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HEAVY ION PHYSICS : THEORY

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Lattice quantum chromodynamics (QCD) predicts a new state of matter, called quark-gluon plasma (QGP), at sufficiently high temperatures or equivalently large energy densities. Relativistic heavy ion collisions are expected to produce such energy densities, thereby providing us a chance to test the above prediction. After a brief introduction of the necessary theoretical concepts, I present some critical comments on the experimental results with an aim to examine whether QGP has already been observed experimentally.

1 Introduction

The standard model of particle physics has been tested with great precision at LEP. Most of these tests exploit the fact that the corresponding coupling is weak and hence usual weak coupling perturbation theory can be employed in deriving the required theoretical predictions for them. The electromagnetic and weak couplings are indeed rather small in the currently accessible energy range: $\alpha_{em} \simeq 7.3 \times 10^{-3}$ and $\alpha_w \simeq 3.4 \times 10^{-2}$. However, the strong interaction coupling, α_s, is (i) a strongly varying function of energy in the same range, (ii) about 0.11 at the highest energy at which it has been measured so far, and (iii) ~ 1 at typical hadronic scales. Therefore, testing the strongly interacting sector of the standard model using only perturbation theory is a major shortcoming of the current precision tests of the standard model.

Formulating quantum chromodynamics (QCD), which is an $SU(3)$ gauge theory of quarks and gluons, on a discrete (Euclidean) space-time lattice, as proposed by Wilson [1], and simulating it numerically, as first done by Creutz [2], one can obtain several post-dictions [3] of QCD in the non-perturbative domain of large α_s. These include both the qualitative aspects like confinement and spontaneous chiral symmetry breaking, and quantitative details such as hadron masses and their decay constants. While the latter agree with the known experimental results within the sizeable theoretical errors, it is fair to say that no serious experimental test of any non-perturbative prediction of QCD has so far been made, with the possible exception of the D-meson decay constant. Relativistic heavy ion collisions offer a great window of opportunity to do so. Application of lattice techniques to finite temperature QCD has resulted [4] in the prediction of a new state of matter, called Quark-Gluon Plasma(QGP), at sufficiently high temperatures or energy densities. Chiral symmetry, broken spontaneously at zero temperature, seems to be restored in this new phase characterised by a much larger degrees of freedom characteristic of almost "free" quarks and gluons.

Let me sketch in very brief the reason this prediction needs to be regarded as a crucial test of QCD in the non-perturbative domain. Starting from the text-book expression for the partition function,

$$\mathcal{Z} = \mathrm{Tr}\ \exp\Big[- (\hat{\mathrm{H}} - \mu \hat{\mathrm{N}})/\mathrm{T} \Big] , \tag{1}$$

where $\hat{H}$ is the Hamiltonian for QCD, $\hat{N}$ is the baryon number operator, and the trace is taken over all physical states, various thermodynamic quantities of interest, such as the energy density or the pressure at a given temperature T and baryonic chemical potential μ, can be obtained as expectation values of appropriate operators with respect to Z. These are computed by first rewriting the partition function exactly in terms of an Euclidean path integral over the underlying quark and gluon fields:

$$\mathcal{Z} = \int \mathcal{D}A_\mu \mathcal{D}\bar{\psi}\mathcal{D}\psi \exp\Big[- \int_0^{1/T} dt \int d^3x\ \mathcal{L}_{QCD}(A_\mu, \bar{\psi}, \psi; \mu, g)\Big] . \tag{2}$$

This expression resembles the corresponding one for QCD at $T = 0$ a lot. It only differs in having a finite extent ($= 1/T$) for the (compact) Euclidean time. This suggests that lattice techniques can be useful in extracting information on QCD thermodynamics non-perturbatively. Discretizing the space-'time', and using a gauge invariant formulation of QCD on lattice, thermal expectation values can be computed at a finite lattice spacing (or equivalently at a finite ultra-violet cut-off) using, e.g, numerical Monte Carlo techniques. Repeating these calculations for a decreasing sequence of the lattice spacings at a fixed physical scale, one can obtain results in the desired continuum limit, although it needs massive computational efforts.

