Signals of the quark-gluon plasma in nucleus-nucleus collisions

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This talk is a brief overview of the present status of our understanding of nucleus-nucleus collisions at high energy and the search for signals of the quark-gluon plasma.

1. INTRODUCTION

The main motivation for studying nucleus-nucleus collisions at high energy is to learn the properties of the densest and hottest forms of matter that one can produce in the laboratory. One hopes in particular to reach the conditions under which hadronic matter is expected to turn into the quark-gluon plasma, a new phase of matter whose degrees of freedom are the hadron constituents, the quarks and the gluons. Understanding the behaviour of bulk matter governed by QCD elementary degrees of freedom and interactions, and studying how it turns into hadronic matter, offers challenging perspectives and touches fundamental issues in the study of Quantum Chromodynamics in its non perturbative regime, such as the nature of confinement, of chiral symmetry breaking, etc.

Unfortunately, the tools with which we are probing these fascinating features of dense and hot matter are not ideal. The dynamics of nuclear collisions is complicated and at present allows at best for only semi-quantitative predictions. In absence of a definite signal to look for, we need to learn details of how nucleus-nucleus collisions work before one can draw any general conclusion about properties of hadronic matter. Progress in the field is therefore largely conditioned by progress in experiments which, in fact, has been quite impressive.

The data accumulated over the last 10 years both at the BNL/AGS and at CERN/SPS, in particular those involving the heavier projectiles and targets, start to draw a consistent picture of what happens in nucleus-nucleus collisions at high energy. There is clear evidence that at the highest energy achieved so far, nuclear collisions deviate substantially from a naive picture based on a mere superposition of independent nucleon-nucleon collisions; collective behaviour is seen. As the collision energy is tuned up the relevant degrees of freedom change, from nucleons to hadronic resonances and hadronic strings, and hints that quark degrees of freedom are playing a role have been obtained.

But while a coherent picture of the collision dynamics is emerging, finding unambiguous signatures of quark-gluon plasma formation remains an open problem. Presumably, unless one is very lucky, confirmation of plasma production will not come from a unique signal,
and evidences based on systematic and well focused observations will have to be accumulated. Some may wish to argue that, perhaps, we are lucky. Indeed, several anomalies have been observed in the data. Among these are the suppression of \( J/\Psi \) production, the excess emission of lepton pairs in the mass range below the \( \rho \) resonance and the enhanced production of strange and multistrange baryons. The temptation is great to associate these anomalies with the production of the quark-gluon plasma but, in my opinion, this is a bit premature.

This Quark-Matter meeting is special. It is the last conference before RHIC starts to produce data, opening a new area in the field. This is also the time where the CERN SPS program is coming to an end. RHIC physics will be reviewed in a special session organized by M. Gyulassy, while E. Shuryak will discuss the CERN SPS program and its future perspectives. The present talk is a brief introduction to the field. My goal is to indicate where the focus of the present discussions is without going into the details of the interpretations of the various results. Recent, more systematic, reviews can be found in Refs. [1–3], and there is some overlap, unavoidable, with E. Shuryak’s talk [4]. The talk is organized as follows. I start with theoretical considerations on the phase diagram of hot and dense hadronic matter and the properties of the quark-gluon plasma. Then I review the general patterns of ultrarelativistic collisions. In the last part of the talk I briefly discuss the specific signals for which anomalous behaviour has been observed. The last section contains conclusions.

2. THEORETICAL CONSIDERATIONS

There is some rough analogy between the transition from hadronic matter to the quark-gluon plasma and that from a neutral atomic gas to the corresponding ionized plasma. In both cases as the temperature or the density rises, the basic degrees of freedom in the system change, becoming, in the high temperature/high density phase, the elementary constituents. However, in spite of the fact that the neutral atomic gas and the completely ionized plasma have very distinct physical properties, no phase transition separates them, and the process of ionization is a very gradual one. In contrast, QCD predicts that the transition from hadronic matter to the quark-gluon plasma is a sharp one, accompanied by the rapid increase of the entropy density corresponding to the liberation of quark and gluon degrees of freedom. Because of QCD asymptotic freedom, it is not surprising that quarks and gluons become free at high temperature (or high density); what is not a priori obvious is the sharpness of the transition, and also the fact that it occurs for a relatively low temperature. The critical temperature for pure gauge theory is now determined with an accuracy of a few percent in pure SU(3) gauge theory: \( T_c \approx 264 \) MeV. With dynamical quarks, calculations are more complicated and the resulting critical temperature more uncertain, \( T_c \approx 150 – 200 \) MeV.

