Quark Matter ’99 — Theoretical Summary: What Next?

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Introduction

Having been asked by the organizers of this conference to summarize what we learned here from a theoretical perspective — to be followed by Reinhard Stöck’s experimental summary — I will first review the three broad areas where major progress has been reported: The phase structure of strongly interacting matter, the properties of matter at the instant when it freezes out into individual hadrons in the final stage of the expansion of the hot fireball, and the status of the main signatures of the formation of a quark-gluon plasma. In the final section I will offer some thoughts about what should be done next, both in the experimental and the theoretical arena.

The Phases of QCD

Insight into the phase structure that quantum chromodynamics imposes on the world continues to be full of surprises. This issue, which lies at the basis of the experimental relativistic heavy ion programs around the world was the subject of several talks at this meeting.

Di Giacomo reminded us that quarks are, indeed, confined. Arguments based on cosmological evidence show that free quarks are at least $10^{-15}$ less abundant than expected. This implies that the Gibbs factor for a free quark at the confinement phase transition must have been limited by $\exp(-E_q/T_c) \ll 10^{-15}$ or $E_q > 10$ GeV. This number is so large (on the QCD scale $\Lambda$) that one expects a general principle at work: a kind of dual Meissner effect. If the QCD vacuum is a color-magnetic superconductor, i.e. if color-magnetic monopoles form a condensate in our normal world, the Meissner effect would naturally explain the absence of any color-nonsinglet excitation around us [1].

Color-magnetic monopoles do not exist as fundamental objects in the QCD Lagrangian, but the Yang-Mills equations allow for extended, though unstable, topological excitations with the quantum numbers of magnetic monopoles in a $[U(1)]^{N-1}$ subspace of the SU($N$) gauge group. These excitations can be identified in the lattice gauge theory by abelian projection of the link variables after choosing an appropriate gauge. Thus, any attempt to prove the existence of a monopole condensate is inherently gauge dependent. However, by repeating the study in several different gauges, the general nature of the result can be checked.

Di Giacomo showed us the results of lattice simulations investigating the dependence of the quantity $\rho = d(\ln(\mu))/d\beta$, $\langle \mu \rangle$ being the monopole condensate, on the inverse temperature $\beta$. He presented impressive evidence [2] that the quantity behaves as $\rho \propto$
with an exponent $\nu$ indicating a second-order phase transition in SU(2) and a first-order transition in SU(3). These results constitute strong evidence that color-magnetic monopole condensation is the cause of color confinement in non-abelian gauge theories without dynamical quarks. It will be very interesting to see how the result extends to real QCD.

A quite different picture of the QCD phase transition was presented to us by Helmut Satz, who argued that QCD undergoes a percolation phase transition \cite{Satz} at $T_c$. In the poster session, Fortunato showed that the percolation idea can be made precise by studying the domain structure of the sign of the Polyakov loop, i.e. the trace of the timelike Wilson line

$$\sigma(x) = \text{sgn} \left( \text{tr} \left( e^{-\int A_d \tau} \right) \right),$$

in the SU(2) gauge theory on an euclidean lattice. The numerical results demonstrate cluster percolation exactly at the critical temperature identified in the conventional way. Again, this study needs to be extended to SU(3) and to the theory with dynamical quarks before one can safely claim relevance to the real world.

However, it is tempting to speculate that cluster percolation is related to the Hagedorn transition in string theory, which is known to have the nature of a Kosterlitz-Thouless transition with topological defects proliferating on the world-sheet of the string wrapped around the periodic euclidean time dimension \cite{Hagedorn}. In terms of simple concepts, at the critical temperature the dilute string gas assembles into a dense web of interconnected strings that permeates the whole of space. It would be interesting to see whether this analogy could be made more precise in some of the exactly solvable models of supersymmetric gauge theories derived from superstring theory.