Simulations of lattice QCD at finite temperature thus results in parameter free information on QCD thermodynamics starting from first principles, since the only parameters, quark masses and the scale of QCD, can be fixed from zero temperature simulations. There are, however, some caveats and subtleties which make these computations difficult and nontrivial. E.g., defining a chiral symmetry on the lattice with a given number of massless (or light) flavours is still a thorny subject. How small a lattice spacing is adequate is not clear. Nevertheless, the existence of a new chirally symmetric phase seems [3,4] well established. Furthermore, this phase appears to be inherently non-perturbative in the experimentally interesting range of $1 \leq T/T_c \leq$ 4-10, where $T_c \sim 170$ MeV is the transition temperature at which the energy density varies most rapidly. The energy density, ϵ, in this range is 15-20% smaller [5] than the value of the corresponding ideal gas of quarks and gluons whereas a maximum of 3-5% deviation is allowed for a weakly interacting perturbative QGP. While the precise values for ϵ, or T_c, as well as the nature of the phase transition (whether first order or second) depend on the number of light quark flavours, the quoted values above being for 2 flavours of mass about 15 MeV, many simulations with varying numbers of light flavours suggest that an energy density greater than 1 GeV/fm^3 is needed to reach the QGP phase.

Collisions of heavy ions at very high energies can potentially produce regions with such large energy densities. Furthermore, since the transverse size of such regions is given by the diameter of the colliding nuclei, one can hope that these collisions will satisfy the necessary thermodynamical criteria of large volume ($L \sim 2R_A \gg \Lambda_{QCD}^{-1}$) and many produced particles. A crucial, and as yet unanswered, question is whether thermal equilibrium will be reached in these collisions, and if yes, when and how. A reliable estimate of the the energy density attained is consequently hard to get. Assuming *i*) a "plateau" in the rapidity distribution (in the central region of the cm frame) and *ii*) a "leading baryon" effect or a baryon-free central region, Bjorken [6] argued that for sufficiently high energies, the colliding nuclei with mass number A bore through each other, leaving behind a baryonless blob of produced particles in the center (around $y_{cm} = \frac{1}{2} \ln\ [(E+P_L)/(E-P_L)] \sim 0$). The energy density in the blob after an equilibration time τ_0 was estimated by him to be

$$\epsilon = \frac{1}{\mathcal{A}\tau_0} \cdot \frac{dE_T}{dy} , \tag{3}$$

where the effective area $\mathcal{A} = \pi R_A^2 = 3.94\ A^{2/3}\ \mathrm{fm}^2$ and dE_T/dy is the measured transverse energy per unit rapidity round $y_{cm} \approx 0.0$. Depending on the value of this initial energy density and the equation of state, the blob goes through various stages of evolution such as QGP, mixed phase and hadron gas, as it cools by expanding. A further rapid expansion of the hadron gas leads to such large mean free paths for the hadrons that they essentially decouple from each other. If this freeze-out is sufficiently fast, the free-streaming hadrons, $\pi, K, \cdots$ etc. will retain the memory of the thermal state from which they were born by having thermal momentum distributions. Thus the information from observables related to light hadrons can tell us about the temperature at this 'thermal freeze-out' and the velocity of expansion. To get a glimpse at still earlier times, one has to turn to harder probes which typically involve larger scales such as masses of heavy quarkonia, as we will discuss below.

Although both the Bjorken scenario and Eq. 3 are widely used in all current data analyses seeking to extract information on whether QGP did form in those collisions, even the present highest CERN collision energies may not be sufficient for either to hold. This is mainly because many baryons appear to get deposited in the central region of $y_{cm} \approx 0.0$ and the rapidity distribution also seems to be a Gaussian. A more reliable analogue of Eq. 3 is however not available in such a case. Note that even the theoretical estimate from lattice QCD above was for a baryonless case which too may be inapplicable for the present day collisions. In addition to temperature, one needs to increase the baryon density of the strongly interacting matter or equivalently increase the baryonic chemical potential μ to obtain a baryon-rich plasma. In principle, one knows how to handle the case of a nonzero baryon density on the lattice but it has so far turned out to be difficult in practice. Usual lattice techniques fail for nonzero μ due to technical reasons [4] and attempts to overcome [3] these have not been successful either. Thus a greater theoretical effort is required to obtain a QCD prediction for the energy density for nonzero μ, which may be more relevant to the existing heavy ion data, and also to obtain the analogue of Eq. 3 in that case. Of course, one can in stead go for higher energies to test QCD, where one expects to obtain a baryon-free region, making both the lattice estimate and Eq. 3 more accurate descriptions. While this will be done in the near future at RHIC, BNL and LHC, CERN, the existing data already show many new and exciting features.