The nature of this (phase) transition has been somewhat clarified, but not entirely. In pure SU(3) gauge theory, one has evidence of a first order transition. With massless or light quarks, the transition seems to be dominated by the effects of chiral symmetry breaking and the associated soft modes. Universality arguments suggest then an O(4) critical behaviour for 2 light flavors, whereas for 3 massless quarks the transition is first order. What happens in the real world depends on whether the mass of the strange quark
can be considered as large or small. A heavy strange quark is inert in the transition which is then, as for two flavors, a second-order one. If the strange quark is effectively light, the transition is first order. Unfortunately, the actual mass of the strange quark is of the order of the typical QCD scale, and the situation is still controversial. It cannot be excluded that with non vanishing masses for all quarks, the sharp phase transition disappears and becomes simply a crossover.

How can we characterize the phases before and after the transition? This question, related to that of finding an unambiguous signature of the quark-gluon plasma, has no simple answer. In the real world where quark masses are non vanishing, no order parameter has been found to distinguish the two phases. What is meant then by confinement or deconfinement transition? A plausible picture which is receiving support from lattice calculations is that of the dual superconductor involving color magnetic monopole condensation. This picture is reviewed here by A. Di Giacomo [7]. One interesting consequence of this picture is the existence of strings between heavy quarks. This leads to a linearly increasing potential at zero or low temperature, and provides a simple view of color confinement. Quite remarkably, the string tension drops rapidly as $T$ approaches $T_c$ and vanishes at $T_c$. Above $T_c$ the potential is a screened potential, with the screening radius a decreasing function of the temperature. We shall refer to this behaviour in our discussion of $J/\psi$ suppression.

Another perspective on what happens at the transition is given by chiral symmetry. The quark condensates are expected to decrease with increasing temperature and density and, in the case where the quarks are massless, to vanish for some values of these parameters: at this point chiral symmetry is restored. In the limit of small temperature $T$ and baryon density $\rho$, the variations of the condensates can be obtained from model independent considerations: $\delta \langle \bar{q}q \rangle_T \propto -T^2$ and $\delta \langle \bar{q}q \rangle_\rho \propto -\rho$. For higher density however, interaction effects must be taken into account; these may strongly affect in particular the value of the density at which chiral symmetry is restored [8].

Lattice results show that the ideal gas limit is approached as $T$ becomes large, but this approach is slow: typically, the energy density at $2T_c$ is about 85% of the Stefan-Boltzmann limit value. These results can be accounted for reasonably well by phenomenological fits involving massive quasi-particles [10]. Although the quasiparticle picture suggested by such fits is a rather crude one, it supports the idea that one should be able to give an accurate description of the thermodynamics of the quark-gluon plasma in terms of its elementary excitations and encourages the development of analytical calculations of the thermodynamic potential using weak coupling techniques. Such calculations are difficult: although the gauge coupling $g$ is small if the temperature $T$ is sufficiently high, the perturbative series shows rather poor convergence properties (see [11], and also [12–14]). However, sophisticated rearrangements of the perturbative expansion and various resummations have been applied to the calculation of the thermodynamic potential [15]. Particularly promising in this context are self-consistent approximations of the entropy which have been shown recently to accurately reproduce lattice data at high temperature [16]. Although much remains to be done, the results obtained so far are quite encouraging and give us the hope that an analytical control of the high temperature phase of QCD is within reach.

A main limitation of present lattice calculations is their inability to deal with finite
chemical potentials. There is little progress to report on this issue, although some of the pathologies of the quenched approximation have been clarified with the use of random matrix models \[17\]. There has been however recently exciting developments in analytical investigations of the high density part of the phase diagram with the resurgence of the old idea of color superconductivity \[18\], but with totally new perspectives. Among all possible quark pairings, it has been recognized in particular that a special condensate involving a correlation between color and flavor, possible with massless flavors, has very special properties. This “color-flavor locked state” \[19\] leads to substantial gaps, of the order of 100 MeV and has many remarkable features. A most intriguing one is the apparent continuity between this phase of quark matter and some form of nuclear matter, as it has been suggested in Ref. \[20\]. This may offer the chance to explore such properties as confinement or chiral symmetry breaking using weak coupling calculations at high density, a most fascinating possibility indeed!

