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Quark Gluon Plasma - A New State of Matter

Bikash Sinha
Variable Energy Cyclotron Centre
and
Saha Institute of Nuclear Physics
1/AF Bidhan Nagar Calcutta-64
India

Abstract: In very energetic collisions of heavy nuclei a novel state of matter - Quark Gluon Plasma is expected to be formed. The suitability of electromagnetic probes for such a state is discussed.

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The familiar cartoon of any talk on Quark Gluon Plasma (QGP), I am afraid, is my first transparency.

Curiously enough, although it is entirely possible to mimick in the laboratory the very early universe scenario, to an extent at least,with no net baryon but only high temperature with a large energy density, (fig.1) it is not possible to envisage a scenario of cold, highly dense system in a laboratory set up. The ideal opportunity of detecting QGP lies in the central region with no net baryon density. To start with I intend to dwell on some of the important and contemporary milestones of lattice QCD (Quantum Chromodynamics).

There are evidently non perturbative effects in the infra-red scale even for $T > T_c$, where T_c is the critical temperature of the phase transition. Non perturbative (NP) domain (fig.2) is confined in a a finite volume in momentum space thus it should not affect bulk properties at high temperature when typical frequency of quarks and gluons ($n \times T$)>> $Q(T)$ (some scale factor); n can be any reasonable number!(fig.2). However if one probes the low frequency region or goes down to $T \rightarrow T_c$, NP region emerges. This may lead to hadronic correlations above T_c, NP physics leading to hadronic modes above T_c.

Recent calculations [1] for energy density and pressure on the lattice for a pure gauge system $16^3 \times 4$ lattice leads to the following scenario. For perturbative physics, at high temperature both ϵ and P go over to Stefan Boltzmann limit with weakly interacting massless gluons dominating. In the non perturbative domain, as $T \to T_c$ there is substantial departure from $\epsilon = 3P$, indeed P turns less than Stefan Boltzmann limit; the system is not a free gluon gas (fig.3) anymore.

Physics at $T < T_c$ (Order of the phase transition):

The determination of QGP phase transition at finite T is one of the most important issue of lattice QCD. For a pure gauge system $m_q \to \infty$, the effective Z(3) symmetry predicts first order confinement-deconfinement phase transition (fig.4). For $m_q \to 0$,chiral symmetry instead of Z(3) symmetry is expected to dominate the $< qq >_T$ order parameter. For finite $m^q (m^{u,d} \sim 10$ MeV, $m^s \sim 200$ MeV) chiral symmetry is broken again. The conclusions however seem to be not completely time invariant, the lattice size being the key element. The future looks interesting with a large degree of correlation with the chosen lattice size!

Hot hadrons, $m^h < 0.8 T_c$

In the chiral limit

$$< qq >_T / < qq >_0 = 1 - K(N_f^2 - 1)/3N \quad (1)$$

where $K = T^2/4f_\pi^2$, since the low lying hadron masses (m_{hadron})is strongly correlated with quark condensate, m_{hadron} is expected not to change so much in this domain.

For even a stable particle in the vacuum it acquires a width at finite temperature due to scattering of particles with thermally excited pions, as shown in fig.5.

QCD at finite baryon density ($T = 0; \rho \neq 0$)

The system ($T = 0, \rho \neq 0$) is different from system ($T \neq 0$, $\rho = 0$). The main difference is the behaviour of the condensates. In this domain the variation of mass with density is given by

$$\frac{M_v^*}{M} = 1 - C_v(\frac{\rho}{\rho_0})$$

where $C_v \approx 0.18(0.15y)$ for $\rho - \omega$ (ϕ mesons) y being the strangeness content of the nucleon. $y \sim 2 < \bar{s}s >_N / < \bar{u}u + \bar{d}d >_N \sim 0.12 - 0.22$ [2].

The next subject I wish to talk is the signals of QGP [3]. However, at this stage it is worthwhile to point out as I have learnt from Klaus Werner [3] that there exists a fairly extensive industry based on non QGP models, using the soup of strings and pomerons for digestion. A comprehensive list is presented by Werner [3]. I don't wish to go into the merits and demerits of all the models, except to point out, even warn the community, that there exists a large degree of uncertainty in the input of all these models; the predictions not necessarily agreeing with each other.Thus, while comparing results from typical QGP models with the predictions of these N-N level models, one should be somewhat cautious in drawing conclusions, the model predictions are not "gospel truths"!

Going over to the signals of QGP , I only take a subset of the total set, somewhat relevant for our group.

Thermal Photons

First we consider boost invariant longitudinal flow and try to understand the contemporary scenario with a typical space time evolution going over from QGP to a mixed phase of hadrons and QGP and then on to a free streaming non interacting hadrons going over to the detector after the hadrons have frozen to a non interacting system.

The cross-section of photons from annihilation $q\bar{q} \rightarrow g\gamma$, Compton process $q(\bar{q})g \rightarrow q(\bar{q})\gamma$ from the initial QGP sector are well known [4]. The contemporary interest lies in the mixed phase. Kapusta et al [5] have computed photons shining from QGP at a fixed temperature and compared the cross-section with photons shining from a hot hadron gas at the same temperature with heavier mesons, i.e, π's with ρ, ω and η mesons. They conclude that the light from hadron gas with heavier mesons shine just as brightly as the QGP.

However taking into account the space time evolution of the initial fireball with $T \rightarrow T(\tau)$ the scenario changes substantially [4], as shown in fig 6; for an initial time $\tau_i = 1$ fm/c (it can be quite smaller than that $\tau_i = 1/3T_i$; for example,please note).

With the space time evolution, clearly the heavier mesons soak up some of the initial energy for their mass, thus reducing the lifetime of the mixed phase in contrast to just a pion gas; so the photons, in this case, are shining no doubt the QGP photons shining more than the hadronic counter part but the photons from the QGP do not have that much time to shine.

