Highlight of the Parallel Session on QCD

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I will give a review with some comments of the parallel session on QCD and the related talks in the Quark Matter’97 meeting.

1. Introduction

As pointed out by T. Matsui in his overview talk [1], QCD is really at the heart of the field of ultrarelativistic heavy-ion collisions. Virtually every talk in this conference is in some way related to the study of QCD. It is neither possible nor my assignment to summarize the whole conference in just twenty minutes. I will only give some highlights of one parallel session titled QCD. Even this is already formidable given the time limitation. Since it is unnecessary to repeat what the individual speakers have written in their contributions to this proceedings, I will give a critical review of their talks with my own emphasis.

Though ultrarelativistic heavy-ion collisions are engineered to discover and study the deconfined phase of nuclear matter, i.e., Quark Gluon Plasma (QGP), it encompasses virtually every aspect of QCD theory, from perturbative QCD (pQCD) hard processes to nonperturbative hadronization, from parton equilibration to medium modification of hadron properties. They provide an unprecedented opportunity to study the QCD theory at vastly different environments. These different aspects of QCD, dominant at different stages of the high-energy heavy-ion collisions, can be characterized by the time or energy scales as shown in Table 1. During the earliest stage of the collisions at energy scale larger than \( Q_0 = 2 \text{ GeV} \), pQCD processes dominate and are responsible for production of Drell-Yan dileptons, direct photons, jets and \( J/\Psi \). Minijet production at this stage is also important to form a dense partonic matter \( \Psi \). Among all proposed probes of high-energy heavy-ion collisions, these are the only ones whose initial production rate can be calculated within the pQCD framework which has been successfully tested in \( e^+e^- \) annihilation, deeply inelastic \( e^-p \) and \( pp \) or \( p\bar{p} \) collision processes \( \Psi \). The few uncertainties involved are the effects of initial state interactions, e.g., parton shadowing and the so-called Cronin effect, which are also interesting by themselves. Talks by Sarcevic \( \Psi \) and Guo \( \Psi \) are devoted to these topics.

At late times when the system is still dominated by partonic degrees of freedom, interactions among the produced partons will drive the system toward equilibrium. The question of equilibration of the system bears significant importance in the study of the formation of quark-gluon plasma. It determines how strongly partons interact with each
other in the system and how long the partonic phase will last. During this period of time, or the life-time $t_{QGP}$ of the parton system, there will be associated thermal production of particles which can also be used as signals of the dense QGP matter. Talks by Sakai [6] and Wong [7] address some issues in this stage.

Table 1
Physics at different stages of high-energy heavy-ion collisions

| $t$(fm) | $Q$(GeV) | Physics |
|---------|----------|---------|
| $\leq 0.1$ | $\geq 2$ | pQCD: Drell-Yan, $J/\Psi$, direct $\gamma$, and jets production |
| $t_{QGP}$ | $1 \sim 2$ | pQCD or Finite temperature QCD: Parton equilibration, thermal production of particles, $J/\Psi$ suppression, and jet quenching |
| $t_{Mix}$ | $\Lambda_{QCD} \sim 0.2$ | Hadronization (in equilibrium?): Partition in phase space and flavor which may be modeled by “fireball model”. |
| $t_H$ | $< \Lambda_{QCD}$ | Hadronic interaction: medium effects, chiral condensates, etc, studied in effective models. |

When the energy scale in the system drops to around the value of $\Lambda_{QCD}$, hadronization will convert partons into hadrons. The process is purely nonperturbative and so far there has not been any known description of this process from QCD theory. It is not clear at all whether the system is in equilibrium during the hadronization process. When the hadronization happens in the vacuum as in $e^+e^-$, $ep$, $pp$ and $p\bar{p}$ collisions, phenomenological parameterizations of the so-called fragmentation functions are normally used. An exponential form motivated by vacuum tunneling in a strong field is normally used to describe the mass and transverse momentum distribution of the produced particles [8]. Under different environments such as in high-energy heavy-ion collisions, the parameters governing the hadronization will also be different. If the hadronization happens in a nonequilibrium environment, then the signals of the initial strangeness enhancement during the partonic phase might easily get lost in the hadronization process which also produces strange particles. One might also use statistical approach as by Becattini et al [9] to describe the particle production based on the occupation of the phase space. However, one must bear in mind that the so-call temperature parameter extracted from such an analysis has nothing to do with the temperature of an equilibrated system and thus cannot be put on the usual phase diagram.