I would like to end this section by returning to the real world and list a few questions for experiments. Clearly, given the complexity of nuclear collisions, we cannot probe all the detailed features discussed above. So what can we hope to “see”? Can we observe changes in the equation of state, see the phase transition? Can we trace deconfinement, or chiral symmetry restoration, in an unambiguous way? Does matter produced at the early stages of the collisions behave as non interacting quarks and gluons? Note that most of these questions refer to systems in thermal equilibrium; it is for such systems that our theoretical tools are best developed. Colliding nuclei are not at all systems in equilibrium, although there is some evidence that local thermal equilibrium may be achieved at the late stages of the collisions. There may exist interesting genuine non equilibrium phenomena, an example being provided by the so-called Disoriented Chiral Condensate \[21\]. Finally let us remark that in all these experimental studies we have very few control parameters at our disposal, essentially the nuclear sizes (and the impact parameter) and the beam energy. However, data with high statistics allow various cuts and may effectively provide new ones.

3. NUCLEUS-NUCLEUS COLLISIONS. GENERAL PATTERNS

Measurements of the transverse energy distributions \[22,23\] provide access to the energy density achieved in the collisions. Simple estimates using Bjorken’s formula,

$$\epsilon_0 = \frac{1}{\tau_0 \pi R^2} \frac{dE_T}{dy},$$

lead to $\epsilon_0 \approx 1.3 \text{ GeV/fm}^3$ at the AGS ($dE_T/d\eta = 200 \text{ GeV for Au+Au central}$) and $\epsilon_0 \approx 3 \text{ GeV/fm}^3$ at the SPS ($dE_T/d\eta = 450 \text{ GeV at SPS for Pb-Pb}$), taking for $\tau_0$ the generic value of 1 fm/c. Although they should be viewed as crude estimates, these numbers indicate that appropriate conditions are possibly met for the formation of a transient quark-gluon plasma at the SPS. The measurement of baryon densities reveal a large baryon stopping at the SPS \[24\], larger than expected, although the maximum baryon density is there lower than that achieved at the AGS.

There is evidence that hadronic matter at freeze-out is nearly “thermal” (for a review see \[25\]). Rather remarkably, particle ratios are well fitted by simple statistical models.
involving only two parameters, a temperature $T_f$ and a baryon chemical potential $\mu_B$. One should distinguish here between the chemical freeze-out at which point matter composition is frozen, from the thermal freeze-out where particles undergo their last collisions. Particle ratios determine the parameters of the chemical freeze-out, while the parameters of the thermal freeze-out can be obtained with additional information from momentum distributions. Transverse momentum spectra are seen to be “blue-shifted”, reflecting the collective flow of particles moving towards the observer. This effect is seen on spectra as an increase of the inverse slope (effective temperature) with the mass of the particle considered. The freeze-out temperature and the collective expansion velocity thus determined are compatible with interferometry measurements [20].

Thermal freeze-out occurs at a temperature lower than chemical freeze out, that is, given the expansion, at a later time. Freeze-out parameters evolve with beam energy, moving from high density/low temperature at small beam energy to low density/high temperature at high beam energy. These parameters can be displayed in a phase diagram which has been shown many times at the last Quark Matter meeting [27]. A striking feature of this diagram is that the line representing matter at freeze-out is quite close to that representing the phase boundary toward the quark-gluon plasma [28]. Another interesting observation is that the energy per particle on the freeze-out line is about 1 GeV [29]. Although they are highly suggestive, the significance of all these observations is still unclear. The fact that similar models reproduce the particle production in $e^+e^-$ collisions [30] signals a universal behavior, reminiscent of the Hagedorn’s picture [31], and suggests that phase space is statistically populated in the prehadronization phase.

Various collective flows have been observed (for a review see [32], and Danielewicz at this meeting). For central collisions, particle emission is azimuthally symmetric, and leads to transverse or radial flow responsible for the distortions of the momentum distributions referred to earlier. In non central collisions, directed flow and elliptic flow can occur. The nature of the elliptic flow changes with the beam energy, from low energy where it is out of plane (also referred as squeeze-out), to high energy where the flow is enhanced in the direction of the impact parameter in which the pressure gradient is the strongest. Analysis of the various flow patterns, and their evolution with the collision energy, can give information on the equation of state.

With the increasingly accurate measurements of two particle correlations and interferometry [33], the space-time picture of nucleus-nucleus collisions at high energy is altogether becoming more and more precise. New perspectives are offered by analysis of event by event fluctuations [34,35], which are made possible by the high statistics data now available.

4. SPECIFIC SIGNALS

I turn now to specific “signals”, that is observables for which anomalous behavior has been detected. At least for two of them, namely the enhancement of strangeness [36,37] and the suppression of $J/\Psi$ production [38], the observed effects were anticipated, although it is fair to say that the predictions were not quantitative: the results obtained in Pb-Pb collisions came as a surprise, and their interpretation is still under debate. On each of these subjects there is much to say (strangeness for instance having its own topical
meetings!) and I shall only give a few indications.

