New form of matter at CERN SPS:
Quark Matter but not Quark Gluon Plasma

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I argue that a new form of matter is indeed seen in Pb+Pb collisions at CERN SPS. This Quark Matter (QM) is different from the theoretically predicted Quark Gluon Plasma (QGP) because its effective degrees of freedom seem to be the massive (dressed) constituent quarks instead of almost massless quarks and gluons. The equation of state of QM is hard, the time of its rehadronization is short, while the equation of state of a QGP is soft and the time of its rehadronization is long. Other similarities and differences are also summarized.

'' Never test for an error condition you don’t know how to handle. "
Steinbach’s guideline
for systems programming

1. Introduction

2000 has been a very exciting time in high energy heavy ion physics, marked by two press announcements: On 10 February, CERN summarized the results of its heavy ion program with claims related to the formation of a new state of matter in fixed target 158 AGeV Pb+Pb collisions [1,2]. On 13 July, the BNL reported on the observation of the first collisions of Au + Au nuclei at the recently completed RHIC accelerator as detected by the STAR, the PHENIX, the PHOBOS and BRAHMS collaborations [3].

The purpose of the heavy ion program at CERN SPS and at BNL RHIC accelerators is to produce a new state of matter, the quark gluon plasma (QGP), where color degrees of freedom are deconfined and the basic degrees of freedom are quarks and gluons. Due to their relatively large color degrees of freedom, the properties of QGP are dominated by that of massless gluons. In particular, the equation of state is soft, the entropy density is high due to the large number of deconfined color degrees of freedom and due to this reason it takes a long time for the system to rehadronize. Direct photons are emitted from the QGP by the fractionally charged quarks and the production of the $J/\psi$ mesons is expected to be suppressed due to color screening.

Based on a critical review of the experimental results of the CERN heavy ion program (summarized in ref. [4]), I argue that such a QGP state has not yet been reached in the CERN SPS heavy ion experiments. The circumstantial evidence seems to point towards the formation of a quark matter (QM), where the dominant degrees of freedom are massive (dressed, constituent) quarks, but the of effective role of gluons is secondary. In the followings I will argue, that in contrast to the soft QGP equation of state, the equation of state of QM has to be hard to explain the strong three-dimensional expansion observed in the hadronic final state, based on a combination of the data analysis in refs. [5-8]. The entropy density of QM seems to be relatively low (with no experimental evidence for a dominant role of gluons). This low initial entropy density and the strong three-dimensional expansion of QM may then lead to a sudden rehadronization, where the abundances of directly produced particles are determined with the help of quark combinatorics as described in refs. [27]. Such combinatorics may also govern $J/\psi$ and other charmed particle production, a topic that deserves further investigations [28].
1.1. Summary of CERN Announcement

On February 10, the official CERN press release summarized the results of its heavy ion program as follows: “Compelling evidence now exists for the formation of a new state of matter at energy densities at about 20 times larger than that in the center of atomic nuclei and temperatures about 100000 times higher than in the center of the sun. This state exhibits characteristic properties which cannot be understood with conventional hadronic dynamics (i), but are qualitatively consistent with expectations from the formation of a new state of matter (ii) in which quarks and gluons no longer feel the constraints of color confinement (iii).” Both the CERN press release and the summary manuscript of Heinz and Jacob clearly and consciously distinguished between the claim for evidence for a new state of matter (that they claimed) and between the “discovery of QGP” (that they did not claim). The physical picture was summarized in the following straightforward manner:

“(1.) Two colliding nuclei deposit energy in the reaction zone. The energy materializes in the form of quarks and gluons, which strongly interact with each other.

(2.) This early, very dense state has an energy density of 3-4 GeV/fm$^3$ and the equivalent of a temperature of around 240 MeV. The conditions suppress the number of J-ψ-s (charmonia), enhance strangeness, and begin to drive the expansion of the fireball.

(3.) The “quark-gluon plasma” cools down and becomes more dilute.

(4.) At an energy density of 1 GeV/fm$^3$ (and a temperature of 170-180 MeV), the quarks and gluons condense into hadrons, and the final abundances of the different types of particles are fixed.

(5.) At an energy density of around 50 MeV/fm$^3$ (and a temperature of 100-120 MeV) the hadrons stop interacting completely and the fireball freezes out. At this point it is expanding at over half the speed of light.”

It had been emphasized, that the evidence for the above QGP picture is circumstantial and this picture had been put together from many little observations just like a complicated jigsaw puzzle.

2. Controversies in the QGP picture

I think it is important to highlight some of the controversial points in the above QGP picture, that are more or less well known but may have not been summarized before.

It is well known that the search for a new state of matter in the CERN SPS heavy ion program focused on two kind of QGP signatures: the early, penetrating probes of QGP formation (photons and lepton pairs that do not participate in the hadronic processes after their creation) and the late, hadronic probes that are produced when the relevant kinds of strong interactions become negligible, due to the expansion and the related rarification and cooling.

It is also well known that almost any calculation of e.g. direct photon production or dilepton emission is sensitive to the time evolution and the equation of state of the system, as the penetrating probes are emitted from the whole volume integrated over the time evolution of the hot and dense strongly interacting matter. Hence the emission pattern of the penetrating probes depends sensitively on the time evolution of the temperature and density profiles, for example.

The time evolution of the temperature or the local rest energy / entropy/ baryon densities, on the other hand, depend drastically on the dimension of the expansion. The time evolution has to satisfy the boundary condition, that it ends up on the proper hadronic final state that has been determined from the analysis of the late, hadronic signals. The hadronic final state thus imposes a severe constraint on the possible time evolution scenarios.