2 Results from CERN

The experimental programs of high energy heavy ion collisions are being pursued actively at present in the Brookhaven National Laboratory (BNL), New York and CERN, the European Laboratory for Particle Physics, Geneva. *Au*-*Au* collisions at $\sqrt{s} = 4.7A$ GeV $\simeq 0.92$ TeV have been studied at BNL while *Pb*-*Pb* collisions at $\sqrt{s} = 17.3A$ GeV $\simeq 3.6$ TeV have been investigated at SPS, CERN using beams of gold ions at 2.1 TeV/c and lead ions at 32.9 TeV/c respectively. Earlier sulphur beam at 6.4 TeV/c was used on sulphur and uranium targets at SPS, CERN and those results form a benchmark over which several aspects of *Pb*-*Pb* collisions have been compared. I will focus largely on the latter since they correspond to the highest $\sqrt{s}$ used so far. Due to space restrictions, I will also have to restrict myself to highlights and I have to refer the reader for more details to the proceedings of Quark Matter conferences [7].

2.1 Initial Energy Density

The NA49 experiment reported measurements on $dE_T/d\eta$ quite a while ago [8] and reported $dE_T/dy \simeq 405$ GeV for *Pb-Pb*. Using a canonical guess of 1 fm for the formation time, one obtains from Eq. 3

$$\epsilon_{Bj}^{Pb-Pb}(1\text{fm}) = 2.94 \pm 0.3\text{GeV/fm}^3 \ , \tag{4}$$

which is certainly above the characteristic QGP-phase values from lattice QCD mentioned in Sec. 1. Since appreciable numbers of baryons at $y_{cm} \sim 0$ have been observed at SPS, it is doubtful that the current energies are high enough for creating a baryon-free region assumed for Eq. 3. One has to be cautious therefore and make sure that other independent estimates are also similar and they do appear to be so. Using the lattice results for baryonless plasma of 2 light flavours, the above estimate suggests a plasma temperature of about 220 MeV or about 1.3 T_c.

2.2 Hadron Yields

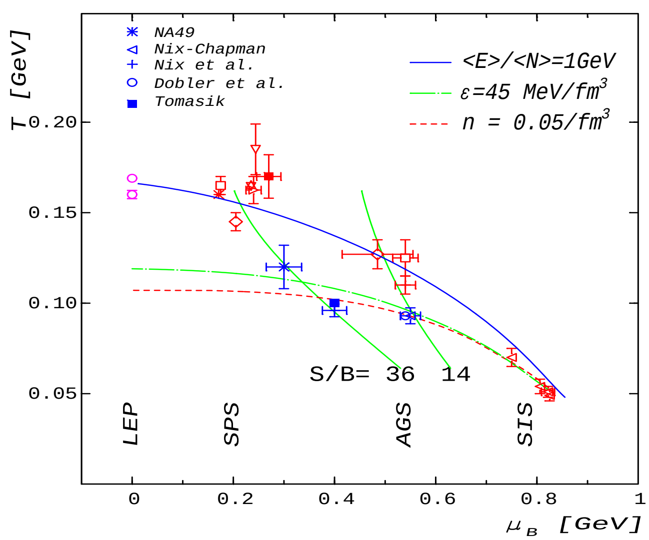

Figure 1: Chemical and thermal freeze-out points [11] in the (T, μ_B) plane for various experiments.

Assuming that a thermal freeze-out is triggered by a rapid expansion, one expects the momentum spectra of various hadrons to reflect the freeze-out temperature, T_{fo}, which will be blue-shifted by the collective expansion. For small transverse momenta, $p_T \ll m$, we expect the inverse slope of transverse mass distribution, $d\sigma/d(m_T - m)$ with $m_T^2 = p_T^2 + m^2$, to be given by $T_{\text{slope}} = T_{fo} + \frac{1}{2}m\langle v_T\rangle^2$. Thus one expects, T_{slope} to vary linearly with the mass of the observed particle, m. Such a linear rise has been seen in the Pb-Pb data, leading to an estimate for T_{fo}. On the other hand, the same transverse momentum distributions can also be equally well explained [9] using a non-thermal model, indicating the non-uniqueness of the thermal interpretation and hence of T_{fo}.