There is therefore, as expected a shoulder that opens up beyond $p_T \sim 2$GeV, with all the typical numbers.The question that arises now is the polluting influence of hard QCD photons (see later), so the local(!)conclusion is: Increase in degrees of freedom cause no change in QGP contribution in an appropriate kinematic window but shorter lifetimes for mixed and hadronic phases, thus, for initial temperatures $T > 2T_c$ and transverse momentum> 2GeV photons from QGP outshine the photons from hadronic matter in a particular p_T window.

In searching for quark gluon plasma one is essentially trying to distinguish between the following two scenarios,

(a)Nucleus+Nucleus→ Hadrons ⟶ γ's, leptons, hadrons etc.

(b)Nucleus+Nucleus→QGP → Hadrons ⟶ γ's, leptons, hadrons etc.

In the case (a) it is assumed that the matter is formed in the hadronic phase initially after the nucleus nucleus collisions (no phase transition scenario). It mantains thermal equilibrium upto a temperature T_f(=140 MeV), after which it freezes out and detected experimentally. Whereas in case (b) a QGP is assumed to be formed, it cools due to expansion, goes over to the mixed phase in a first order phase transition scenario when temperature is reduced to T_c(= 160 MeV). When all the latent heat is liberated, the system goes to the pure hadronic phase in the usual fashion.

Recently, the WA80 [6] data (preliminary) for S+Au collisions at SPS energies has been analysed [for details see 7] to see which of the above two scenarios mentioned above is consistent with the data within a reasonable value of the parameter, τ_i (=1 fm/c). Bjorken's hydrodynamical model [8] has been used for the space time evolution.

For an isentropic expansion, the initial thermalisation time (τ_i) and the initial temperature (T_i) is related through the total multiplicity density in the rapidity space dN/dy by,

$$\frac{dN}{dy}\Big|_{y=0} = \frac{45\zeta(3)\pi R_A^2 4a_k}{2\pi^4} T_i^3 \tau_i \tag{3}$$

R_A is the nuclear radius, the value of the parameter a_k depends on the statistical degeneracy of the initial state. The photon spectrum from an expanding QGP is given by,

$$\frac{d^3N}{d^2p_T dy} = \pi R_A^2 \int \tau d\tau d\eta \Bigg[\left(E\frac{dR}{d^3p}\right)_{\text{QGP}} \Theta(s - s_Q)$$
$$+ \left[\left(E\frac{dR}{d^3p}\right)_{\text{QGP}} \left(\frac{s - s_H}{s_Q - s_H}\right) + \left(\frac{s_Q - s}{s_Q - s_H}\right) \left(E\frac{dR}{d^3p}\right)_{\text{HAD.}} \right] \Theta(M)$$
$$+ \left(E\frac{dR}{d^3p}\right)_{\text{HAD.}} \Theta(s_H - s) \Bigg] \tag{4}$$

where

$$\Theta(M) = \Theta(s_Q - s)\Theta(s - s_H)$$

Here s_Q and s_H are the entropy densities at the critical temperature.

$$E\frac{d^3R}{d^3p} = \frac{5}{9}\frac{\alpha\alpha_s}{2\pi^2} T^2 e^{-E/T} \ln\left(\frac{2.912}{g^2}\frac{E}{T} + 1\right) \tag{5}$$

Scenario (a)

In this case we have assumed an equation of state (EOS) which is consistent with π, ρ, ω and η in the hadronic phase [4]. We get the value of $a_k = a_h = 0.504$. Taking $(dN/dy)_{ch} = 150$ from the experiment, we get $dN/dy = 1.5 \times (dN/dy)_{ch} = 225$, assuming $\tau_i = 1$ fm/c, a cannonical value, we get $T_i = 407$ MeV.

Scenario (b)

We assume that at the initial time $\tau_i = 1$ fm/c the two flavours u and d, their anti quarks and the gluons are thermalised. The value of a_k is 4.06 in this case. The corresponding $T_i = 203.4$ MeV.

With the two sets of inputs we have solved eq.(5), the results are shown in fig.7. The result shows that the scenario (b) i.e. the formation of the QGP at the initial state is consistent with the data. Although many more checks have to be done before we reach to a firm conclusion. The important point to realise is that even for a first order phase transition scenario, most of the photons are emitted from the coexisting phase of hot hadrons and quark droplets. Werner's outlook [9] of quark droplets seem to come close to such a picture.

The discussion so far assumes that the quarks and the gluons thermalise at the same time. In the following we argue that a more realistic scenario would be that the gluons thermalise before the quarks, because of their different and larger colour degrees of freedom.

Perturbative estimates of the qq, qg and gg cross sections indicate that in ultrarelativistic heavy ion collisions, gluons may thermalise earlier than the quarks. This may affect the diagnostics of quark gluon plasma quite substantially. It is therefore a most current and important problem to investigate if and when a total (local) thermal equilibrium among the gluons as well as all the flavours of quarks is achieved.

We proposed a model where the thermalised gluons provide a temperature bath in which the quarks execute a random Brownian motion [10]. While retaining the salient features of the microscopic kinetic theory formulations, this picture has the tremendous advantage of easier calculability and the transparent physical picture allows us to compare with the intuitive expectations even the predictions of the cascade model. The operative equation for the Brownian motion is the Fokker Planck eqn.

$$\frac{\partial f}{\partial \tau} = \frac{\partial}{\partial p_z}\left(\frac{a_p p_z}{\sqrt{p_z^2+m_T^2}} f\right) + D_F \frac{\partial^2 f}{\partial p_z^2} \tag{6}$$

where a_p corresponds to the 'friction constant' and D_F, the diffusion co-efficient($= a_p T$). All other symbols (f, τ, p_z, m_T etc.) have their usual meaning.