4.1. Strangeness

An enhancement of strangeness (properly defined) is observed in all experiments which measure particles carrying strange quarks: $K$, $\phi$, $\Lambda$, $\Xi$, $\Omega$. While at the AGS most of strangeness production can be understood in terms of independent nucleon-nucleon collisions and hadronic reinteractions \[39\], this is not so at the SPS. In particular precise measurements of the individual hyperon yields ($\Lambda$, $\Xi$, $\Omega$, and the corresponding antiparticles) in Pb-Pb collisions has revealed a systematic increase with respect to p-Pb as the strangeness content of the particle increases \[40\]. This observation is difficult to account for by invoking hadronic rescattering, and in fact none of the hadronic models which successfully reproduce the bulk of the data fit the strange particle yields without ad hoc adjustments. Note that $K$ and $\Lambda$ are relatively easy to produce in a hadron gas, but the cross section for the production of $\Omega + \bar{\Omega}$ is small \[37\]. One could imagine a scenario where multistrange hadrons are produced in steps, but this seems to take more time than is available.

Another important observation is that the mechanism responsible for strangeness enhancement in Pb+Pb collisions seems to be independent on the centrality when the number of participants is $N_{part} \gtrsim 100$ \[40\]. It is clearly important to explore smaller systems or more peripheral collisions to determine where the effect sets in. A similar remark applies to the energy dependence of the effect, and pinning down the onset of the phenomenon as the function of beam energy is one of the most compelling motivations to perform a low energy run at the CERN/SPS.

These observations, combined with the remarks made earlier on the properties of matter at freeze-out, and in particular the fact that the ratios of strange particles are compatible with statistical models \[11\] \[12\], convey the impression that much of the strangeness observed in Pb-Pb collisions is already present in the early stages of the collision.

4.2. Dileptons

The vector mesons, through their decay into dileptons, provide access to the properties of the dense matter at various stages in the collisions. The $\rho$ meson plays a particular role because its lifetime (1-2 fm/c) is such that it decays much of the time while being in matter. Since the dileptons produced in the decay interact weakly with the surrounding matter they carry direct information about the state of matter at the time of the decay.

The CERES Collaboration \[13\] has obtained evidence for a significant excess of dileptons with invariant mass below that of the $\rho$. The excess, which is concentrated at low transverse momentum $p_T$, is not accounted for by $\pi^+\pi^-$ annihilation in vacuum. Typical dilepton production processes involve the $\rho$ meson as an intermediate state, and the $\rho$ meson can be affected by the surrounding medium.

There has been much effort devoted lately to understanding how the basic properties of hadrons are modified in matter. The way hadronic interactions modify the spectral density of the $\rho$ meson, leading in particular to a shift of its mass and an increase of its width, has been analyzed with increasingly sophisticated theoretical models (see for instance \[14\] and the talk by R. Rapp at this meeting). Certainly the most exciting issue here is the potential relation of such modifications to the onset of chiral symmetry restoration, which could occur under the conditions realized at the SPS.
Much progress in the field is expected from the coming runs which should provide high precision data, allowing in particular to distinguish the behaviors of the various resonances in matter, while the low energy run should demonstrate the sensitivity of the effect to a change in the the baryonic density.

4.3. $J/\Psi$ suppression

With the $J/\Psi$, a tiny bound state made of a pair of heavy charm quark and antiquark, we can probe the very early stages of the collisions. Contrary to the $\rho$, the $J/\Psi$ has a very long lifetime and it decays into dileptons only when it is far from the collision zone. However, as pointed out by Matsui and Satz [38], the binding of the $J/\Psi$ meson is sensitive to the screening of the $c - \bar{c}$ potential by a quark-gluon plasma, and the meson bound state will not survive in a hot enough quark-gluon plasma. Hence the original argument suggesting that a decrease of the observed $J/\Psi$ yield could reveal the formation of the quark gluon plasma. An alternative scenario for the $J/\Psi$ suppression involves $J/\Psi$ collisions with hard “deconfined” gluons present in the quark-gluon plasma [15].

The first run of experiments at CERN indeed showed that the rate of $J/\Psi$ production was less than the rate expected from extrapolations of nucleon-nucleon collisions. But it soon appeared that this phenomenon, as well as the corresponding one observed in proton-nucleus collisions, could be accounted for by what is usually referred to as nuclear absorption [45].