Strangeness changing – chemical– reactions are typically slower than the elastic processes and hence are expected to freeze-out before the thermal freeze-out. The temperature and chemical potential at this freeze-out decides the particle yields of various types, provided these yields are measured for the full 4π-integrated region; otherwise the measurements will depend upon the details of the collective flow mentioned above. Furthermore, taking ratios of such yields, one can reduce the dependence on the collective dynamics even more. A simple thermal model of free particles at a temperature T, volume V and chemical potential μ_B has been shown [10] to describe beautifully 22 ratios of particle yields which vary by three orders of magnitude, leading to $T_{fo}^{chem} \simeq 170$ MeV and $\mu_{B,fo}^{chem} \simeq 270$ MeV. Fig. 1 displays the thermal and chemical freeze-out points for the SPS *Pb*-*Pb* collisions along with those of other experiments. A comment about $\mu_{B,fo}^{thermal}$ may be in order, since I discussed above only the corresponding T_{fo}. As chemical equilibrium is lost earlier, it is strictly speaking not well defined. One simply adjusts $\mu_{B,fo}^{thermal}$ such that the particle ratios at T_{fo}^{therm} agree with the observed values.

Since T_{fo}^{chem} turns out to be very close to that expected for the quark-hadron transition from lattice QCD, it is plausible that the hadronic chemical equilibrium is a direct consequence of a pre-existing state of uncorrelated quarks and antiquarks and not due to hadronic rescatterings/reactions, since there is not much time for the latter. Hadron formation is then governed by the composition of the earlier state in a statistical manner and an expansion later does not change their yields. Needless to say though, the proximity of the two temperatures mentioned above is only suggestive. Indeed such temperatures and chemical potentials could still be reached via an expanding hadron gas as well. One then would expect though that the particle yield ratios will not reflect the underlying quark symmetries, as have been seen in the strangeness enhancement [12] pattern observed by the WA97 collaboration.

2.3 J/ψ Suppression

As remarked in the introduction above, one needs to employ harder probes to explore the physics of the fireball at earlier times when QGP may have existed. Production of J/ψ is one such hard probe. Since it is a tightly bound meson of charm and anticharm quarks, Matsui and Satz [13] argued that color Debye screening of these heavy quarks will prevent formation of J/ψ, if QGP is formed in the heavy ion collisions. Due to a finite size and lifetime of the fireball, the observable effect is expected to be a suppression in the production of J/ψ. The NA38 and NA50 collaborations [14] measured J/ψ cross sections for a variety of collisions, starting from $p + d$ to $Pb + Pb$ using the same muon spectrometer in the same kinematic domain ($0 \leq y^{cm}_{\mu^+\mu^-} \leq 1$ and $|\cos\Theta_{cs}| \leq 0.5$). While the systematic errors are thus minimised, the lighter beams were necessarily of high energies; $\sqrt{S_{NN}}$ thus varies from 17 GeV to 30 GeV.

Comparing the σ_{obs}^{DY} with $\sigma_{LO,th}^{DY}$ a universal K-factor was found in pp, pA and AB collisions: $\sigma_{A\cdot B}^{DY} \propto A \cdot B$ for all of them, where A and B are the mass numbers of the projectile and target respectively. Normalizing $B_{\mu^+\mu^-}\sigma_{AB}^{J/\psi}$ by dividing by $A \cdot B$ therefore, where $B_{\mu^+\mu^-}$ is the branching fraction of J/ψ in to $\mu^+\mu^-$, one could expect QGP formation to be signalled by a drop at some value of $A \cdot B$. Fig. 2 shows the NA38 and NA50 results where one notices a gradual fall in with $A \cdot B$ for *all* values. Note that some measurements have been re-scaled so that all are for the same energy in this figure. The decreasing cross section for all values of $A \cdot B$, including small ones, is an indication of the presence of yet another mechanism for J/ψ-suppression in these collisions. Thus any suppression due to QGP will have to be over and above this ‘normal suppression’.