Note however that the transverse mass m_T has also a contribution from the *thermal* mass ($m_{th} \sim g_s T/\sqrt{6}$) so that $\left(m^q_{eff}\right)^2 \equiv (m^q_{current})^2 + (m^q_{th})^2$ and $m_T^2 = p_T^2 + m^2_{eff}$. For u and d quarks we take the current mass to be 10 MeV while it is 150 MeV, 1.5 GeV and 5 GeV for s, c and b quarks respectively.

In writing eq.(7), we have employed the condition of boost invariance along p_z, so that the phase space distribution function f reduces to only a momentum distribution which we further assume to be factorizable, ie. $f(p,\tau) = f(p_z,\tau)G(p_T)$. Since the friction constant is expected to be largely determined by the properties of the 'bath' and not so much by the nature of the test particle, we take $a_p(p_z,\tau) = a_p(\tau)$. Furthermore, as the system must keep on expanding, the temperature of the bath must fall with time. The scaling solution implies $T(\tau) = \tau_g^{1/3} T_g \tau^{-1/3}$ where $T_g = T(\tau_g)$.

The approach to equilibrium for the different quark species is then determined by eq.(7), where $a_p(\tau)$is the crucial parameter. There have been some recent developments [11,12] in connection with jet quenching studies in QGP which may shed light on this issue. Realising that the friction force $F = -a_p p_z/E$, we can write the energy loss dE of a test quark in traversing a distance dx due to the friction force as

$$dE = -a_p \frac{p_z}{E} dx \tag{7}$$

so that $ap =< -\frac{E}{p_z}\frac{dE}{dx} >$. The energy loss of quarks in the QGP has been estimated by various authors [11,12]. We solve the Fokker Planck equation (7) with the boundary conditions:

$$f_i(p_z,\tau) \stackrel{\cdot\ \ \cdot\cdot g}{\longrightarrow} \Delta_i \delta(p_z) \tag{8}$$

and

$$f_i(p_z,\tau)^{\ |p_z|} \qquad 0 \tag{9}$$

where Δ_i in equation (9) is equal to the central rapidity density of the quarks (antiquarks); i refers to the quark flavours.

To estimate [10] the thermalisation time for various flavours of quarks we determine the time scale at which the solution of Fokker Planck equation becomes stationary.

The corresponding values of τ is taken to be the thermalisation time for the species q_i. The calculated values for the flavours u, d, s, c and b are shown in Table I. We find that at LHC energies, all flavours may thermalise within the lifetime of the QGP. At RHIC energies, b

remains out of equilibrium though all other flavours may thermalise. The values for the τ_{life}^{QGP} shown in Table I have been estimated for $T_c = 160$MeV.

We can also compute the rate of production of heavy flavours during the *preequilibrium* era $\tau_g < \tau < \tau_{th}$. The dominant reactions producing pairs of heavy flavours ($Q\overline{Q} = s\overline{s}, c\overline{c}$ or $b\overline{b}$) are $q\overline{q} \rightarrow Q\overline{Q}$ and $gg \rightarrow Q\overline{Q}$ where q stands for u and d quarks. The total cross section $\sigma_{Q\overline{Q}}$ for these processes are well known. The production rate of heavy flavours is given by

$$\frac{d^4N_{Q\overline{Q}}}{d^4x} = N_{a,b}\int \frac{d^3p_a}{(2\pi)^3}\frac{d^3p_b}{(2\pi)^3} f(p_a,\tau)f(p_b,\tau)\sigma_{Q\overline{Q}}\delta\left(p_a + p_b - \sqrt{s}\right) \mid v_{rel} \mid ds \qquad (10)$$

where for $a, b = q, \overline{q}$, the f's are obtained from the solution of Fokker-Planck equation multiplied by $G(p_T)$, for gluons, they correspond to the thermal Bose distribution at $T(\tau)$, $N_{a,b}$ is the statistical degeneracy factor. The results for heavy quark productions is shown in Fig 8. Our results are similar to the parton cascade model calculations [13]. Jet quenching is yet another very exciting area; can a thermalised QGP evolve out of the interaction of hundreds and thousands of minijets, can we shed some light (knowledge not QGP light) on what value of initial time we can choose from such a scenario?

Alam et al [14] have demonstrated the effects of transverse flow; constant energy density curves with transverse flow are shown in figs.9 and 10 for LHC and SPS respectively. Clearly at higher energies, with transverse flow the role of heavier mesons ρ ,ω and η turn more significant. The broad conclusions are:

⋆ At SPS, transverse expansion sets in only during the hadronic phase. Both the hadronic and the mixed phase are long lived.

⋆ At RHIC, transverse expansion sets in during the mixed phase which is very long lived; physics is thus dominated by mixed phase.

⋆ At LHC, the rapid transverse expansion sets in during the QGP phase,mixed phase is suppressed, physics is dominated by a very hot QGP and cold hadronic phase.

There will be however soft photons and dileptons kicked transversly, going over to the thermal photon (dilepton) window, can we identify these photons; the latest I understand is to see not just photons but (γ/π^o), there may be some interesting clues!Can we identify,finally the decay products of pions or heavier mesons?

Strangeness enhancement has been a source of hope; enhancement candidates are $\phi/(\rho+\omega)$, antihyperons,K^+/π^+ ,there is already a factor of (3-4)enhancement compared to pp. Can we explain all these without invoking QGP? We have to sharpen up our theoretical and experimental tools to get rid of some of the effects of nuclear debris!