Rajagopal, in his talk, gave an overview of the recent developments that have made the QCD phase diagram even more interesting. We now understand, as first pointed out seriously by Bailin and Love \cite{Bailin} in the mid-1980s, that di-quarks condensate at large baryon density when the temperature is not too high \cite{Bailin}. The high-density ground state of QCD is thus a color superconductor while, as discussed before, the QCD vacuum is most likely a dual color superconductor. Depending on the masses of the light quarks, the detailed properties of the high-density phase vary, but in some cases may be quite exotic: rotational symmetry as well as parity may be spontaneously broken! Most of these studies are based on phenomenological models of the quark-quark interaction, but the existence of Cooper pairing between quarks can be proven rigorously in the very-high density limit where one-gluon exchange becomes perturbatively calculable. Unfortunately for our field, because of their restriction to “low” temperature but high density, these phenomena probably cannot occur in heavy ion collisions; but they remain of astrophysical interest and may occur in the dense, cold cores of collapsed stars.

We were also reminded that symmetry arguments suggest the presence of a critical point somewhere along the QCD phase boundary, which is the remnant of the tri-critical point separating the regions of first- and second-order phase transition in a world with two massless quark flavors \cite{Symmetry}. Because lattice calculations at finite baryon density are still impossible, we do not know exactly where this critical point is, but we can look for it experimentally by searching for anomalously large fluctuations caused by the critical fluctuations in its vicinity. Since no evidence for such fluctuations has been observed at the
SPS, where the quark chemical potential $\mu \approx 90$ MeV is already quite low, it is reasonable to expect that the critical point could be located somewhere between the conditions accessible at the SPS and those created in nuclear collisions at the AGS ($\mu \approx 180$ MeV). If critical fluctuations persist within a sizable region around the critical point (models suggest for $|\mu - \mu_c| < 0.2\mu_c$), experiments at just a few beam energies may be sufficient to locate the critical point.

Our understanding of the fully developed quark-gluon plasma also has recently made significant progress. Several groups of theorists have shown that the picture of the QGP as a plasma of weakly interacting quasi-particles with effective masses $m_{q}^{\text{eff}}, m_{g}^{\text{eff}} \sim gT, g\mu$ accounts remarkably well for the thermodynamic properties of the QGP phase \[8\]. Comparisons with the results of lattice gauge theory for $\mu = 0$ indicate that this simple description may work until very close to $T_c$. Since this analytic technique can be easily extended to nonzero $\mu$, it could provide a useful description of the full QCD phase diagram for phenomenological purposes.

There has been much progress in QCD transport theory recently, which was not reported at this conference. The extension of the kinetic mean-field theory of non-abelian plasmas to a Boltzmann equation including collisional effects, as well as the formulation and numerical solution of the mean-field theory on real-time lattices are especially noteworthy \[9\]. Other interesting work concerns the description of dynamical color screening in nuclear collisions within the framework of Geiger’s parton cascade model \[10\]. Independently, the perturbative QCD calculations shown by Eskola in the RHIC predictions session, predict perturbative saturation of partons in Pb+Pb at RHIC for a cut-off momentum $p_0 \approx 1$ GeV/c. In such a picture, the entire transverse energy generated in the collision could be produced by minijets! While this may be exaggerated, it indicates that the idea that a quark-gluon plasma is created by partonic processes is not totally unreasonable.

Obviously, the challenge is to put such a picture on firm ground by developing a formalism of parton transport with medium effects built in self-consistently. Work in this direction is proceeding steadily if slowly \[11\]. In the meantime, the theoretical concept of gluon radiation by rapidly moving color charges, developed by the Minnesota group and others, has been successfully applied to electrodynamic processes. The fast-moving, peripherally colliding nuclei are viewed as sheets of electric charge along the intersecting light-cones which generate a flash of electromagnetic field energy when they briefly meet. This pictures allows for calculations of important processes, such as electron-positron pair creation with and without capture of the electron, ionization, and Coulomb fission of the colliding nuclei, to all orders in the nuclear charge in the high-energy limit \[12\].