Production of heavy quarkonia is an old and mature area of perturbative QCD. In particular, hadroproduction of J/ψ has been explained both in the colour evaporation model [15] and the colour octet model [16] at $\sqrt{s}$ comparable to those in Fig. 2. So it is a natural question to ask whether the decrease in Fig. 2 can be explained using pQCD. Unfortunately, sufficient information on the gluonic nuclear structure functions is not available at present; assuming them to be independent of mass number A or B is perhaps incorrect in view of the famous EMC-effect. Using the existing models of the EMC-effect, on the other hand, one finds hardly any decrease in the cross section in Fig. 2. The lack of decrease of $B_{\mu^+\mu^-}\sigma_{AB}^{J/\psi}/AB$ with AB appears to be a generic feature, since the dominant contribution to the cross section in Fig. 2

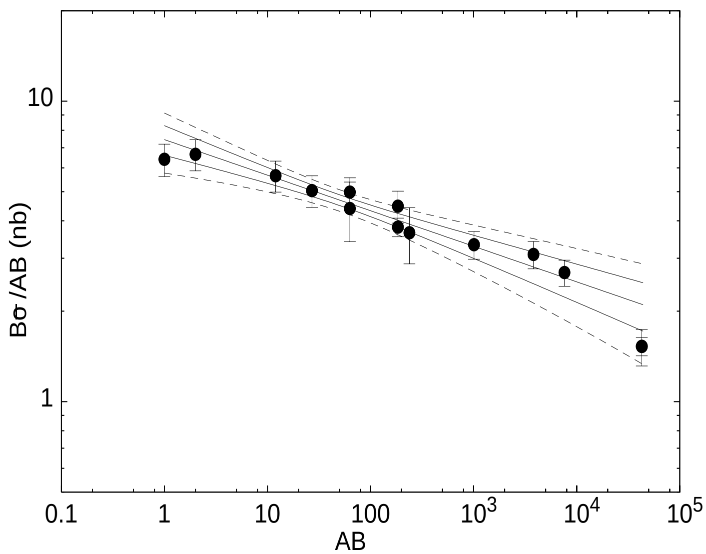

Figure 2: The data [14] for J/ψ cross section times its branching fraction into dimuons as a function of product of the mass numbers of target and projectile AB with the 1σ (full lines) and 2σ(dashed lines) theoretical predictions[18].

comes from the so-called anti-shadowing region in x which ought to be there for even the gluons due to the momentum sum rule. In view of the continuous decrease in Fig. 2, i.e. even for $p+$ light-A, where the radius of the target is only 2-3 times larger than that of proton, i.e, for hadroproduction [15,16], one has to ask whether a pQCD description of total cross sections for J/ψ is at all possible. It would be interesting and desirable to thrash out this question by extensive investigation of the nuclear glue and its impact on the J/ψ cross section.

The normal suppression in Fig. 2 has been explained [17] as a final state interaction. The produced J/ψ-state or its precursor can get absorbed in the nuclear matter (of the target and beam). Treating $\sigma_{abs}^{\psi N}$ as a free parameter and using the known nuclear profiles, one finds that a $\sigma_{abs} \sim 6.4$ mb can explain the linear fall in Fig. 2 quantitatively in Glauber type models. However, the Pb-Pb data point seems to be off this linear fall, and exhibits thus an 'anomalous suppression'. One can alternatively use an empirical $(AB)^\alpha$ fit to all points except the Pb-Pb, which too will be linear on the scales of Fig. 2, and the Pb-Pb data point stands out again.

Unfortunately, the issue of how statistically significant this anomalous suppression is gets affected by the crudeness of the theory described above as well as by the assumptions needed to rescale some of the data points. Ignoring these systematical theoretical errors, one finds the anomalous suppression to be a 5σ effect [14], while including them leads [18] to a conclusion that no anomalous suppression exist at a 2σ or 95% confidence level, as shown by the 2σ-band (enclosed by dashed lines) in Fig. 2.

The NA50 collaboration also measures J/ψ-suppression as a function of the total produced transverse energy E_T. By taking the ratio of the number of J/ψ events and the Drell-Yan events in each E_T-bin, one obtains a less systematic error prone $R_{\rm expt} = B_{\mu^+\mu^-}\sigma^{J/\psi}/\sigma^{DY}_{M_1-M_2}$ as a function of E_T, where M_1-M_2 is the range of dimuon mass over which the Drell-Yan cross section is integrated. Using simple geometrical models, E_T can be related to the impact parameter b at which the two nuclei collide. Furthermore, any given $b(E_T)$ can be related to an average nuclear path length L which the produced J/ψ (or its precursor) has to traverse and which will determine the probability of its absorption in nuclear matter.