2.1. The hadronic final state

Let us follow the strategy of backwards extrapolation: It has been discovered in 1994-95 that the hadronic final state can be reconstructed only from a combined analysis of single particle spectra and two-particle Bose-Einstein correlations of pions and kaons. The hadronic final state of Pb + Pb collisions has been reconstructed with this method using the Buda-Lund hydro model in ref. The very different kind of experiments: NA44, NA49 and the preliminary WA98 data on
Figure 1. Simultaneous fit to NA49 single particle spectra and two-pion correlation data with the Buda-Lund hydro model.

Figure 2. Simultaneous fit to NA44 identified single particle spectra and two-particle correlation data with the Buda-Lund hydro model.
central Pb+Pb collisions at CERN SPS, the average value of the temperature as well as the value for of the mean transverse flow, the transverse radius for the central and the surface temperature of the fireball similar fitted values were obtained, as well as for the mean proper-time of particle freeze-out and the width of the freeze-out time distribution. Furthermore, the mean transverse flow is found to be about the same as that of an independent analysis of ref. [10]: the mean transverse flow at the transverse radius was found to be \( \langle u_t \rangle = 0.55 \pm 0.06 \), the transverse radius parameter was \( R_G = 7.1 \) fm, the mean freeze-out time after the onset of the scaling longitudinal expansion was found to be \( \langle \tau_0 \rangle = 5.9 \pm 0.6 \) fm. The central temperature at the mean freeze-out time was found to be \( T_0 \simeq 139 \pm 6 \) MeV, the surface temperature after the particle production was about to end was \( T_s \simeq 85 \) MeV, yielding an average freeze-out temperature of about 100 -120 MeV.

The presence of a quasi-linear, Hubble-like flow in the final stage of Pb+Pb collisions is very well established, based on the observed approximately linear rise of the effective slope parameters of heavier resonances with the increasing mass:

\[
T_{\text{eff}} \simeq T_0 + m \langle u_t \rangle^2
\]  

(1)

The reconstructed final state of ref. [6] has been extrapolated backwards in time by T. S. Biró [7] using exact quasi-analytic solutions of three-dimensional (3d) relativistic hydrodynamics assuming the presence of mixed Quark-Gluon Plasma - hadron gas phases, as given in Figure 3. The result implies many things:

i) Due to the strong 3d expansion, the system is able to convert a large amount of latent heat into hadrons in a relatively short time. Assuming a phase mixture of QGP and hadron gas, the QGP phase should have started to hadronize as early as \( \tau = 1.14 \) fm/c. This time scale is very close to the canonical guess of \( \tau_i = 1 \) fm/c that is frequently used in an over-simplified Bjorken formula [11] to estimate the initial energy density \( \epsilon_3 \) in contradiction with the result of the 3d relativistic hydrodynamical solution, where

\[
\epsilon_{\text{3d}} \approx \epsilon_c \approx 0.6 \text{GeV/fm}^3 \quad \text{at} \quad \tau_i = 1.14 \text{fm/c} \quad (4)
\]

Thus the estimation of the initial energy density with the help of Bjorken’s formula is uncertain and can become unreliable quantitatively (a factor of 4 over-estimate) and qualitatively (because it assumes a 1d instead of a 3d expansion).

ii) Even if we assume that the initial state is an equilibrated, thermalized QGP consisting of (massless) gluons and quarks, Biró’s backward extrapolation implies that the volume fraction \( \langle x \rangle \) of QGP decreases below \( \langle x \rangle < 1/3 \) within the first 1.3 fm/c of the 3d expansion, and the hadronization is fully completed within a time
period of 6 fm/c. This in turn suppresses the production of all the penetrating probes and implies that the signal in direct photon production, $J/\psi$ suppression and dilepton production must be very weak, much weaker than signals calculated for an optimistic one dimensional Bjorken-type expansion with a long-lived rehadronization.

iii) Inspecting figure 3 one finds that in order to generate the strong transverse flow by the end of the expansion as required by the experimental data, the transverse flow has to be even stronger at the beginning of the rehadronization than at the end of this phase transition, if a soft equation of state is assumed. Indeed, if the pressure is constant during the rehadronization, the flow can only decrease, due to the radial expansion. However, the backward extrapolation depends not only on the boundary condition (the final state requested by the data) but also on the equation of state (EOS). So, one may assume that final state requested by the data) but also on the equation of state (EOS). So, one may assume that the hypothesis of being at the softest point is in-equation of state (EOS). So, one may assume that the hypothesis of being at the softest point is incorrect, $c_s^2 > 0$. If the equation of state is hard, then the radial flow can be generated during the transverse expansion, perhaps even a Bjorken-type initial condition can be connected to the observed final state. The sensitivity of the extrapolation on the choice of EOS to the final state has been studied recently by Schlei and collaborators [8, who performed a similar but forward extrapolation using a lattice QCD inspired QGP equation of state and a hadron gas equation of state. However, the Hylander model calculations under-estimated the transverse flow in the observed final state. The sensitivity of the extrapolation to the hadronic final state must have been generated on the primordial level in the binary nucleon-nucleon collisions [8].

iv). Biró’s full 3d hydrodynamical backwards solution also that the time of hand-waving arguments and order of magnitude estimates is over for the expansion stage of the “Little Bang” fireballs.

This observations can be summarized as follows: a soft equation of state together with a zero or small primodial transverse flow is in disagreement with the boundary condition imposed by the hadronic final state. If one accepts the premiss that the strong transverse flow has not been present from the very beginning in the initial state, then the strong transverse flow of the observed hadronic final state must have been generated by a hard equation of state.