### The Hadronic Freeze-Out

Tremendous experimental and theoretical progress has been made recently towards the full characterization of the conditions at the moment of the final freeze-out of hadrons emitted from the nuclear reactions, both in the AGS and SPS energy domain. We have almost complete data on the spectra and yields of a wide variety of hadrons, including $\pi^{\pm, 0}, K^{\pm, 0}, \phi, p, \Lambda, \Xi^-, \Omega^-$, and their antiparticles. Pair correlations of charged and neutral pions, positive kaons, protons, and even $\Lambda$-hyperons have been measured. We have seen remarkable data, especially from the AGS, of yields of light (anti-)nuclei: from d up to...
Li, d, \( ^{3}\text{He} \), and the hypernucleus \( ^{3}\Lambda \text{H} \).

As was pointed out by Wiedemann in his review lecture, a highly consistent picture is emerging from these measurements [13]. The single-particle momentum spectra, the \( p_{T} \)-dependence of the pair correlations, and the fragment yields all can be explained by a freeze-out from a thermal, dilute hadronic fireball with a final temperature (at the SPS) around \( T_{f} \approx 100 \text{ MeV} \), an average transverse flow velocity \( \langle \beta_{T} \rangle \approx 0.55 \), and a baryon chemical potential \( \mu_{f} \approx 400 \text{ MeV} \). The transverse rms radius of the fireball at freeze-out is approximately 10 fm; and one obtains a lower limit for the average freeze-out time of about 6–8 fm/c after impact, spread over a rather short period of 2–3 fm/c. Thus, the freeze-out occurs quite suddenly, after the fireball has expanded considerably from its original size.

Systematic differences between various fits using different parametrizations of the freeze-out geometry still need to be resolved, but it is clear that the required data are now available. These high-quality data impose severe constraints on any phenomenological model. For example, Bose-Einstein correlations of identical pions show [14] that the average density of phase-space occupation of pions at freeze-out cannot much exceed the value \( \langle f \rangle = 0.3 \).

The data also prove that the chemical composition of the expanding hadronic matter is frozen much earlier. Equilibrium fireball model fits give values [15]

\[
T_{ch} = 170 \pm 10 \text{MeV}, \quad \mu_{B} = 270 \pm 25 \text{MeV}
\]

for Pb+Pb at the SPS and

\[
T_{ch} = 125 \pm 10 \text{MeV}, \quad \mu_{B} = 540 \pm 25 \text{MeV}
\]

for Au+Au at the AGS. The hadronic yield data for the AGS are not quite as complete, but the obtained values are compatible with the nuclear cluster data.

It remains contentious whether there is evidence for chemical non-equilibrium at mid-rapidity. Although it is clear that the chemical composition changes as function of the rapidity \( y \), especially at the AGS, this effect may be at least partially described by \( y \)-dependent thermodynamic parameters. To avoid such complications, many chemical analyses only consider phase-space integrated hadron yields. This procedure tends to obscure non-equilibrium effects. Some theorists still argue vehemently that such effects exist and constitute important evidence [16]. I believe that the data now are sufficiently precise to settle this issue once and for all, and to establish the separation of chemical and thermal freeze-out objectively and unambiguously. Microscopic models of the late stage of the expansion of the hot hadronic fireball could serve to help identify distinctive signatures of non-equilibrium [17]. One specific case is the “early” freeze-out of the \( \Omega \) hyperon seen by experiment WA97 and its prediction by hadronic cascade models [18].

This brings me to the topic of microscopic theoretical models for nuclear reactions in the SPS energy domain. Hadronic cascade models, some with mean-field interactions, have succeeded in reproducing the gross and many detailed features of the nuclear reactions. They have become indispensable tools for experimentalists who wish to identify interesting features in their data or make predictions to plan new experiments. However, the

\[\text{The mean freeze-out time cannot be unambiguously deduced from the data and is model dependent.}\]
general success of these models can easily lead to misconceptions. As detailed comparisons with the new high precision data reveal, none of the existing hadronic cascades really works correctly at SPS energies. As Antinori impressively demonstrated in his talk, the comprehensive data of WA97 on (anti-) hyperon yields rule out even those models that have been specifically “tuned” by the addition of novel mechanisms \[13,20\]. Moreover, all model descriptions based on hadronic dynamics are fundamentally inconsistent at high densities, calling their application to describe collisions among heavy nuclei at the SPS into question.