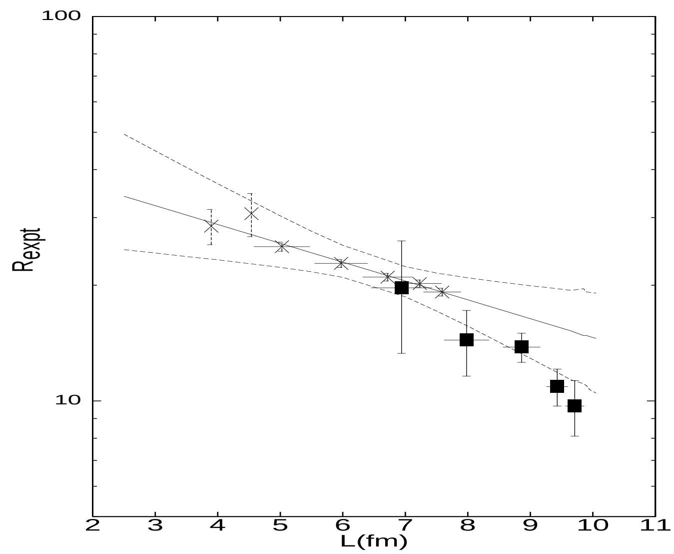

Figure 3: The data [14] from NA38 (crosses) and NA50 (squares) with 4σ errors for the ratio of J/ψ cross section and the Drell-Yan cross section as a function of L in fm along with a theoretical fit and a 4σ band [19] around it.

Fig. 3 shows $R_{\rm expt}$ as a function of L, as determined by the NA50 collaboration, using M_1 = 2.9 and M_2 = 4.5. The normal nuclear suppression can be well approximated by $R_{\rm expt} = A \cdot \exp(-\rho_{nucl} \cdot \sigma_{abs} \cdot L)$ or can be calculated more exactly in a Glauber model. The straight line in Fig. 3 displays the fit for the light nuclei for $\rho_{nucl} = 0.17/\ {\rm fm}^3$ and $\sigma_{abs} \simeq 6.6$ mb. The low L point for *Pb*-*Pb* collisions, corresponding to peripheral collisions, falls on the fitted line while all the large L points fall below it. Again, one can ask for the statistical significance of this anomalous behaviour. Since the fit above uses data from E_T-bins, or equivalently L-bins, for lighter nuclei, there are again sizeable errors on the theoretical prediction. For the 1995 data, which seem broadly in agreement with the 1996 data and the latest 1998 data, it has been estimated [19] that all the *Pb*-*Pb* data points fall in a 4σ-band although they are all systematically below the theoretical prediction, as shown in Fig. 3.

It seems thus likely that an additional mechanism to suppress J/ψ production in *Pb*-*Pb* collisions is needed over and above the normal nuclear absorption. This is even more so for the second shoulder in the E_T-spectrum, observed [20] in the 1998 data. There have been several theoretical attempts to provide such a mechanism including a possible a quark-hadron transition. A key non-QGP scenario invokes the possibility of destruction of the J/ψ by the so-called co-mover debris of the collisions. While the second shoulder was anticipated [21] in a QGP model, it has been explained [22] in the co-mover picture as due to fluctuations in the tail of the E_T-spectrum. The difference between the two models may, therefore, show up at the upcoming RHIC collider in BNL where *Au* (19.7 TeV) + *Au* (19.7 TeV) collisions will be studied this year and the E_T-tail will extend much farther, although in another QGP-like model [23] fluctuations in E_T have been argued to explain the second shoulder in the NA50 data successfully.

3 Conclusions and Outlook

An important non-perturbative prediction of (lattice) QCD is the existence of a new phase of matter, Quark-Gluon Plasma, at sufficiently high temperatures. Since the Standard Model has so far been tested experimentally only in the weak coupling regime, it seems desirable to confront this prediction with experiments. Collisions of heavy ions at very high energy may be able to deposit the required high energy density over a reasonable volume. The experimental programs at BNL, New York and CERN, Geneva have by now provided results for Au on Au and Pb on Pb at $\sqrt{s} \simeq 0.9$ TeV and 3.6 TeV (or $\sqrt{s}_{NN} \simeq 5$ GeV and 17 GeV) respectively. The year 2000 should witness a factor of about 39 increase in the colliding CMS energy at BNL while LHC at CERN should achieve a $\sqrt{s} = 1150$ TeV. The experiments so far have provided tantalizing hints of the new phase and therefore of the exciting physics in the years ahead.