2.2. A few caveats on single particle spectra and two-particle correlations

Figure 4 indicates the $M_t$ scaling of the effective source sizes of various particles in central Pb+Pb collisions at CERN SPS energies. Such a scaling has been predicted in an analytic calculation of the Buda-Lund hydro model (BL-H) in refs. [8], with a large number of caveats that cannot be discussed here. See also ref. [8] for some of the details and most recent results. However, I would like to highlight one aspect of the BL-H calculation: in order to be able to calculate the scaling function precisely, and in order to obtain an approximate scaling in the transverse mass variable $M_t$, the BL-H model had to assume a non-vanishing value for the temperature inhomogeneity inside the particle emitting source. In the center of the plane transverse to the beam axis, the temperature of the source had to be slightly hotter than at the transverse r.m.s. radius at the mean freeze-out time, so that to keep the point of maximum emittivity close to the beam axis even for large values of $M_t$. This in turn implied a saturation of the effective slope parameters $T_*$ with the increasing values of the particle mass,

$$ T_* = T_0 + m \langle u_t \rangle^2 \frac{T_0}{T_0 + m\langle \Delta T \rangle_r} \quad (5) $$

$$ R_*^2 = \frac{R_G^2}{1 + \frac{M_t}{T_0} \langle \langle u_t \rangle^2 + \langle \Delta T \rangle_r^2 \rangle} \quad (6) $$

and the competition between the transverse flow $\langle u_t \rangle$ and the transverse temperature inhomogeneity $\langle \Delta T \rangle_r$ controls the $M_t$ dependence of the effective source sizes as well as the flattening of the initial linear mass dependence of the effective slope parameters of the single-particle spectra. Very heavy particles resolve the temperature inhomogeneities of the source, as the Boltzmann factor that characterizes their abundances focuses strongly their production to the hottest central parts, where the flow effects become limited.
Figure 4. $M_t$ scaling of the effective source volume as measured by M. Murray and the NA44 Collaboration.

The central temperature is $T_0 \approx 140$ MeV, the flattening of the slopes sets in at about $m = 1400$ MeV, which implies about 10% – 15% temperature inhomogeneity in the Pb+Pb source. This amount is rather small and it is in agreement with the results from a combined analysis of the single-particle spectra and the two-particle correlations in ref. [6], which resulted in $\langle u_t \rangle \approx 0.55 \pm 0.06$ and $\langle \frac{dT}{dT} \rangle_t \approx 0.06 \pm 0.05$, which suggests a slope parameter of about $T_{eff} \approx 315$ MeV for a particle with a mass of 1400 MeV.

For more details on this specific point and on a discussion of the significance of the temperature inhomogeneity and the transverse flow in shaping the transverse density profile, I recommend ref. [13].

This 10% transverse inhomogeneity in the central temperature becomes rather important when discussing the hadron-chemical composition. In my opinion, this temperature inhomogeneity prohibits the association of a single temperature value to the hadron-chemical composition. However, it allows for the interpretation of the observed $M_t$ scaling of HBT radii and the linearly rising than flattening effective slope parameters of the single particle spectra in a self-consistent and controllable manner, within the same framework. It is also clear, that the net baryon density is inhomogeneously distributed even in the central reaction zone due to surface effects, $\mu_B = \mu_B(r_x, r_y)$.

Due to the importance of the inhomogeneities of the temperature, and the net baryon number distributions (baryon chemical potential), I think that it is premature to discuss the hadronization in Pb+Pb collisions at CERN SPS in the framework of a complete hadrochemical and thermal equilibrium. The simultaneous analysis of the two-particle correlation functions and the single-particle spectra indicates [6,13] that the production of the observable hadrons happens in a relatively narrow longitudinal proper-time interval, characterized by a width of $\Delta \tau = 1.6 \pm 1.5$ to be compared with the mean freeze-out proper-time of $\tau_0 = 5.9 \pm 0.6$ ( as measured from the onset of the scaling longitudinal expansion). By the time the particle production is over, the surface of Pb + Pb collisions cools down from 139 MeV to about 83 MeV [6,3]. It is very interesting to note, that this value is similar to the surface temperature of $T_s = 82 \pm 7$ MeV found in h+p reactions as a consequence of transverse tem-
perature inhomogeneities, see ref. [16,13]. Such “snow-balls” with relatively low values of surface temperature and a possible hotter core were reported already in $S + Pb$ reactions in ref. [9].

Other hydro parameterizations, as reviewed in ref. [17], frequently neglect the effects of temperature inhomogeneities during the expansion and particle production stage. Energy conservation implies that the temperature cannot be exactly constant when particles are freezing out in a non-vanishing period of time from a three-dimensionally expanding source. Fixing the temperature to a constant in this time period, one finds some approximate average values of freeze-out temperatures in the range of $T_f = 110 \pm 30$ MeV.

In the physical situation of Little Bangs, expansion competes with the drop of the pressure gradients, which in turn is induced by the drop of the temperature on the surface. If the flow is small enough, a sudden drop of the temperature on the surface may result in a sudden drop of the pressure gradients on the surface, which implies density pile-up and a formation of a “ring of fire”, frequently seen in images of planetary nebulae as well, see ref. [13] for further details. On the other hand, if the flow is strong enough, it blows away the material from the surface, preventing the formation of such shells of fire, and an ordinary expanding fireball is obtained. The former case seems to be realized in $h + p$ reactions measured by the NA22 CERN experiment: a ring of fire is formed in the transverse plane due to the low transverse flow and due to the large temperature inhomogeneities. Pb+Pb collisions at CERN SPS are characterized with large transverse flows and relatively small transverse temperature inhomogeneities, hence they correspond to a exploding fireball with a more uniform, close to Gaussian density distribution [13]. This result indicates that non-trivial time-evolution of fireball hydrodynamics is intimately connected with the spatial inhomogeneities of the temperature and the corresponding density profile.