After the hadronization stage, the interaction among hadrons might be described by some effective theories in which one can discuss physics phenomena such as medium effects in hadron properties and disoriented chiral condensates. The talk by Mishustin [10] discusses a model of chiral phase transition. Talks by Alam, Rajagopal and Schäfer [11–13] demonstrate the renewed interests in the physics at high baryon densities. In the following, I will summarize these talks in the QCD parallel session with some comments.
2. Effects of Initial-state Parton Interactions

All of the hard probes of the quark-gluon plasma involve hard parton scattering which can be studied within the framework of perturbative QCD. The current analysis of the \( J/\Psi \) data from NA50 \[^{14}\] has already demonstrated how important it is to understand accurately the initial production rates of these hard probes and their spectra. One important problem one has to study in this aspect is the effect of initial-state parton scatterings. Only after such effects have been completely understood, can one disentangle the true QGP signals from other conventional nuclear effects. Initial parton interactions and the interference in them can lead to an apparent depletion of the effective parton density inside a nucleus, the so-called nuclear shadowing of the parton distributions. They can also modify the momentum spectra of the produced hard probes which is often referred to as Cronin effect \[^{13}\].

There are many models for the nuclear shadowing of the parton distributions. A partonic picture with Glauber-Gribov interference effect along the line of a similar study by Levin \textit{et al.} \[^{16}\] was reported by Sarcevic. In this model the virtual photon in deeply inelastic \( e^{-}p \) (or \( e^{-}A \)) scatterings is converted into a \( q\bar{q} \) pair first which then interacts with the proton (or nucleus) via Pomeron exchanges. The proton (or nucleus) structure function \( F_{2}^{p(A)} \) can then be directly related to the cross section of this \( q\bar{q} \) pair with the proton (or nucleus). One can then derive the DGLAP evolution equation for the parton distributions. They assume that eikonalization can be applied to the coherent multiple scatterings of the \( q\bar{q} \) pair with the nucleus (at small \( x \) the coherent length of the \( q\bar{q} \) pair is much larger than the nuclear size, \( 1/m_{N}x \gg R_{A} \)), so that

\[
\sigma_{q\bar{q}A} = 2 \int d^{2}b[1 - e^{-\sigma_{q\bar{q}N}T(b)/2}]
= A\sigma_{q\bar{q}N} \left(1 - \frac{A\sigma_{q\bar{q}N}}{8\pi R_{A}^{2}} + \cdots \right). \tag{1}
\]

Since \( \sigma_{q\bar{q}N} \) and \( \sigma_{q\bar{q}A} \) are related to the structure function of a nucleon and nucleus respectively, one can then derive the DGLAP evolution equation for the nucleus structure function which depends on the gluon distribution in a nucleon. It is interesting to point out a term in the evolution equation arising from the second term in the above equation that corresponds exactly to the gluon fusion term in the Mueller and Qiu’s \[^{17}\] model of shadowing. With some choice of the initial parton distributions in nuclei (at a fixed scale \( Q_{0} \)), they reproduced the measured nuclear shadowing effect of the structure function. They further predicted the shadowing effect for gluon distribution using the approach and concluded that the depletion of gluon density will not saturate at very small \( x \). I believe this is only because they did not take into account similar shadowing due to gluon fusion in a nucleon. At very small \( x \) the same mechanism causes the gluon distribution in both a nucleon and a nucleus to saturate and then the depletion inside a nucleus due to shadowing will also saturate.