Dileptons

In a rather similar and analogous approach, for emission of dileptons from the QGP we consider the annihilation contribution ($q\bar{q} \to l\bar{l}$). For the hadronic matter we consider all possible reactions of the type $V + P \to l\bar{l}$, $P + P \to l\bar{l}$, and $V + V \to l\bar{l}$. The $V+P$ initial states $\omega\pi^0$, $\rho\pi$, $\phi\pi^0$, $\omega\eta$, $\phi\eta$, $\rho^0\eta$, $\omega\eta'$, $\phi\eta'$, $\rho\eta'$, $\bar{K}^* K$, and $K^* \bar{K}$, have been included. The rates corresponding to the initial states πa_1 and $a_1 a_1$ leading to $l\bar{l}$ have been included to account for the consequences of the a_1 resonance. Below the $\pi a_1 \to e^+e^-$ threshold, the decays $\rho \to \pi e^+e^-$, $K^{*\pm} \to K^\pm e^+e^-$, $K^{*0}(\bar{K}^{*0}) \to K^0(\bar{K}^0) e^+e^-$, $\omega \to \pi^0 e^+e^-$, $\rho^0 \to \eta e^+e^-$, $\eta' \to \rho^0 e^+e^-$, $\eta' \to \omega e^+e^-$, $\phi \to \eta e^+e^-$, $\phi \to \eta' e^+e^-$, and $\phi \to \pi^0 e^+e^-$ have been considered. This is possibly the most exhaustive list of dielectron producing processes in the hadronic matter considered in the literature. The details can be seen in [15]. The net rate obtained by summing all the processes for producing pairs with invariant mass-squared M^2 and transverse mass $M_T = \sqrt{p_T^2 + M^2}$, where p_T is the transverse momentum, can be shown (see Ref.[16,17]) to scale as,

$$\frac{d^6N}{dM^2 dM_T d^4x} = \frac{\sigma_{eff}(M)}{2(2\pi)^4} M^2 M_T K_0(M_T/T) \left[1 - \frac{4m_\pi^2}{M^2}\right] \tag{11}$$

with

$$\sigma_{eff}(M) = \frac{4\pi}{3}\frac{\alpha^2}{M^2}\left[1 + \frac{2m_l^2}{M^2}\right]\left[1 - \frac{4m_l^2}{M^2}\right]^{1/2}\left[1 - \frac{4m_\pi^2}{M^2}\right]^{1/2} . F_{eff}(M) \tag{12}$$

where $F_{eff}(M)$ is the effective form-factor, to a high degree of accuracy between $M = 0.3$ GeV and 3 GeV. This is possible since the majority of the reactions considered in Ref.[15] share the pion electromagnetic form-factor. The corresponding results for the emissions from the QGP, due to the $q\bar{q} \rightarrow l\bar{l}$ process is obtained from the above by replacing m_π by m_q and $F_{\rm eff}$ by 24/3.

The dilepton transverse mass spectrum is then obtained by convoluting the rates for the emission of dileptons from the QGP and the hadronic matter with the space-time history of the system; for details see [18]. In our calculation we have taken $T_c = 160$ MeV and $T_f = 140$ MeV. The invariant mass spectrum is obtained by transforming the above rapidity distribution to pseudorapidity distribution and by integrating over the detector acceptances as in the CERES experiment. The CERES detector spans the pseudorapidity window $2.1 < \eta < 2.65$. A suppression of close pairs, with opening angle $\theta_{ee} < 35$ mrad, and a rejection of electron (and positron) tracks having $p_T < 200$ MeV/c is used to obtain a substantial improvement in the signal to background ratio.

In fig. 11, we give our results for thermal dileptons after incorporating the cuts as for the CERES detector. We have shown the contribution of the QGP phase, the QGP part of the mixed phase, the hadronic part of the mixed phase, and the hadronic phase separately. We see that the largest contribution for the $S + Au$ system comes from the mixed phase [19], which has a life time of the order of 13 fm/c, in this model. This is a reflection of the fact that the hadronic matter occupies an ever increasing space-time volume of the system after the end of the QGP phase. In addition, in the region of the ρ peak, the form factor for the hadronic matter is much larger than the form factor for the quark matter. The contribution of the QGP phase is quite small in the case studied here, as the initial temperature is still quite small, which leads to a rather small life time for the QGP phase. If, however, we use the other extreme of the initial time $\tau_i \simeq (1/3T_i)$, the initial tempertaure of the QGP phase will go up, leaving the contributions of the later phases unaltered. Its effect will be felt mostly at larger masses, and in fact, will improve the description of the data to be discussed later. Even though a temperature of 380 MeV for a hot hadronic matter does seem to be rather unrealistic, it is seen that the theoretical predictions for the scenario which does not invoke a phase transition start differing substantially from the results for the scenario involving a phase transition just beyond $M \approx 1.5$ GeV/c^2, which is the upper limit of the CERES data. We should add here that the peaks around 1.7 and 2.2 GeV/c^2 seen in the hadronic contribution have their origin in the πa_1 and the $a_1 a_1$ reactions evaluated with the assumption that the a_1 resonance is in thermal equilibrium in the system. This structure will change if they are less abundant than given by the Bose-Einstein distribution without a chemical potential.

Finally, in fig.12, we compare our results for the thermal dileptons produced in the scenario involving a phase transition along with the hadronic background as estimated by the CERES group with the CERES data [20,21]. We see a near quantitative description except at the lowest masses, without any arbitrarily adjusted parameter. We feel that the discrepancy at the masses well below the ρ peak may stem from the neglect of the pionic- and the quark-bremsstrahlung processes [22] and our initial estimates [23] put this contribution at a level of 50% of the thermal contribution obtained in this work at $M \approx 0.3$ GeV/c^2, but negligible at lower masses as compared to the Dalitz decays, and at higher masses as compared to the thermal contributions. We have checked that the contribution of the higher order QCD processes in the QGP [24] are small for masses larger than 200 MeV/c^2 in the present case. There could also be a contribution from the annihilation of the free-streaming pions [25] after the freeze-out just in this mass window. The available treatment [25], however, is only approximately valid; it treats the expansion of the system even after the freeze-out as a purely longitudinal expansion. We have, however, resisted the temptation of lowering the freeze-out temperature, or introducing a pionic chemical potential [17], which could enhance the production of low mass dileptons, but would amount to introduction of a freely adjusted parameter. Finally, we may add that there could also be a contribution to the low mass window from reactions of the type $\pi\rho \rightarrow a_1 \rightarrow \pi e^+e^-$ and $\pi\pi \rightarrow \rho e^+e^-$, etc.; this is under investigation. As seen from fig. 11, the no phase transition scenario, would also explain the data limited to $M < 1.5$ GeV/c^2, if one could seriously believe the existence of a hot hadronic gas at a temperature of 380 MeV (!).