3. The new-old picture: Quark Matter

If one accepts the arguments of the previous section about the important role of temperature inhomogeneities in the source, the question arises: can we draw a phase diagram about the rehadronization process? Can we introduce the concept of a unique hadrochemical and kinetic temperature? In my opinion, these concepts are limited by the above shown variation of the local temperature during particle production (e.g. between 140 to 85 MeV at the kinetic freeze-out) so perhaps a ball-park value can be given, but the non-homogeneity is important and even in idealized cases the precision of a kinetic or chemical freeze-out “temperature” cannot be decreased below the 20 - 30 % relative error level. Thus the “data points” on the beautifully drawn phase diagrams e.g. in ref. [12] have large systematic uncertainties, and due to this reason I think it is premature to conclude at present about the separation of a hadrochemical freeze-out temperature of the order of 175 MeV from the and kinetic freeze-out temperature of the order of 110 MeV as well as about the precise value of the baryochemical potential and the temperature in various reactions: within 20 -30 % relative systematic error, these values can be the same. The validity of the method to extract these points can be questioned not only because it relies on the concept of spatially homogeneous temperature distributions, but also because the method yields a well-defined value for the hadrochemical and kinetic freeze-out temperatures even for $e^+e^-$ reactions at LEP [13]. However, we know that the $e^+e^-$ reactions are characterized by jet production and non-thermal fluctuation patterns like jets within jets within jets etc. Hence the well defined values of the baryon chemical potentials and the freeze-out temperatures in these kind of analyzes seem to be more characteristic to the method than to the physical system under consideration.

If the concept of the chemical freeze-out is maintained and embedded in a model of an exploding fireball, a statistically acceptable $\chi^2$ fit to the observed hadronic abundances by Rafaelski and collaborators resulted [13] in a chemical freeze-out temperature of the order of 140
MeV, within errors similar to the central kinetic freeze-out temperature obtained from the statistically acceptable $\chi^2$ fits to the observed single-particle spectra and two-particle correlation data of NA44, NA49 and WA98 collaborations using the Buda-Lund hydro parameterization \cite{6}. Hence a clear separation of the chemical and thermal freeze-out, (steps 4) and 5) of the Introduction) cannot be taken for granted at present.

4. Big Bang and Little Bang

Table 1 briefly summarizes the similarities between the physics of the Big Bang that resulted in our Universe and the physics of high energy heavy ion collisions or “Little Bangs” that are studied in the laboratory at CERN SPS and at Brookhaven AGS and RHIC accelerators.

5. Strangeness enhancement

The enhancement of strange particle production has been long thought to carry signals of QGP formation. Strangeness enhancement was intimately related to the question of chemical equilibration times in a QGP.

In the earliest discussions of high energy heavy ion collisions it was assumed, that in this reactions a long lived, thermally and chemically equilibrated QGP is formed. In such a QGP a large amount of $s\bar{s}$ pairs can be formed, hence the enhancement of strangeness production was proposed as a signature of QGP formation \cite{20}. Later, however, it was questioned if the equilibrium value of the $s\bar{s}$ number can be reached or not during the lifetime of a QGP phase, and it was shown, that the rate of the $g + g \rightarrow s\bar{s}$ reaction is too small to reach the equilibrium values \cite{21}. Following this observation, Rafelski and Müller showed that the inclusion of the $g + g \rightarrow s\bar{s}$ reaction a large enough strangeness production rate is achieved \cite{22} which seems to be enough to reach the equilibrium value of the concentration of $s\bar{s}$ pairs.

The problem of the recombination of quarks and antiquarks into hadrons was studied by Biró and Zimányi in ref. \cite{23}. In this work the mechanism of hadronization was assumed to be a non-linear, (quark number conserving) coalescence process. A few years later this model was extended by taking into account the effects of gluons: the gluons were assumed to fission into $q\bar{q}$ and $s\bar{s}$ pairs, increasing the number of quarks and antiquarks entering into the hadronization process described above. Further, these authors assumed a hadrochemical evolution after the hadronization in order to obtain the final hadron numbers \cite{24}.

If a quark-gluon plasma state is formed in a heavy ion reaction, one thus expects that the $s$-quark distributions are equilibrated in a few fm/c, and that the production of $s\bar{s}$ quarks is enhanced as compared to strange particle production in normal hadronic interactions, because the following reasons: i) In a QGP, the dominant degrees of freedom are the gluons that can easily enhance the strangeness content in the gluon fusion process $g + g \rightarrow s\bar{s}$; ii) at $T \geq T_c$ chiral symmetry is (at least partially) restored, and the mass of strange quarks is expected to decrease to $m_s \approx 150$ MeV, which implies that the thermal production rate is relatively high, $N(s) \propto e^{-m_s/T} \propto 1$, iii) in a baryon-rich Quark Gluon Plasma, the Pauli blocking of the $u$ and $d$ quarks favours (at SPS energies also) the $s\bar{s}$ production over the $u\bar{u}$ or $d\bar{d}$ production. Finally, one expects that the strange quarks are converted into hyperons during the rehadronization and their abundances are thus enhanced reflecting the reduced threshold of strange quark production in the deconfined phase.

The question arises: how important is the dominance of gluons in the above picture? Actually, only the following feature matters: that the production threshold for a $s\bar{s}$ creation is reduced and that this process starts to compete with the production of light quark pairs. Zimányi and Biró studied the problem of how quarks recombine \cite{25} into hadrons after the gluons have already disappeared from the system. For clarity, we shall refer to this situation as to the Quark Matter (QM), which name does not include the name of gluons, in contrast to the QGP acronym. The kaon and hyperon enhancement has been observed to be a common feature of both QM and QGP \cite{21,25,22,24}. The question arises, what are
the most natural observables and can one generalize the results to non-equilibrium situations?

I have argued that particle production in CERN SPS heavy ion reactions happens most likely in a sudden, non-equilibrium manner. What are the consequences of this mechanism, can one quantify e.g. the effect of such a mechanism on the hydrochemical composition of the produced particles?

