t) T_{12}(x',t') >_{\text{ret}}$ is related to the Green’s function of the energy-momentum tensor. Using the spectral function, the green’s function with Matsubara frequencies can directly be related to the shear viscosity, $\eta$.

Figs. 2 and 3 depicts the results for temperatures up to $30 T_c$. In the perturbation theory, the shear viscosity reads [14]

\[
\eta = \frac{\eta^3 T^3}{g^4 (ln(\mu^3 / gT))},
\]

where $\eta^1 = 27.126$, $\mu^3 / T = 2.765$, $\mu = T_c / \Lambda_{QCD}$ and $g$ is the running coupling constant.

As mentioned above, only the gluonic sector has been taken into account in these lattice QCD calculations. The fermionic part entirely vanishes. In this case, the bulk viscosity is almost zero. It is clear that lattice calculations agree with the perturbation theory\(^1\).

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\(^1\)The official press release had the title: “RHIC scientists serve up perfect liquid”. This mainly has been based on a comparison with hydrodynamics. Because in the hydrodynamic codes, one has to introduce “many” inputs, e.g., initial conditions, equation of state, phase transition, chemical freeze-out and thermal local equilibration in order to solve the equations of motion numerically and describe the hydrodynamical evolution, one has to be very careful with this kind of comparison.
at high temperatures. However, for temperatures $\leq 3T_c$, we find that the lattice results lie below the perturbative lines.

It is needed to include quarks. By doing this, we can describe the transport properties of matter above $T_c$ and make a better comparison with phenomenological results. Also, we need to improve the inputs for the hydrodynamical codes.

The currently available collision energy is sufficiently high to catapult hadrons into a new phase. Thus, we now have the situation that the properties of recently discovered new state of matter has to be confirmed by three independent methods: analytical, numerical and experimental.

The QCD-like models and/or effective models can be used in the analytical method. To the author’s knowledge, the only analytical method applied so far - apart from limitations - is in Ref. [11].

The most powerful numerical method is lattice QCD with dynamical quarks, which still uses unphysically heavy or almost vanishing quark masses and faces a serious challenge when the chemical potential becomes finite. As mentioned above, the properties of new state of matter are studied in lattice QCD in quenched approximation [12, 13]. The lattice results have to be interpreted with respect to all these approximations. For example, the critical energy density and temperature at the physical quark masses are larger than those given above, namely, $T_c \simeq 200$ MeV, $\varepsilon_c \simeq 2$ GeV/fm$^3$. This has the consequence that $T_c \neq T_{fo}$. The deconfinement point is not the same as that of chemical freeze-out [1, 2].

The experimental method is the ultimate goal. The proof that a new phase of matter is produced has to be adduced experimentally. A recent critical review on RHIC results is given Ref. [15]. Experimentalists have maintained this position since more than two decades. Particle theorists used to tell them that hadrons for $T > T_c$ will go into an "ideal" deconfined phase and into free plasma.

The plasma is a phase of matter in which charges are screened due to the existence of other mobile charges. This will modify Coulomb's law. Recent lattice QCD results on spectral functions show that the $J/\Psi$ bound state can survive even at $\sim 2T_c$. (Fig. 4). In these quenched lattice calculations, $T_c \simeq 270$ MeV. As mentioned above, RHIC results imply that the new state of matter is a fluid rather than a free gas.

![Figure 2](image.png)

**Figure 2.** $\eta/s$ obtained by quenched lattice simulations (symbols) compared with perturbative results (lines) as function in $T/T_c$.

![Figure 3](image.png)

**Figure 3.** Shear viscosity in GeV$^3$ units is given in dependence on $T/T_c$. $\mu$ is a parameter given in Eq. 4.

![Figure 4](image.png)

**Figure 4.** $J/\Psi$ bound state has been found to survive at almost twofold $T_c$. Panel a) shows the results around $T_c$. Panel b) shows the results explicitly above $T_c$. The graphs are taken from [16].
3.2 Gluon condensates and correlations

Many ideas about the complex structure of the phase transition have been suggested, so far. For instance, the soft modes of confined hadrons can survive the restoration of the chiral symmetry breaking [17] and that hadron plasma can be formed instead of QGP [18–21]. Also there are many lines of evidence that the deconfined matter do not behave like free gas. For example, the gluon condensates [22, 23] remain finite above $T_c$. The gluon condensates have been calculated at a finite temperature and in the presence of massive quarks [23]. It has been assumed that such quarks due to the strong interactions will modify the thermal properties of gluon condensates. Therefore, the gluon condensates remain almost unchanged with the half of their value in the confined phase [22]. This means that the matter seems to be sticky [24].

$$\langle G^2 \rangle_T = \langle G^2 \rangle_0 + m_q \langle \bar{q} q \rangle_0 - m_q \langle \bar{q} q \rangle_T - \langle \Theta_{\mu} \rangle_T. \tag{5}$$

Fig. 5 depicts this quantity. At $T > T_c$, the condensates at a zero chemical potential seem to be $T$–independent.