We have already mentioned that the HELIOS-3 experiment has measured an excess of dimuons in $S + W$ collisions in the pseudorapidity window of $3.7 < \eta < 5.2$ and extending upto the J/ψ peak. One could use these results with advantage to confirm or to rule out the no phase transition scenario discussed above. However, as these data do not correspond to the central rapidity, one may have to use at least the minimal extention of the Bjorken hydrodynamics formulated as the frozen motion model and employed earlier by Shuryak and Xiong [19]. We shall, instead, follow the treatment of Sinyukov et al [26], which retains the distinction between the fluid and the particle rapidities. Thus it is assumed that the initial system ("fluid") undergoes a boost invariant longitudinal expansion according to the Bjorken hydrodynamics, with the condition that the "fluid" rapidities are limited to $[-Y, +Y]$ in the centre of mass system. The (gaussian like) dN/dy for the secondary particles, say, is then obtained by convoluting their thermal distribution with the motion of the surface of the fluid at the time of freeze-out. For the case of $^{32}S +^{32} S$ collisions at 200 A GeV, $Y = 1.7$ was found to provide a reasonable explanation to the particle rapidity density. This corresponds to y_{lab} of about 4 units, which lies within the range of the rapidities covered by the HELIOS-3 data. In brief, these considerations permit us to use the Bjorken hydrodynamics, even at such forward rapidities, with the same initial conditions as at the central rapiditiy.

In the absence of a direct information about the dN/dy vs. y for the HELIOS-3 experiment, we now proceed with the assumption that the "fluid rapidity density" has remained flat over the rapidity window covered by the experiment, and further take the initial temperature and the initial time as we obtained earlier for the $S + Au$ collisions, which amounts to ignoring the slight difference between the masses of the two targets. If these assumptions are considered as not very accurate then the production of the dimuons may be overestimated, to some etent. The results obtained after incorporating the transverse mass and the rapidity windows are given in fig. 13. The excess dimuons [20] have been defined as "the difference of the number of dimuons/charged particle for the $S+W$ and $p+W$ collisions at 200 A GeV". Considering the many simplifying assumptions made, the scenario involving the QGP phase transition is seen to provide a fair description of the data. In addition, one may perhaps rule out the scenario which did not involve a phase transition. It should be interesting to see if a more detailed treatment of the dynamics of the system as attempted by the authors of Ref.[27] confirms this simplified treatment. For example, it is not unlikely that in a boost non-invariant expansion e.g., we may have an early freeze-out at larger rapidities (which will in fact improve the results around the ρ peak). We also note that the dynamics of the production of resonances in $p+A$ and the $A+A$ system may be different, which will add to the uncertainties of the excess dimuons as defined by the HELIOS experiment.

The limitations of the present model are well known and have already been discussed in detail before [7]; we shall repeat our arguments only about the inclusion of baryons. Firstly we recall that, at least in the central rapidity window the net baryon rapidity density is only about 10% of the particle rapidity density. We can see that the inclusion of a substantial number of baryons will modify the results in several competing ways. While it will lower the temperatures (for the same energy density), it will also add a list of dilepton producing reactions involving baryons, and it is felt that the final outcome may not be altered significantly.

It is gratifying to see that the picture, of a thermalized QGP produced in a relativistic nucleus-nucleus collision undergoing expansion, cooling, and hadronization in a first order phase transition provides such a quantitative description to the first data for the dielectron excess seen in the CERES experiment, and a fair description of the dimuon excess measured by the HELIOS-3 experiment at more forward rapidities. We also note that using the same approach, the yield of single photons is predicted [7] to be in agreement with the present experimental results [6].

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Table I

Energy	Domain Flavours Thermalisation Time in fm/c					
	τ_g^{th}	$\tau_{u,d}^{th}$	th	th	τ_b^{th}	τ_{QGP}^{life}
RHIC	0.3	1	1 2	2.6	17 5	9
LHC	0.25	0.7	0.8	1.6	7.5	17 5

Table I : Thermalisation times for various flavours at RHIC and LHC energies.

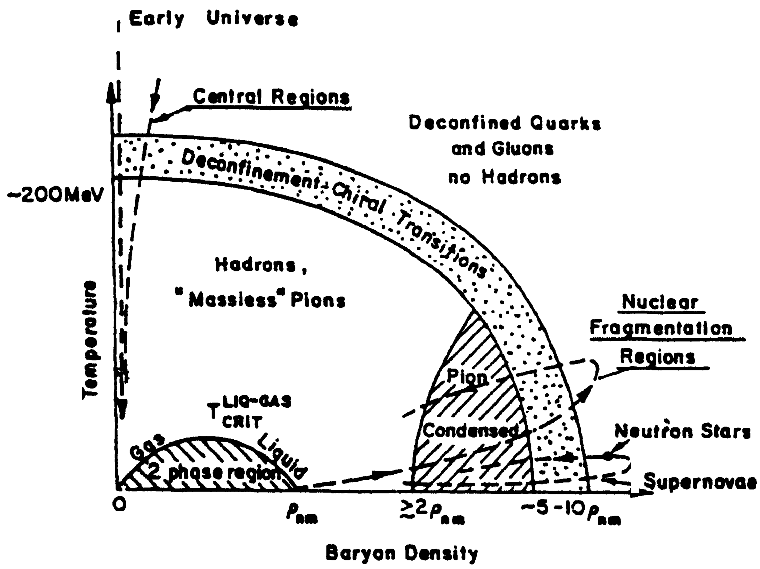

Fig.1 Phase diagram of strongly interacting matter in $(T - \rho)$ plane.