Fortunately, the answer to this theoretical question is positive, provided that hadron production is characterized by the sudden recombination of constituent quarks into hadrons, as described by the ALCOR model \[27\]. Also, the experimental results at CERN SPS Pb+Pb measurements clearly and convincingly indicated a huge enhancement in the production of strange particles \[14\].

Bialas realized recently, that simple relations hold between various (multi-strange) antibaryon to baryon ratios \[15\] and the Budapest group has proven that these relations hold not only in a linear approximation to quark recombination, but also they are valid in general, if the hadron production happens through a sudden and complete, non-linear recombination of constituent quarks into hadrons \[26\]. The simplest formulation of such a recombinative hadron production method is described by the ALCOR model (ALgebraic COalescence for Rehadronization) \[27\]. The particle abundances are connected by the following simple relations \[15,26\]:

\[
\begin{align*}
\frac{\Lambda + \Sigma}{\overline{\Lambda} + \overline{\Sigma}} &= \frac{N}{N} \left[ \frac{K}{K} \right], \\
\frac{\Xi}{\overline{\Xi}} &= \frac{N}{N} \left[ \frac{K}{K} \right]^2, \\
\frac{\Omega}{\overline{\Omega}} &= \frac{N}{N} \left[ \frac{K}{K} \right]^3.
\end{align*}
\]

(7) (8) (9)

In these equations, \(N\) is the number of directly produced nucleons, \(\overline{N}\) is the directly produced anti-nucleons, \(\Lambda\) is the number of directly produced \(\Lambda\) baryons etc, so care must be taken when comparing with the experimental data, because of corrections from the resonance decays. Recent data from the WA97, NA44 and NA49 experiments indicate, that these relations are satisfied (after resonance decays are corrected for) in central Pb+Pb collisions at CERN SPS. This can be considered as a model-independent proof \[15,26\] that constituent quark degrees of freedom are liberated in these reactions and hadron production proceeds via a sudden and complete coalescence of constituent quarks to hadrons in central Pb+Pb collisions at CERN SPS.

At this point, it is natural to ask whether such constituent quark degrees of freedom reveal themselves in \(p+p\) or \(p+A\) collisions or not? This question has been investigated thoroughly by the E910 experiment at the AGS \[29\]. The detailed analysis of the dependence of leading baryon production, strange particle production and pion production suggests that \(i\) baryon stopping proceeds through a mechanism that is different from energy stopping; \(ii\) most of the energy carried away from precursors of energetic pions can be used for strange particle (e.g. \(\Lambda\) production), \(iii\) a break-up picture of the projectile to constituent quarks is a possible explanation of the \(\Lambda\) and \(K^0_S\) production, which is very close in spirit to the additive quark model.

In a QGP picture, strangeness enhancement happens through the large gluon density that create \(s\overline{s}\) pairs by gluon fusion. Chiral symmetry restoration reduces the constituent mass of strange quarks from 450 MeV to about 150 MeV, thus reducing their production threshold.

The question arises, do the gluonic degrees of freedom indeed have to play a dominant role for an enhancement of strange quark production? I think that the key requirement for strangeness enhancement is the reduction of the production threshold for \(s\overline{s}\) pairs. If the quarks are confined, the even the minimal excitations require the presence of additional light quarks to make a hadron; if a Quark Matter is formed, constituent \(S\overline{S}\) pairs can be created without the need for additional light quarks that also reduces the production threshold. Hence strangeness enhancement can be expected both in case of QM and in case of QGP formation, if the \(S\overline{S}\) production threshold is reduced.

A very interesting theoretical explanation of the process of enhanced strangeness production and a hard equation of state was given by Lévi...
and Heinz in ref. [30]. Using effective, massive quarks and gluons to describe the lattice QCD equation of state, they observed that the effective mass of gluons is strongly increased if one approaches from above the critical temperature. At the same time, the mass of quarks approached the constituent mass and the speed of sound remained rather large, $c_{s}^2 > 0.15$. The increase of the effective gluon mass with decreasing temperature may explain why the gluonic degrees of freedom seem to be less evidently required by the Pb+Pb data, than that of the constituent quarks [30].

The picture of the dominant role of constituent quarks and constituent antiquarks in the strangeness production, the integration of the gluonic degrees of freedom into an effective, confining equation of state was emphasized recently by the calculations of Biró, Lévai and Zimányi in refs. [31,32]. The necessity of a fast rehadronization and a three-dimensional expansion has been realized already in ref. [33].

6. Charm production and $J/\psi$ suppression

In a QGP, color degrees of freedom are liberated, both quarks and gluons become active degrees of freedom. If a $c\bar{c}$ pair is created from a gluonic fusion, the color interaction between these quarks is screened and the formation of charm quark antiquark pairs is suppressed, as predicted by Matsui and Satz [34].

There are a number of controversies related to the presentation of the NA50 data on $J/\psi$ suppression. Let me mention some of them: The horizontal axes of some of the figures indicates $L$, a variable that is thought to be characterizing the length of a path that the $J/\psi$ has to travel inside a medium. In a three-dimensionally expending, rarifying and cooling fireball, such a variable is difficult to define, not mentioning the problem how to determine it experimentally. On another plot, the ratio measured/expected is plotted versus the initial energy density as calculated from Bjorken's formula. Not only the theoretical expectations differ from model to model, but also the uncertainty in the initial energy density is at least as big as a factor of 4. Experimental data points should be determined as a function of measurable quantities, and not as a function of theoretical calculations.

A particularly interesting plot has been predicted theoretically by Kharzeev, Nardi and Satz [35]: the well measurable mean transverse momentum $\langle p_t^2 \rangle$ of the $J/\psi$'s in a hadron gas increases monotonically with increasing transverse energy, due to increased number of rescatterings with increasing centrality. However, if a QGP phase is reached in the center of the collision zone, the production of $J/\psi$'s are suppressed there, which implies that the $\langle p_t \rangle$ of the $J/\psi$'s starts to decrease with increasing transverse energy $E_t$ produced in the experiment, after an initial rise. In some sense, this decrease of the $\langle p_t^2 \rangle$ of the $J/\psi$'s is due to the softening of the equation of state when a QGP is produced.