$J/\Psi$ produced somewhere in the nucleus has to cross a certain region of nuclear matter before escaping, and because it can interact inelastically with nucleons on its way out, it may be destroyed. A survival probability can then be defined, $\exp\{-L/\lambda\}$, where $L$ is the distance traveled by the $J/\Psi$ in nuclear matter, and $\lambda = 1/(n\sigma_{abs})$ an absorption mean free path with $n$ the nuclear density. Several analysis lead to a value of $\sigma_{abs}$ of the order of 6 to 7 mb [48].

The fact that the Pb-Pb data [19] do not obey this simple behaviour was a surprise. And the temptation to speculate about a new mechanism at work has been irresistible [50,51]. Interestingly, if one assumes that the extra suppression observed in Pb-Pb collisions is a local phenomenon (in space-time), sensitive for instance only to the local energy density, one can account quantitatively for the bulk of the data. But to prove that we are dealing with a phenomenon related indeed to local energy density one would need data at lower beam energy, which is hard, if not impossible, to get. Alternatively, one could explore smaller systems for which the new mechanism would set in within the covered $E_T$ range.

While the present NA50 data show clear deviations from the normal nuclear absorption pattern, whether or not they present a threshold remains a subject of controversy. Observing a threshold behaviour would be very suggestive of a qualitative change in the properties of matter at some energy density. Progress has been made in the analysis of both the low $E_T$ and the high $E_T$ regions, with in the latter case the elimination of spurious reinteractions in the target. Worth emphasizing is the development of a new method of analysis making use of minimum bias events; the new procedure removes in particular the statistical fluctuations in the Drell-Yan spectrum, which was a limitation in previous analysis [52].
5. THE EARLY STAGES OF NUCLEAR COLLISIONS AT RHIC AND LHC

With RHIC coming, one may attempt to extrapolate the knowledge gained at the AGS and SPS to higher energies. The corresponding “predictions” of various models will be reviewed at the end of this meeting. Let me concentrate here on a few conceptual issues of relevance when exploring higher energies.

At high energy, semi-hard interactions leading to minijets are believed to play an important role. They start to compete with “soft” phenomena presumably already at RHIC where they may contribute a significant fraction of the total transverse energy \[53,54\]. The reasons why theorists are interested in this regime is because it is one where one could hope to do reliable calculations form first principles in QCD. The regime is indeed one of weakly coupled many particles, which is perhaps amenable to a classical description.

In fact Monte Carlo simulations, the so-called parton cascade calculations \[55,56\] treat partons as free particles and study their evolution, taking into account QCD interactions, and assuming that the initial distributions in phase-space are given by the structure functions of the nuclei. These calculations provide a detailed description, at the partonic level, of the beginning of a nucleus-nucleus collision. They allow the study of thermalisation, the build up of energy density and so on. However, they raise a number of theoretical questions. To which extent can partons be treated as classical particles? What is the role of quantum mechanical coherence effects?

In the last few years, efforts have been made to provide a more satisfying theoretical framework. Simple and and physically appealing pictures of the initial wave function have been constructed \[57\]. But relating these initial wave functions to the initial conditions for parton cascades, that is understanding how the gluon initially in the wave functions are freed in the collision, remains an open problem \[58\].

6. CONCLUSIONS

The analysis of the various data collected from BNL/AGS and CERN/SPS have led to a truly impressive progress in our understanding of nucleus-nucleus collisions at high energy: A-A collisions are clearly distinct from N-N collisions. Large energy densities are produced, providing appropriate conditions for the creation of a quark-gluon plasma. Collective behaviour of matter is seen and we have hints from several observables that quark degrees of freedom play a role in the collision dynamics. There are good indications that thermal and chemical equilibrium may be reached at freeze-out. The space-time pictures of the collisions are becoming more and more precise with flow and interferometry measurements, and the large multiplicities of Pb-Pb collisions allow for promising event by event analysis. Flows patterns start to be used to reveal details of the equation of state. Finally, several anomalies have been identified in observables considered as potential “signatures” of the quark-gluon plasma.

It is fair to say, however, that we are not yet in a position to offer to outsiders to the field compelling evidence that quark-gluon plasma has been produced. For one thing, our theoretical picture of the quark-gluon plasma is still very incomplete. Calculating the properties of the quark-gluon plasma, even in equilibrium, turns out to be a difficult task, beyond the trivial level of the free gas (on which most experimental analyses rely). And the off-equilibrium properties of the plasma are essentially unknown. Thus we have so
far no unique “signature”, and what we are looking for is evolving as we progress in our understanding of nucleus-nucleus collisions. But the progress which has been made since the very first run of experiments is really remarkable, and gives great confidence in the future of the field. And with RHIC coming out now, there are all reasons to be optimistic.

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