A fireball of QGP produced in these collisions cools by expanding and converts into ordinary hadrons and leptons fairly quickly. Since this makes a distinction of events with QGP formation from those without it a very tough task, it seems prudent to look for a congruence of various signatures in as many different ways of detecting QGP as possible. The current results do indicate such a trend. Soft hadron production data can be interpreted in terms of a chemical freeze-out followed by a thermal freeze-out. The freeze-out temperature for the former for the CERN SPS data turns out to be ~ 170 MeV $\simeq T_c$ (quark-hadron transition). The strangeness enhancement pattern seen by the WA97 experiment, showing larger enhancement for the heavier particles with more strange quarks, also suggests that the hadrons at chemical freeze-out were formed from an uncorrelated QGP-like state.

Finally, anomalous J/ψ suppression seen by the NA50 experiment for Pb-Pb collisions can be understood as arising out of a deconfined quark-gluon plasma. Nevertheless, much more theoretical and experimental work will be needed to make a convincing case of quark-gluon plasma formation in the heavy ion experiments since the signals are still not spectacular in their statistical significance and credible alternative explanations exist in many cases for the observed results . Clearly, the commissioning of RHIC will be a big boost and will hopefully result in making a definitive case for quark-gluon plasma.

1. K. G. Wilson, *Phys. Rev.* D **10**, 2445 (1974).
2. M. Creutz, *Quarks, gluons and lattices* (Cambridge Mongraphs 1983).
3. See, e.g., Proceedings of Lattice 99, *Nucl. Phys.* B (PS)**83-84**, 2000.
4. R. V. Gavai in *Quantum fields on the computer*, ed. M. Cruetz (World Scientific 1992).
5. C. Bernard et al., *Phys. Rev.* D **55**, 6861 (1997).
6. J. D. Bjorken, *Phys. Rev.* D **27**, 140 (1983).
7. See, e.g., Proceedings of Quark Matter 99, *Nucl. Phys.* A **661**, 1999.
8. T. Alber *et al.*, *Phys. Rev. Lett.* **75**, 3814 (1995).
9. N. van Eijndhoven, hep-ph/0005165.
10. P. Braun-Munziger, I. Heppe and J. Stachel, *Phys. Lett.* B **465**, 15 (1999).
11. J. Cleymans and K. Redlich, *Phys. Rev. Lett.* **81**, 5284 (1998).
12. E. Andersen *et al.*, *Phys. Lett.* B **449**, 401 (1999).
13. T. Matsui and H. Satz, *Phys. Lett.* B **178**, 416 (1986).
14. M. C. Abreu *et al.*, *Phys. Lett.* B **450**, 456 (1999); *ibid*, **410**, 337 (1997).
15. R. V. Gavai, D. Kharzeev, H. Satz, G. A. Schuler, K. Sridhar and R. Vogt, *Int. J. Mod. Phys.* A **10**, 3043 (1995).
16. S. Gupta and K. Sridhar, *Phys. Rev.* D **54**, 5545 (1996).
17. A. Capella, J. A. Casado, C. Pajares, A. V. Ramallo and J. Tran Thanh Van, *Phys. Lett.* B **206**, 354 (1988); C. Gerschel and J. Hüfner, *Phys. Lett.* B **207**, 253 (1988)
18. R. V. Gavai and S. Gupta, *Phys. Lett.* B **408**, 397 (1997).
19. R. V. Gavai, *Mod. Phys. Lett.* A **14**, 821 (1999).
20. M. C. Abreu *et al.*, *Phys. Lett.* B **477**, 28 (2000).
21. S. Gupta and H. Satz, *Phys. Lett.* B **283**, 439 (1992); H. Satz, *Nucl. Phys.* A **661**, 104c (1999).
22. A. Capella, E. G. Ferreiro and A. B. Kaidalov, *Phys. Rev. Lett.* **85**, 2080 (2000).
23. J.-P. Blaizot,P. M. Dinh and J.-Y. Ollitrault, nucl-th/0007020.