This plot has been compiled from the available NA50 data by J. Nagle in ref. [36]. The result did not show the expected decrease of the $\langle p_t^2 \rangle$ with increasing $E_t$, but followed a pattern similar to the prediction for a hadron gas equation of state [33,36], see figure 6. This result casts doubt on a $J/\psi$ suppression from a QGP in central Pb+Pb collisions at CERN SPS. However, the detailed study performed in ref. [37] indicates that the $E_t$ dependence of the $J/\psi$ yield is incompatible with a Glauber-type calculation without initial energy loss, the total $J/\psi$ yield can be reproduced only with the help of an approximately 15 % initial energy loss, see fig. 6. Using this energy loss, the mean $\langle p_t \rangle$ transverse momenta of the $J/\psi$'s is under-predicted.

However, this result may be a fingerprint of the action of a hard equation of state, and a strong 3-dimensional expansion in the hot hadronic matter, that eventually enhances the $\langle p_t \rangle$ of the $J/\psi$'s (a transverse flow effect) in agreement with the results of the combined analysis of the single particle spectra and the two-particle correlation functions of pions, kaons and protons in the hadronic final state.

If one assumes that quark degrees of freedom are liberated but gluonic degrees not, and that the resulting quark matter has a hard equation of state, the abundances of various charmed mesons and baryons can be calculated with the help
of the extension of quark combinatorics to the charm flavor. The resulting ALCOR_c model implies simple relationships between the ratios of (multi)charmed antibaryon to baryon ratios, generalizing the results presented in the section on strangeness [28].

It is particularly interesting to note, that the following simple relationships are predicted by ALCOR_c for the multi-charmed baryon/antibaryon ratios:

\[
\frac{Y_c}{Y_c} = \frac{N}{N} \left[ \frac{D}{D} \right],
\]

\[
\frac{\Xi_{cc}}{\Xi_{cc}} = \frac{N}{N} \left[ \frac{D}{D} \right]^2,
\]

\[
\frac{\Omega_{ccc}}{\Omega_{ccc}} = \frac{D}{D} \left[ \frac{D}{D} \right]^3,
\]

\[
\frac{\Omega_c}{\Omega_c} = \frac{\Omega}{\Omega} \left[ \frac{D_s}{D_s} \right],
\]

\[
\frac{\Omega_{cc}}{\Omega_{cc}} = \frac{\Omega}{\Omega} \left[ \frac{D_s}{D_s} \right]^2,
\]

\[
\frac{\Omega_{ccc}}{\Omega_{ccc}} = \frac{\Omega}{\Omega} \left[ \frac{D_s}{D_s} \right]^3,
\]

and the mesonic step factors are related by a simple relationship,

\[
\frac{D_s}{D_s} \frac{D}{D} = \frac{K}{K}.
\]

Quark combinatorics predicts not only the rates but also the slope parameters of charmed mesons as well, as calculated recently in refs. [37].

The measurements of multi-charmed antibaryon to baryon ratios, the strange/charmed mesonic ratios of eq. (16), as well as the effective \( m_t \) slopes \( D \) and \( J/\psi \) mesons can thus provide an important constraint and test of the hadronization process, and can exclude or confirm the possibility that charmed hadron production happens through quark recombination and coalescence similarly to that of the strange hadrons.

7. Penetrating probes

Due to lack of space, time, and expertise, I cannot discuss these results in detail. As I mentioned
in the section on the particle spectra and correlations, at CERN SPS the final state indicates a strong 3-dimensional expansion with a hard equation of state, which is very efficient in reducing the large energy and entropy densities, which implies the reduction of the signal (if any) carried by the penetrating probes.

7.1. Direct photons

The experimental situation on direct photon production has been summarized recently in ref. [38] and can be briefly recapitulated as follows:

The relative increase of direct photons over photons from a conventional hadronic background is $(N_\gamma - N_{\gamma,hadr})/N_{\gamma,hadr} = 12\% \pm 0.8\% \pm 10.9\%$, a non-significant value. Within the errors this non-significant excess is constant as a function of multiplicity. A systematic study indicates, that the excess of directly produced photons in the most central $Pb + Pb$ collisions (as compared to the hadronic event generator VENUS) is less, than the same excess in $Pb + Nb$ or in $Pb+Ni$ collisions [4], see Figure 8. Indirectly, this result suggests the lack of significant amount of deconfined, undressed light quarks in the most central $Pb+Pb$ collisions at CERN SPS.

Photon production is dominated by the $\pi^0 \rightarrow \gamma + \gamma$ decay and in the observed distributions there is no space for a larger than 10 % contribution of thermally produced photons from a Quark-Gluon Plasma.

This result of the CERES/NA45 experiment is consistent with the picture of a strong three-dimensional expansion which is able to reduce the QGP fraction (if any) to less than 1/3 within the first 1.3 fm/c of rehadronization [5].

One may expect that a long lived QGP is signaled with an enhanced direct photon production together with late freeze-out times and large widths of the freeze-out time distribution, as observed from two-particle correlation studies $(R_{\text{out}} \gg R_{\text{side}})$. Thus, the lack of direct photon enhancement is consistent with a non-significant QGP production scenario and with the experimental results on a sudden particle freeze-out, $R_{\text{out}} \approx R_{\text{side}}$.