This is revealed quite dramatically when one asks, which fraction of the energy is contained in “standard” hadrons, i.e. those with entries in the Particle Data Booklet, and which fraction is temporarily stored in more fictitious components, such as pre-hadronized strings. Bass and coworkers have studied this question within the framework of the UrQMD model \[21\]. They find that up to a time of 8 fm/c most of the energy density resides in strings and other high-mass continuum states that have not fully decayed. Clearly, we know very little from first principles about the physical properties of these objects even when they occur in isolation, and practically nothing about their interactions (or even their existence) in a dense environment. Any skeptical scientist must conclude that the application of these models to the early phase of a Pb+Pb collision at the SPS is highly speculative.

While this insight is not altogether new, it raises the question whether any microscopic hadronic model can sensibly be used to describe nuclear collisions at the SPS in their entirety. Those who believe so need to present arguments that clarify the meaning of hadronic cascades under such conditions and answer to the question how the theoretical consistency of their models can be assessed. Until agreement on this issue has been reached, I suggest that theorists should refrain from:

- trying to “fine-tune” existing codes to describe all details of the final state and claiming that the success has any physical implication;
- writing another, ostensibly “better” code;
- applying purely hadronic cascade models to nuclear collisions at RHIC energies.

Instead, experimentalists should insist that codes based on such models must contain a flag that automatically generates a warning message when the limit of credible applicability of the hadronic cascade is reached (e.g. when strings begin to overlap), or when the final result depends essentially on fictitious components of the model that are not based on experimental evidence (color ropes or quark droplets, interacting baryon junctions, etc.). The users of such codes would then know that the result is not a prediction of known physics but, at least in part, the based on speculative ideas of its author.

In the meantime, I would like to suggest that we begin to use the existing hadronic cascade codes more seriously as marvelous tools for the description of the freeze-out process. These models comprise a large body of information about reactions among hadrons in a dilute environment where the physics is dominated by two-body interactions involving on-shell hadrons and known hadronic resonances. A big step in this direction was recently taken by Bass in collaboration with several other young theorists, when he
used the UrQMD code to model the dynamics of the late hadronic phase that follows the evolution of dense matter described by a parton cascade or a hydrodynamic model [22].

The existing hadronic cascade codes are ideally suited for systematic studies of the chemical and thermal freeze-out of hadrons when the dense phase of the nuclear reaction is over. They are vastly superior to the simple models of hadrochemical equilibration that were used earlier to explore the possible hadronic mechanisms that could lead to strangeness enhancement and equilibration in a hadronic gas [23]. These studies neglected higher mesonic and baryonic resonances and usually only considered small deviations from thermal equilibrium. Significant improvement over these early calculations is possible and would be highly desirable for a complete analysis of the implications of the wealth of freeze-out data now available.

QGP Signatures

Of the many probes for the high-density phase of QCD in nuclear collisions, only four robust signatures have withstood the experimental tests: A: Flow (directed, radial, elliptical); B: Flavor equilibration; C: $J/\psi$ suppression; D: $\rho$-meson broadening or disappearance. The data from the SPS heavy ion experiments presented at this meeting have brought impressive and sometimes spectacular evidence for signatures $A$–$C$. Signal $D$ has also been firmly established, and can be expected to reach a similar state of maturity when data taken with the upgraded CERES detector will become available. I will now discuss the four signatures, in turn.

A. Flow: One of the most exciting new messages of this meeting was the observation of the softening of the equation of state already in the AGS energy range, around 3–4 GeV/u, in Au+Au collisions [24]. Microscopic models predict that the highest baryon density reached at this energy is about 4–6 times normal nuclear density. The precise transition from out-of-plane to in-plane elliptical flow could be explained if baryon dense matter makes the transition from a stiff equation of state to a much softer one in the vicinity of this point [25]. This phenomenon is seen in a wide range of microscopic models. It should be carefully studied whether the softening can be accounted for by the onset of copious baryon resonance production, or whether it requires an additional change in the structure of baryonic matter.