![Figure 5](image_url)

**Figure 5.** Gluon condensate of $SU(3)$ (solid line) and an ideal gluon gas (broken line) compared with the cases where light (heavy) dynamical quarks are included, denoted by open (full) symbols, respectively. Curves cited from [23].

Thus, we have concluded that the hadronic matter is expected to undergo phase transition to a new state of matter at high temperatures. The new state of matter is strongly correlated due to the non-vanishing gluon condensates and the existence of finite hadronic modes.

4. Conclusion

The phase transition at a very large chemical potential is most likely of the first order; at $T_c$, only one phase can exist. This first-order line is expected to end up with a critical endpoint of the second order. Its location was the subject of different lattice simulations. To date, there has been no final result. In dynamical QCD with $2 + 1$ flavors of staggered quarks of physical masses [7], the endpoint has been localized at $T = 162 \pm 2$ MeV and $\mu_b = 360 \pm 40$ MeV. According to the same reference, the critical temperature at $\mu_b = 0$ is $164 \pm 2$ MeV. From Ref. [25] and the comparisons with the resonance gas model [26–29], we assume that $T_c(\mu_b = 0)$ should be $\sim 200$ MeV. The temperature of the chemical freeze-out at a zero chemical potential is $\sim 174$ MeV. Another determination of the endpoint has been reported in [30]; $\mu_b \approx 420$ MeV. The corresponding temperature has not been estimated.

We can summarize that the endpoint is at approximately $\mu_b \approx 400$ MeV or $\mu_b / T_c \approx 2$. This value corresponds to collision energy $\sqrt{s_{NN}} \approx 9$ GeV. The lead beam at 40 AGeV (SPS) can be used to scan this region. Note that, at this energy, we have fully unexplained peaks in the ratios of strangeness to non-strangeness particle yields [31]. That the ratios of strangeness hyperons to non-strangeness hadrons (pions) all have a maximum value at the same energy is an indication of strangeness asymmetry. This can only be achieved in the plasma phase [32–34] i.e., it assumes that the interacting system at this energy should undergo phase transition to QGP. The phase transition is likely of the first order.

On the other hand, we do not observe such a peak at higher energies. It is an open question, why QGP-signatures e.g., color screening and strangeness asymmetry are not seen, when colliding energy increases? It is believed that, at RHIC and SPS [35–37] energies, we have produced the highest thermalized system ever known [38–42]. The reason might be the nature of system produced and the dynamics controlling the phase transition. In other words, the new state of matter might not have the properties of QGP, for which we have suggested phenomenological signatures [43–45].

One possibility to explain the difficulties with detecting phenomenological signatures at low chemical potential is the non-equilibrium quark occupancy of phase space, i.e., $\gamma \neq 1$. At finite temperature $T$, strangeness $\mu_s$ and iso-spin $\mu_I$ and baryo-chemical potential $\mu_B$, the pressure of one hadron is

$$p(T, \mu_B, \mu_S, \mu_I) = \frac{g}{2\pi^2} T \int_0^{\infty} k^2 dk \ln \left[ 1 \pm \gamma \lambda_0 \lambda_5 \lambda_i \epsilon(k) \right],$$

where $\epsilon(k) = (k^2 + m^2)^{1/2}$ is the single-particle energy and $\pm$ stands for bosons and fermions, respectively. $g$ is the spin-isospin degeneracy factor. $\lambda = \exp(\mu / T)$ is the fugacity parameters. $\mu$ is the chemical potential multiplied by corresponding charge. The total pressure is obtained by the summation over all hadron resonances. $\gamma$ appears in front of Boltzmann exponential, $\exp(-\epsilon / T)$. It gives the averaged occupancy of phase space relative to equilibrium limit. Therefore, in the equilibrium limit, $\gamma = 1$. Assuming time evolution of system, we can describe $\gamma$ as ratio between the change in particle number before and after the chemical freeze-out, i.e. $\gamma = n_i(t) / n_i(\infty)$. The chemical freeze-out is defined as the time scale, at which there is no longer particle production and the collisions is entirely elastic. In case of phase transition, $\gamma$ is expected to be larger than one. This is because large degrees of freedom and expanding phase space are likely in non-equilibrium.
The dependence of the single-particle entropy on the collision energy is related to the averaged phase space density. In Boltzmann limit and for one particle, we get that
\[
\frac{s}{n} = \frac{1}{T} \left( 4 \frac{\varepsilon}{3} - \mu \right),
\]
where \( \varepsilon \) is the single-particle energy, \( s \) is the entropy density and \( n \) is the particle number density. In this expression, \( s/n \) directly relates to \( \varepsilon \). Apparently, \( s/n \) gets a maximum value, if \( \partial (s/n)/\partial \mu = 0 \)
\[
\frac{\varepsilon}{n^2} \frac{\partial n}{\partial \mu} - n \frac{2 \varepsilon}{n^2} = \frac{3}{4}.
\]
Depending on \( \mu \), we can insert particles into phase space. Maximum occupation is reached at \( \mu = \varepsilon \). Beyond this limit, it is prohibited to insert more particles. On the other hand, we can expect - at least theoretically - that the occupation value is larger than one, if the phase space itself is changed, which is most likely provoked by the phase transition [41, 42, 46, 47].