Figure 8. A systematic study of centrality and target dependence of direct photon production in Pb +A collisions at 158 AGeV from the WA98 collaboration, ref. [4]. The results indicate that the excess of direct photons is largest in semi-central collisions in Pb+Pb collisions (a) and in collisions with smaller targets like Nb (b) and Ni (c) than in the most central Pb+Pb collisions. This result suggests that the amount of light, deconfined quarks is not significant in the new form of matter created in central Pb+Pb collisions at CERN SPS.
7.2. Dilepton production

The CERES/NA45 experiment observed the inclusive $e^+e^-$ invariant mass spectra and compared the result to the expectation based on dilepton production from a chemically equilibrated, thermalized hadron gas. As compared to this expectation, a factor of $2.6 \pm 0.5 \pm 0.6$ enhancement of dilepton pairs in the $0.25 < m_{ee} < 0.7$ interval has been reported. The enhancement was shown to be concentrated on the low transverse momentum region, $200 \text{ MeV} < p_{ee}^t < 500 \text{ MeV}$, with almost negligible enhancement in the interval $500 \text{ MeV} < p_{ee}^t$. The various theoretical explanations of this effect focused on hadron modification in dense matter, as summarized recently in ref. \[39\].

However, the results can also be interpreted so that the hadron gas is not in full chemical equilibrium. An enhancement of the low $p_t^\eta$ $\eta'$ and $\omega$ mesons by a factor of 5 seems to be able to describe the observed enhancements, compare the left and right panels of Fig. 6 in ref. \[38\]. Such an enhancement has been proposed to signal the onset of a partial $U_A(1)$ symmetry restoration and should be detectable with the help of the measurement of the intercept parameter of the two-pion correlation functions as a function of the transverse mass, $m_t$ \[40\].

The important point of the above paragraphs is the following: the $m_t$ dependent production of $\omega$, $\eta$, and $\eta'$ is constrained by the strength of the two-pion Bose-Einstein correlation function, and this constraint can be utilized to calibrate the expected number of hadronic contributions to dilepton decays in the range of the observed excess. Such consistency checks between two-pion correlation measurements and dilepton production data have not yet been performed as far as I know.

8. Hard Quark Matter – Soft QGP

Let me summarize the results of the CERN heavy ion program by slightly modifying the text of the original announcement (where the modifications are given in italics): “Compelling evidence now exists for the formation of a new state of matter at energy densities at about 5 times larger than that in the center of atomic nuclei... This state exhibits characteristic properties which cannot be understood with conventional hadronic dynamics (i), but are qualitatively consistent with expectations from the formation of a new state of matter (ii) in which valence quarks no longer feel the constraints of color confinement (iii) and the properties of matter are dominated by that of valence quarks, the role of gluons is secondary.”

The physical picture of Quark Matter formation can be summarized in the following straightforward manner:

(1) Two colliding nuclei deposit energy in the reaction zone. The energy materializes predominantly in the form of constituent quarks, which strongly interact with each other.

(2) This early, very dense state has an energy density of about $1 \text{ GeV/fm}^3$ and the equivalent of a temperature of $170 - 180 \text{ MeV}$. The conditions enhance strange quark production and the hard equation of state begins to drive a strongly three-dimensional expansion of the fireball.

(3) Due to the three dimensional expansion, the “quark matter” suddenly cools down and becomes very dilute.

(4) The charmed, strange and light valence quarks recombine to form the hadrons. The allowed range for the “chemical” and the “kinetic” freeze-out temperatures include $140 \text{ MeV}$, so the chemical and the kinetic freeze-out happens almost simultaneously.

(5) At the time of the last interaction, the transverse expansion is characterized by about 10% temperature inhomogeneities, which imply large inhomogeneities (edge effects) in the transverse baryon density (and the baryon chemical potential). At the transverse rms radius the produced hadronic matter expands at over half the speed of light.”

As mentioned, the evidence for the above Quark Matter picture is circumstantial and this picture had been put together from many little observations just like a complicated jigsaw puzzle. This picture is significantly different from the also circumstantial Quark Gluon Plasma picture reviewed in the introduction.
9. Summary : Quark Matter ≠ Quark Gluon Plasma

A new picture is presented here, of a formation of a Quark Matter at CERN SPS. Quark Matter is a new state of matter that can be created in high energy heavy ion collisions. Starting from the reconstructed final state of Pb + Pb collisions, certain inconsistencies are pointed out in earlier attempts that tried to put together the jigsaw picture of these heavy ion collisions on the basis of the formation of a Quark Gluon Plasma.

Constituent (valence) Quark Matter is a new state of matter, that is different from both ordinary hadronic matter and from the much expected Quark Gluon Plasma.

I think that we have to keep an open eye and look for new, unexpected phenomena. Our community has to be able to distinguish between the breakup of hadrons to a Quark Matter consisting of massive constituent quarks and between the complete melting of QCD matter to a Quark Gluon Plasma, that consists of almost massless quarks and gluons.

Quark model provides a successful description of the bulk data on hadron spectroscopy. It is not surprising that the same, constituent quark degrees of freedom are liberated in high energy nuclear collisions. Note that valence gluons are not required in hadron spectroscopy, but valence (constituent) quarks are required, as they carry conserved quantities like charge and baryon number. It is difficult to remove a constituent quark from a Quark Matter, processes like $Q + Q \rightarrow Q$ are forbidden due to the conservation laws. Also, quarks are fermions so they cannot occupy the same quantum state due to Pauli blocking. I think these are the essential reasons why a Quark Matter has to be characterized by a hard equation of state.

On the other hand, if a Quark Gluon Plasma is produced, the number of degrees of freedom increases drastically and the channel $g + g \leftrightarrow g$ opens. As the abundant gluons do not carry any conserved charge, their number can be changed relatively easily. Also, gluons are bosons so any number of them can occupy the same quantum state. I think these are the essential reasons, why a QGP has to be characterized by a soft equation of state. For a more detailed analysis of the QCD equation of state in terms of massive quarks and gluons, let me recommend the work of Lévai and Heinz [30], whose phenomenological predictions (hard equation of state near the critical temperature etc) are in agreement with the qualitative analysis of the Pb+Pb data at CERN SPS.