Many descriptions of baryon-dense matter predict the onset of chiral symmetry restoration for precisely this density range (at $T \approx 100$ MeV). The question is, how can this issue be further studied? One could try to obtain more systematics, e.g. the dependence of the phenomenon on the size of the colliding nuclei. Also, it may be time to reconsider the possibility of a lepton-pair experiment in the AGS energy domain to search for the disappearance of the $\rho$-resonance in the lepton-pair spectrum.

B. Strangeness: The data obtained at the AGS and SPS leave no doubt that strangeness is enhanced throughout the baryonic sector. Nagle [26] reported the value 3.5 for the ratio $\bar{\Lambda}/\bar{p}$ for Au+Au at the AGS (expt. E864), and Antinori [20] showed that the new p+Be run at the SPS has confirmed the enhancement by a factor 15 of the $\Omega$ hyperon in Pb+Pb with respect to p+A collisions (expt. WA97). Few thought such enhancements possible when they were first predicted in the mid-1980s in the framework of models based on quark-gluon plasma evaporation. In order to realize the full power of these experimental
Figure 1. Lattice-QCD equation of state and QGP signatures.

results, new studies of flavor equilibration in the hadronic phase using modern cascade models are urgently needed.

C. Charmonium: The new data presented by NA50 clearly show that the \( J/\psi \) state is nontrivially suppressed in Pb+Pb collisions, with the suppression continuing to increase up to the highest values of \( E_T \) accessible in Pb+Pb [27]. Problems with multiple interactions at high \( E_T \) that contaminated earlier data have been resolved. The use of minimum bias data to normalize the \( J/\psi \) measurements now permits NA50 to fully exploit their high statistics. Unfortunately, the \( J/\psi \) issue is plagued on the theoretical side by an abundance of “cheap” models that prove nothing. As Redlich showed in his talk, the state of the theory of interactions between \( J/\psi \) and light hadrons is embarrassing [28]. Only three serious calculations exist (after more than 10 years of intense discussions about this issue!), and their results differ by at least two orders of magnitude in the relevant energy range [29]. There is a lot to do for those who would like to make a serious contribution to an important topic.

D. Low energy lepton pairs: What is possible when the power of modern hadron theory is brought to bear on a related subject, was clearly demonstrated at this meeting in Rapp’s and Eletsky’s talks about in-medium interactions of the \( \rho \)-meson and applications to low-mass lepton pairs from heavy ion interactions at the SPS. Various different approaches have come to a remarkable convergence [30]. It has become clear that the \( \rho \)-resonance is strongly broadened in hot, baryon-rich matter, while its centroid barely moves. Under SPS freeze-out conditions, predicted values [31] are \( \Delta \Gamma_\rho \approx 300 \text{ MeV}, \Delta m_\rho \approx 10 \text{ MeV} \). It has also been shown that nucleons are more efficient in this respect than pions.

Rapp also pointed out that the hadronic correlator in the \( \rho \)-meson channel \((1^{--})\)

\[
C_{\mu
u}(p) = \int dx e^{ipx} \langle j_\mu(x) j_\nu(0) \rangle
\]

rapidly approaches the form expected from perturbative QCD when \( T \) and \( \mu_B \) approach the critical line separating hadron from quark matter. \( \rho \) broadening and \( \rho - a_1 \) mixing combine to generate a spectral function in the photon channel resembling that of free \( q\bar{q} \) annihilation [32]. The similarity might be even closer if interactions among the quarks
were included, especially the effective mass of the quasiparticle mode with quark quantum numbers in the dense, hot medium.

Let me finally point out that all observations are consistent with a succession of several stages of dissolution of hadronic states as the energy density increases from light to heavy nuclear collision systems at the SPS (see Figure 1). As the critical conditions \((T_c, \mu_c)\) are approached from below, first the \(\rho\)-meson dissolves and strange quarks begin to percolate freely among hadrons. The full population of strange quark phase space within a few \(\text{fm/c}\) probably requires the activation of gluonic excitations. These also lead to the disappearance of the weakly bound \(\chi_c\) state which accounts for the anomalous \(J/\psi\)-suppression in all but the most central \(\text{Pb+Pb}\) collisions. Finally, the gluon density becomes sufficiently high and energetic to dissolve the \(J/\psi\) itself in the innermost core of the \(\text{Pb+Pb}\) fireball. The energy density required is predicted to be around 5 \(\text{GeV/fm}^3\). This value may just be reached in the most central \(\text{Pb+Pb}\) events. It is time for the theory community to focus its efforts on confirming (or refuting) this scenario, and to suggest new experiments or ways of data analysis that can help us to reach a conclusion.