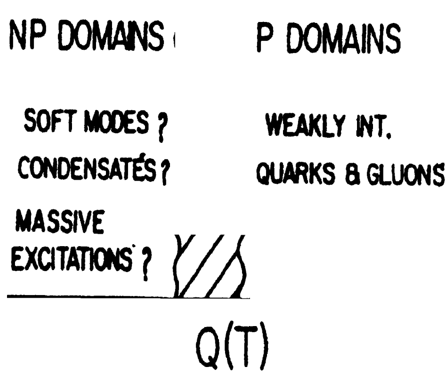

Fig.2 Separation of scales at high temperaute.

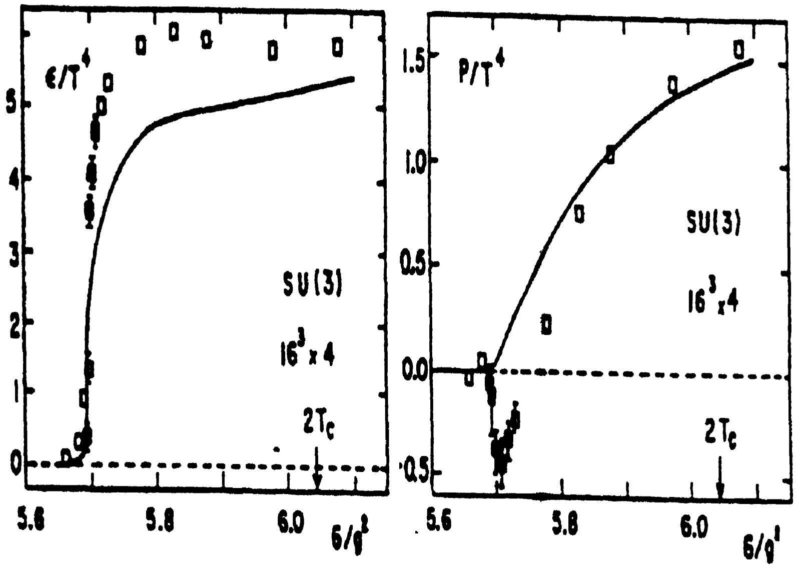

Fig.3 Thermal energy density and pressure in the limit of T from ref.1

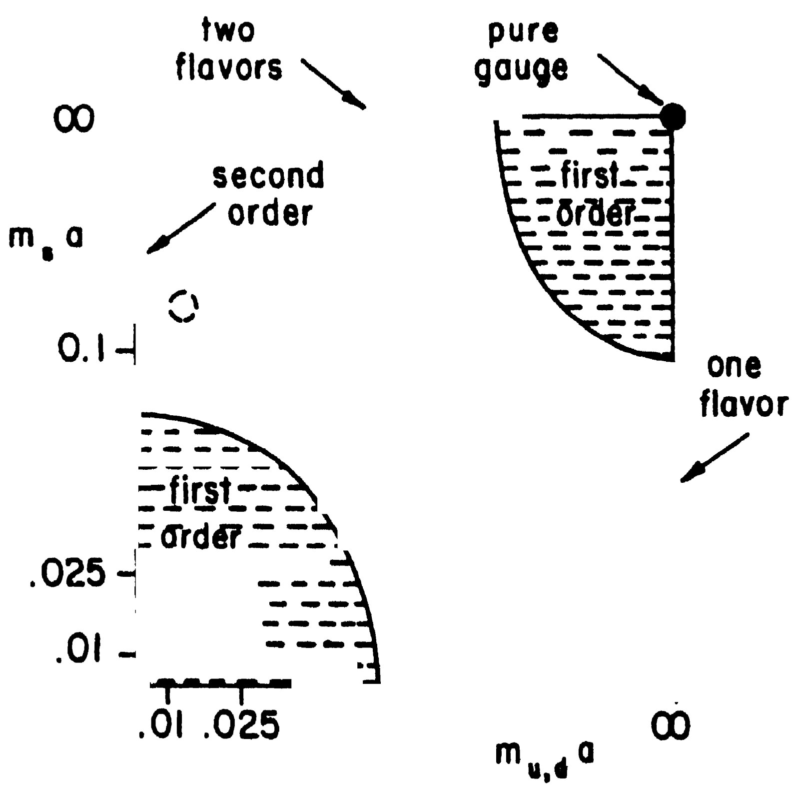

Fig.4 Phase diagram in m_u ,m_d - m_s plane from ref. 1.

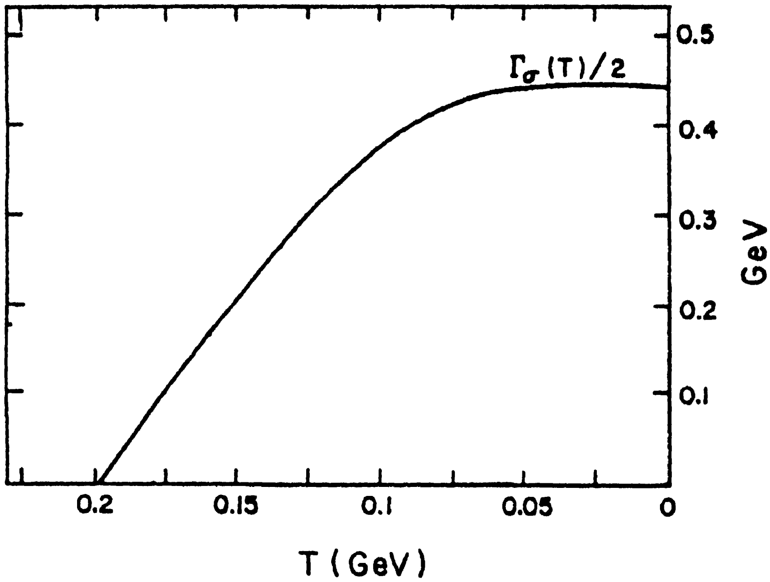

Fig.5 Temperature dependence of half width of *sigma* meson.