Initial parton scatterings not only cause the depletion of the effective parton distribution inside a nucleus, it can also modify the momentum spectra of the produced particles in the hard processes, like the \( p_{T} \) distribution of DY lepton pairs, direct photons and \( J/\Psi \).
There has been a continuing effect by Qiu, Sterman and collaborators [18] to study such effects within the context of double scatterings which corresponds to the next-leading-twist contribution to the hard processes. Guo [5] reported her recent calculation along the same line of double scatterings in DY dilepton production in \(pA\) collisions. One can separate the contribution into three terms depending on the momentum involved in the second scattering in addition to the \(q\bar{q}\) annihilation. If the second scattering is hard, the contribution has a form of classical double scattering, \(\sigma_1\sigma_2/Q^2\). If the second is soft, the contribution is proportional only to \(\sigma_1\) with the coefficient depending on a universal twist-4 nuclear parton correlation function which can be determined from other processes. The third term is then the interference between the first two amplitudes. For large transverse momentum \(q_T\) of the lepton pair which Guo has considered, the interference term is small. The double scattering will then enhance the total cross section. When \(q_T\) is small, the interference term is expected to be large and negative so the contribution from the double scattering will be reduced. But for small \(q_T\), one has to take into account of the resummation of soft gluon radiation. This is still being investigated.

As we see from both Gao and Sarcevic’s talks and as again emphasized in Dokshitzer’s review talk [19], quantum interference effects are important in many QCD processes including high-energy heavy-ion collisions. These important effects have to be considered when one tries to construct a reasonable model. Any model, no matter how open it is, is useless if it does not have the right physics in it. With the coming RHIC experiments and also the high \(p_T\) region the SPS experiments have so far reached, the hard processes will become a test ground for many QCD phenomena and powerful probes of the dense matter.

3. Equilibration Processes in a Parton Gas

While the initial production of the hard probes and minijets can be studied in the framework of pQCD, the early evolution of the produced parton gas can also be similarly addressed via pQCD based parton cascade approach. In the talk by Wong [7], several improvements are reported on the evolution of the initially produced parton gas based upon a Boltzman approach [20]. He included not only the elastic but also inelastic processes of parton-parton scattering in the calculation of the relaxation time in the relaxation-time approximation of the Boltzman equation. They considered radiative correction to the problem and find it important when the strong coupling constant is not very small. It then leads to smaller relaxation time and thus faster equilibration. On the other hand it also accelerates the cooling of the temperature and reduces the life-time of the system (the time before the hadronization happens when temperature drops below the QCD phase transition temperature). When one calculates the yields of thermal particle production during the life-time of the partonic system, these two effects will then compete with each other. The final results will also be very sensitive to the initial conditions one uses and that is the main uncertainty one has to deal with in the partonic approach of heavy-ion collisions.

In a related effort, calculation of the transport coefficients was performed within a lattice QCD approach [6]. What are really calculated in this case are the the Matsubara Green’s functions at finite temperature and by analytic continuation the retarded Green’s
functions. The transport coefficients are then obtained in terms of the retarded Green’s functions in the linear response theory. The coefficients are found at around the QCD critical temperature very close to the perturbative calculation at high temperatures. One, however, should be reminded that in this approach one has to assume an ansatz for the form of the spectrum density of the Fourier transform of the Green’s functions.

4. Physics at High Baryon Density

During the last year, there has been a renewed interest in the physics of dense matter, in particular the possibility of diquark condensates and the associated color superconductivity. The idea of color superconductivity in the matter of high baryon density proposed a long time ago [21] is quite simple. The possible states of a pair of quarks, which are color-triplet and spin-1/2 objects, are color anti-triplet (antisymmetric) and sextuplet (symmetric) and spin zero and one, i.e., with color and spin quantum numbers (\(3,0\)), (\(3,1\)), (6,0), and (6,1). Out of these six possible diquark states, the most attractive is the color-anti-triplet and spin-zero combination (3,0). If the quarks are in a spatial symmetric configuration in this state, the Fermi statistics requires the state to have two quarks with different flavors. This is consistent with the diquark structure of a baryon where color confinement also requires the diquark to be in an color-anti-triplet state. Such a diquark description of a baryon has been successfully implemented in the Lund model of string fragmentation [8] and is also consistent with the results of a QCD sum rule study of the quark distribution inside a baryon [22]. Therefore, in a baryon dense (and chirally symmetric) system quarks tend to form iso-singlet spin-zero and color-anti-triplet pairs, if color confinement is not a necessary condition. This could then happen in a system with very high baryon density where the color could well be deconfined. At low enough temperature the boson-like quark pairs will then go through Bose-Einstein condensation and give rise to nonvanishing diquark condensates <qq>. This system will then resemble a cool electron plasma and the quark pairs bounded together by the attractive Coulomb interaction will be like Cooper pairs on the Fermi surface, thus leading to color superconductivity. Using a perturbative calculation, the corresponding gap and critical temperature were estimated [21] to be in the MeV range.