What next?

The organizers of this conference asked me to say a few words about what, in my opinion, should be done next to resolve the remaining issues that stand in the way of a clear-cut interpretation of the data. Here are some thoughts:

- A high-resolution study of the low-mass lepton pair spectrum in \(\text{Pb+Pb}\) is needed that identifies the \(\omega\) resonance and confirms that the enhancement below the \(\rho\) is accompanied by a suppression of the \(\rho\) itself. This investigation is under way with the upgraded CERES detector.

- The \(J/\psi\) and flavor signals need measurements in smaller symmetric nuclear systems \((\text{Ag+Ag, Ca+Ca ?})\). This would allow to resolve discrepancies between theory and the NA50 data points at low \(E_T\) where systematic errors become serious, and should help locate the onset of strangeness enhancement and flavor equilibration.

- The flow and strangeness signals, as well as the quest for critical or other nontrivial fluctuations need data from collisions at lower beam energies. Again, this is under way with the run at 40 \(\text{GeV/u}\) later this year.

- The indications of an enhanced open-charm background in the di-muon spectrum reported by NA50 calls for a precise measurement of open charm production. Although the enhancement is not anticipated by theory, it needs to be either confirmed or firmly refuted experimentally, to rule out false conclusions about the suppression of the \(J/\psi\). Fortunately, the NA50 collaboration has proposed an experiment that could measure the D-meson yield, and a similar proposal is in preparation by the NA49 collaboration.

- The flow data from the lower AGS energy range \((2–6 \text{ GeV/u})\) call for measurements with smaller nuclei, which would allow to change the baryon density at fixed kinematics. The data also reaffirm the need for a lepton-pair experiment in this energy range.
• The possible termination of the SPS heavy ion program in two years is of serious concern, because it would virtually preclude the careful measurement of the excitation function of the hadronic observables below the maximal SPS energy. The new data from the AGS, covering the energy range between the Bevalac/SIS and the highest AGS energy, many of which were first presented at this conference, have impressively demonstrated the importance of such a program.

If it turns out to be impossible to perform a systematic exploration of the energy range between the top AGS energy and the top SPS energy at CERN, one should seriously consider whether such a fixed target program could not be initiated at RHIC. As Rafelski and Uggerhøj have begun to point out, a small fraction of the RHIC beam could be extracted by means of crystal channeling \[33\]. Since there are already plans at RHIC to use channeling to “clean up” the intersecting beams at one intersection, this might be an inexpensive way to provide a low-intensity beam for fixed-target experiments. Obviously, because of the low event rates, such a program would have to focus on hadronic observables.

• Finally, let me make a few remarks that concern the theory community interested in relativistic heavy ion physics. It is important that we seriously address the challenge posed by the new high-quality data, from the AGS as well as the SPS. The experiences made in other areas of nuclear and high energy physics, telling us how theory can be used in conjunction with experimental data to create lasting scientific progress, may provide useful aid. Here are some suggestions. Theorists should:

  – calculate *carefully* what they can;
  – be mindful of the limits of validity of their favored approach;
  – take recourse to general principles (symmetries, effective theories, etc.) where microscopic approaches are not feasible.

One last thought: If we want to establish the existence of a new phase (or phases) of QCD where quarks and gluons play a more direct role as effective degrees of freedom than in our hadronic world, we cannot hope to do so without direct reference to the beautiful theory of quantum chromodynamics. Much progress is being made in applying QCD to processes that are of interest to relativistic heavy ion physics, and it would be a mistake to ignore QCD as we make the transition to the RHIC era.

Acknowledgements

This work was supported in part by the U.S. Department of Energy under grant DE-FG02-96ER40495. I thank S.A. Bass for comments on a draft of the manuscript.

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