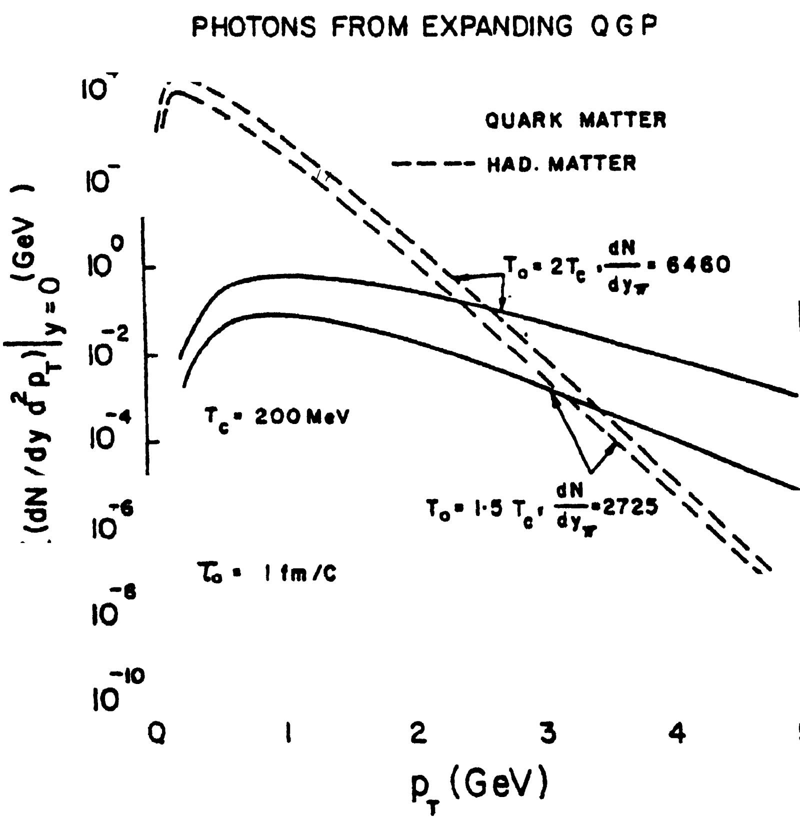

Fig.6 Spectrum of thermal photons emitted from expanding QGP undergoing (1+1) dimensional expansion.

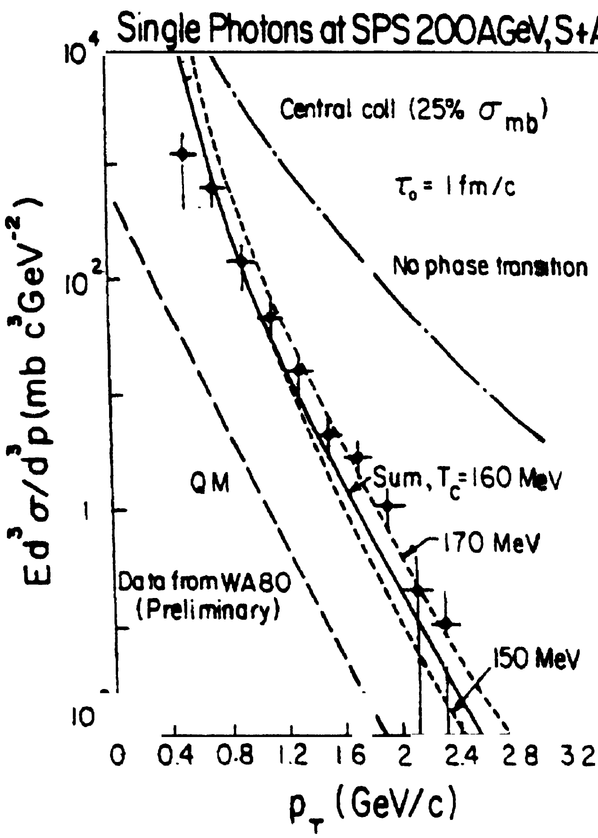

Fig.7 Single Photon Spectra from WA80 experiments and the theoretical model calculation discussed in the text

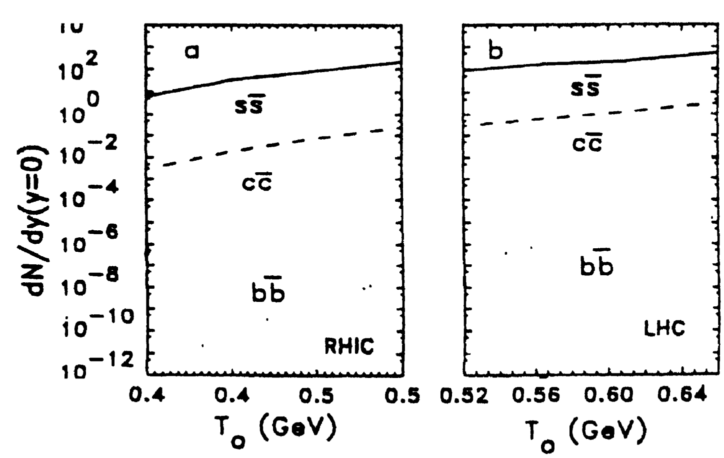

Fig.8 Production of $s\bar{s}$, $c\bar{c}$ and $b\bar{b}$ pairs as a function of initial temperature for $^{208}Pb - ^{208}Pb$ systems; a)**RHIC** energies, b)**LHC** energies