Recent two studies [12,13] presented in this conference argue that non-perturbative interaction among quarks can also lead to the same phenomenon but with the gap and critical temperature two orders of magnitude larger. Both studies have used an instanton-induced interactions between light quarks. They also found that the iso-singlet scalar diquark with color-anti-triplet is the most attractive channel. The corresponding gap and critical temperature are found in the range of 100 MeV.

It is interesting to point out that the formation of diquark condensates requires deconfinement at high baryon density. But the instanton-like interaction could also be screened in such a deconfined phase so that the dominant interaction again will be reduced to Coulomb-like interaction with one gluon exchange. In Bailin and Love’s calculation, they used an effective strong coupling constant of \(\alpha_s = 0.3\). Iwasaki and Iwado [23] recently pointed out that if one uses a larger value of the effective \(\alpha_s\), one can also get larger values of the gap and critical temperature. Therefore, no matter what type of interaction is dominant, color superconductivity is still an interesting possibility. Since the diquark
condensates has to be in one particular direction in the color space, it will also force
the color of the quarks to be aligned in the opposite direction in order to maintain the
color neutrality of the system. Then the question is what are the consequences that one
observe, for example in neutron stars.

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REFERENCES

1. T. Matsui, this proceedings.
2. K. Geiger, Phys. Rept. 258, 237 (1995); X.-N. Wang, Phys. Rept. 280, 287 (1997);
   K. J. Eskola, CERN-TH-97-097.
3. Hard Processes in Hadronic Interactions, eds. H. Satz and X.-N. Wang, Int. J. Mod.
   Phys. A 10, 2881 (1995).
4. I. Sarcevic, this proceedings.
5. X. Guo, this proceedings.
6. S. Sakai, this proceedings.
7. S. Wong, this proceedings.
8. B. Andersson, G. Gustafson, G. Ingelman, T. Sjostrand, Phys. Rep. 97, 31 (1983).
9. F. Becattini, this proceedings.
10. I. N. Mishustin, this proceedings.
11. J. Alam, this proceedings.
12. T. Shäfer, this proceedings.
13. K. Rajagopal, this proceedings.
14. L. Ramello, this proceedings.
15. J. W. Cronin, et al., Phys. Rev. D 11, 3105 (1975).
16. A.L. Ayala, M.B. Gay Ducati, E.M. Levin, Nucl. Phys. B493, 305 (1997).
17. A. Mueller and J.-W. Qiu, Nucl. Phys. B268, 427 (1986).
18. J.-W. Qiu and G. Sterman, Nucl. Phys. B353, 137 (1991); Nucl. Phys. B353, 105
   (1991); M. Luo, J.-W. Qiu and G. Sterman, Phys. Rev. D50, 1951 (1994).
19. Yu. L. Dokshitzer, this proceedings.
20. T. S. Biró, E. van Doorn, B. Müller, M. H. Thoma and X.-N. Wang, Phys. Rev. C48,
    1275 (1993).
21. D. Bailin and A. Love, Phys. Rept. 107, 325 (1984); and references therein.
22. V. L. Chernyak and C. T. Zhitnitskii, Phys. Rept. 112, 1783 (1984).
23. M. Iwasaki and T. Iwado, Phys. Lett. B350, 163 (1995).