The connection between this theoretical discussion and the particle ratios of strangeness hyperons to non-strangeness is given by \( \gamma \). As in [31], \( s/n \) plays the same role as \( \gamma \).

The results of \( s/n \) vs. \( \sqrt{S_{NN}} \) are depicted in Fig. 7. Full grandcanonical statistical set of the thermodynamic parameters is used. In this case, the complete dependence of \( s/n \) on \( T \) and \( \mu \) and consequently on \( \sqrt{S_{NN}} \), can straightforwardly be obtained by deriving \( s \) and \( n \) from Eq. 6.

For \( \gamma_0 = \gamma = 1 \), we find that \( s/n \) increases as the energy raises from AGS until low SPS energies (\( \sqrt{S_{NN}} \leq 9 \) GeV). For higher energies, \( s/n \) remains constant. This behavior might be an indication to strong compensation of collision energy in this region. Although, more energy is introduced to system, number of particles allowed to occupy the phase space remains constant. It is an indirect signature that the phase space itself remains constant.

For varying \( \gamma_0 \) and \( \gamma \), we find a singularity at \( \sqrt{S_{NN}} \approx 7 \) GeV. Equivalently, the phase space is maximum at this energy. At higher energies, \( s/n \) decreases. Although, the energy increases and consequently the produced particles, the single-particle entropy decreases. This means that the phase space shrinks. At RHIC energies, the shrinking becomes slower than at SPS. If this model gives the correct description, we now might have for the first time a theoretical explanation for dependence of phase space on energy. The phase space at SPS energy is apparently larger than at RHIC. Same behavior has been found experimentally [48–52]. The consequences are that QGP might be produced at SPS and detecting its signatures at RHIC might be non-trivial.

The situation is different at small chemical potentials. It is most likely that the transition can not be characterized by a narrow line. As shown above, the transition in this region is a rapid cross-over. The critical temperature is an average, (Fig. 1). Therefore, we expect that the transition is a kind of wide boundary. From Fig. 1, we can roughly estimate that the transition boundary has a width of at least \( 4T_c \). At temperatures up to \( 4T_c \), the degrees of freedom in the new phase of matter are 30% smaller than that in the Stefan-Boltzmann limit, (Fig. 1).

There are indications that the hadronic bound states can survive above \( T_c \), (Fig. 4). We have discussed the hydrodynamical results at RHIC energies. From all these results, it seems physically consistent to suggest that the new phase of matter is a mixture of the surviving hadron gas and a fluid of quarks and gluons [53]. The hadron gas might form bubbles inside the quark fluid. This explains two important features, the degrees of freedom and existing hadronic bound states above \( T_c \).

Based on the above discussion, we suggest a "new" phase diagram in Fig. 6. We separate the line of equilibrium chemical freeze out from that of the phase transition. At a zero chemical potential, the phase transition takes place at \( T \sim 200 \) MeV [1, 2, 25]. The equilibrium chemical freeze-out takes place at \( T \sim 174 \) MeV [1, 2]. The two lines slightly become short with increasing chemical potential. The phase transition at chemical potentials up to the value corresponding to the endpoint is no longer a cross-over. Consequently, QGP is expected at much higher temperatures than \( T_c \). Between the hadron gas and the QGP there is a mixed phase, in which the two degrees of freedom partly exist. The properties of matter in the mixed phase are as follows:

- It is an ordinary "nearly perfect" fluid (it is not free gas or plasma),
- It has very small but finite viscosity (it is not a superfluid),
- It has electric resistance (it is not a superconductor),
- It is a strongly correlated matter, since hadronic bound states can survive above \( T_c \).
- It is a sticky matter, since gluon condensates remain finite above \( T_c \).

Figure 6. Phase diagram of QCD. The values of the chiral symmetry order parameter \( < \bar{\psi} \psi > \) are also given. We distinguish between the freeze-out and transition lines. At small chemical potentials, the hadrons most likely undergo a smooth transition to a thermal phase accommodating a hadron gas and a fluid of quarks and gluons [53]. At high \( T \), the mixed phase entirely disappears. Matter will then be formed in QGP.

In the light of these properties, we still need to answer the following questions:
Figure 7. Entropy per particle $s/n$ as function of $\sqrt{s_{NN}}$. Singularity is located at almost the same energy as the peaks of particle ratios of strangeness to non-strangeness [31].

- What is the order of phase transition at small chemical potentials (related to RHIC, LHC or early Universe)? What is the order of the phase transition from the mixed phase to QGP at very high temperatures?

- How can we confirm the transition at small chemical potentials, phenomenologically?

- What are the in-medium modifications of the hadronic properties at finite $T$ and $\mu_b$ [44]?

- What are the transport properties above $T_c$?

We have to answer all these questions before we face a much difficult challenge with FAIR@GSI and NICA@JINR. We have to have clear theoretical descriptions and non ambiguous phenomenological signatures describing the QCD phase diagram. Non-perturbative QCD is a good candidate to answer some of these questions. Phenomenological studies are also very essential.

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