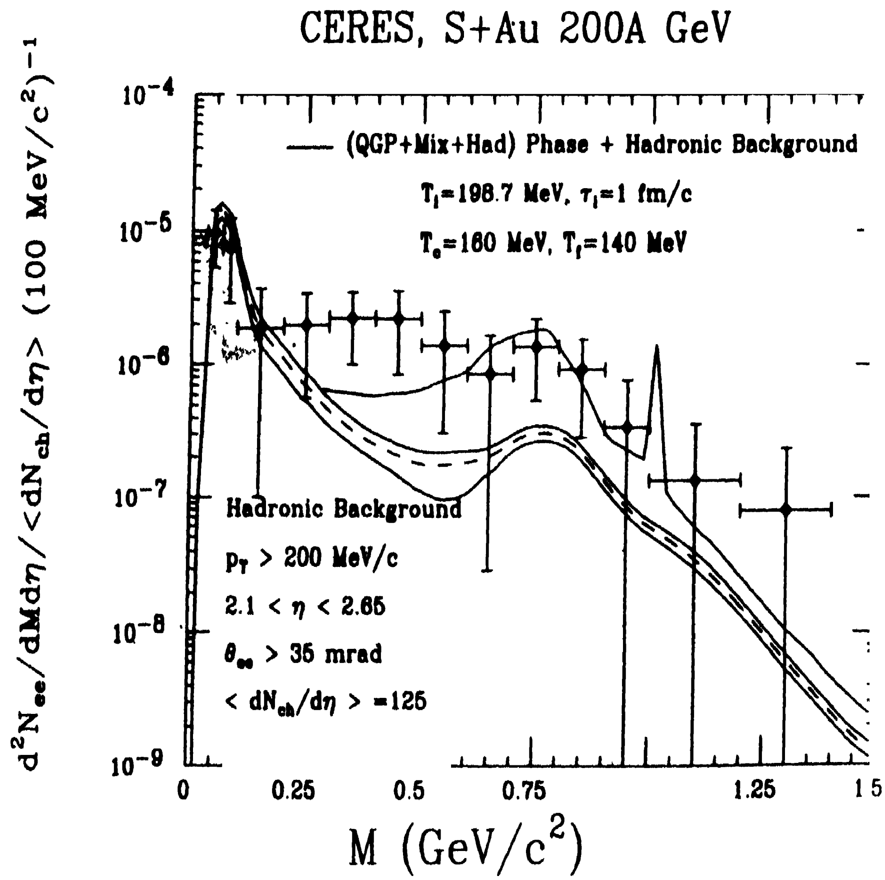

Fig.12 Comparision of the sum of the background from hadronic decays and the thermal dielectrons produced in a central collision of $S + Au$ sytem at CERN SPS, with the CERES data [20]. The system is assumed to be formed at $\tau_i = 1$ fm/c in a state of QGP which then expands, cools, undergoes a first order phase transition to a mixed phase of hadrons and quark matter, moving on to a hadronic phase before undergoing a freeze-out at T_f= 140 MeV. The band with the dashed line in the middle gives the hadronic background estimated by the CERES group. The peak around 1 GeV, originates from the ϕ mesons. Smearing of the data due to mass-resolution of the detector has not been taken into account, while plotting the theoretical curves.

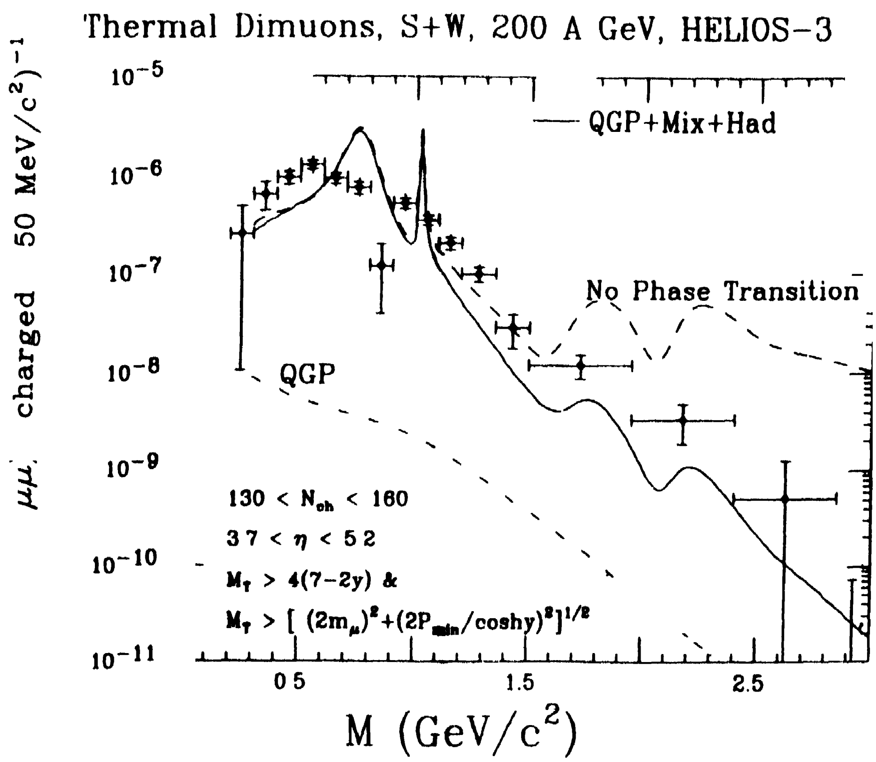

Fig. 13 Comparision of the thermal dimouns produced in a central collision of $S + W$ sytem at CERN SPS, with the HELIOS-3 data [28]. $P_{\text{min}} = 7.5$ GeV/c^2. Initial conditions similar to those of fig. 11 (see text) are used. The expansion is idealized according to the Bjorken hydrodynamics for a fluid having a finite rapidity span [26]. The dot-dashed curve gives the contribution of the QGP phase only.