It seems that constituent quark degrees of freedom play an important role in Pb+Pb collisions at CERN SPS energies, which is clearly demonstrated by the data on strange particle production. However, the liberation of gluonic degrees of freedom, and the softening of the equation of state due to the dominant role of gluons in a QGP is in disagreement with the available data at present, for example the mean transverse momentum of the $J/\psi$-s does not decrease with increasing transverse energy of the events.

A possible interpretation of this result is that a Quark Matter has been created in central Pb+Pb collisions at CERN SPS, however, a Quark Gluon Plasma phase has not yet been reached.

The discovery of QGP can be expected at higher initial energy densities, such as produced by the recently started RHIC accelerator. It is a very exciting challenge for RHIC to distinguish between various new forms of matter, for example between Quark Matter and Quark Gluon Plasma.

I would like to add, that the constituent quark dominated Quark Matter is described in earlier publications on strangeness production under various, perhaps more fancy names like CQP = constituent quark plasma, $Q\bar{Q}P =$ quark antiquark plasma. This picture is somewhat similar to the valon model as well, although the valons were invented to consider soft scattering problems between quarks, as described in refs. [41], while the constituent quarks in the present picture emerge due to the combinatorical description of hadron production which is a bound-state formation problem.

In the light of the recent experimental data on single particle spectra, two-particle correlations, strange particle production, direct photon and dilepton production as well as charmed particle production, as summarized in refs. [1,2] the picture of a formation of a Quark Matter (not
QGP) emerges. This is in a good agreement with the phenomenological analysis of the lattice QCD equation of state by Lévai and Heinz: Instead of an idealized, asymptotically free quark gluon plasma, the lattice results for the QCD equation of state can be parameterized phenomenologically as a mixture of massive quarks anti-quarks, while the gluons pick up a large mass near $T_c$ so that they stop to play a dominant role, and as a consequence the QM has hard equation of state \[^{30}\].

The picture of Quark Matter (not Quark Gluon Plasma) formation at CERN SPS can be summarized in the following manner:

1. Two colliding nuclei deposit energy in the reaction zone. The bombarding energy breaks the nucleons into constituent quarks and materializes in the form of new constituent quark–anti-quark pairs.
2. This early, very dense state has an energy density of about 1 GeV/fm$^3$ and the equivalent of a temperature of more than 140 MeV. The conditions enhance strangeness, suppress the number of gluons, and the hard equation of state drives a strong transverse and longitudinal expansion of the fireball.
3. The Quark Matter cools down fast due to the strong three-dimensional expansion.
4. At the critical temperature of deconfinement, the constituent quarks suddenly recombine into hadrons, and the final abundances of the different types of directly produced particles are fixed. The number of charmed, strange and light mesons and baryons is determined from quark combinatorics and feed downs from the decay of hadronic resonances.
5. The chemical and thermal freeze-out temperature distributions may be rather close to each other, in the range of 140 MeV. The density distribution (baryon chemical potential) is rather inhomogeneous, and the central temperature at the mean kinetic freeze-out time decreases from about 140 MeV to about 85 MeV at the surface. At the time of the last interactions the fireball is expanding transversally at over half the speed of light.\[^{30}\]

Table 2 summarizes briefly the main phenomenological and experimental differences between an idealized, soft Quark Gluon Plasma, and the old-new, non-ideal hard Quark Matter, whose production in central Pb + Pb reactions at CERN SPS seems to be consistent with the current, exciting experimental situation.

Figure 9 illustrates the phenomenological separation of the liberation of constituent (dressed) quark degrees of freedom in form of Quark Matter from the theoretically predicted liberation of light (undressed) quarks and gluons in very energetic heavy ion collisions. If the gluons carry an effective (temperature and density dependent) mass, the gluonic degrees of freedom appear at around the $T = m_*(T, \mu_B, ...) \,$ line, which effectively separates Quark Matter from Quark Gluon Plasma on this illustrative example of fig. 9. Note however, that the “line” separating the QM from QGP may correspond to a crossover instead of a phase transition in a strict sense, similarly to that of the transition of a heated mono-atomic gas to a plasma state. At this line, the dominant degrees of freedom change, but the functional form of the equation of state may not necessarily change.

Finally, Table 3 summarizes the 5 simple but different steps of a hadronizing QGP and a hadronizing Quark Matter.
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Table 1: Similarities between the Big Bang and the Little Bang

| Big Bang | Little Bang |
|----------|-------------|
| Expansion, Hubble flow | Expansion (HBT+spectra), $p_t$ flow |
| Nucleosynthesis | Particle ratios |
| Microwave Background radiation | Direct photons (thermal radiation) |
| Large scale structures | Event structures in $d_n/dy$ |
| Topological defects | Disoriented chiral condensates |
| Dark Matter | $\mathcal{U}(1)$ symmetry restoration |
| B+L asymmetry | Strangelets |
| Hawking radiation | Back-to-back correlations |
| Formation of binary stars | Formation of binary sources |

1. Big Bang

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Table 2: Properties of Quark Matter (QM) versus Quark Gluon Plasma (QGP)

| Quark Matter | Quark Gluon Plasma |
|--------------|-------------------|
| Valence quarks: $Q, \bar{Q}, S, \bar{S}, \ldots$ | Massless gluons and current quarks: $g, q, \bar{q}, s, \bar{s}, \ldots$ |
| $m_Q, m_{\bar{Q}}, m_S, m_{\bar{S}} \geq T_c$ | $m_q = m_{\bar{q}} \ll m_g < T_c$ |
| 3d Hubble expansion | 1d Bjorken expansion, softest point |
| Hard equation of state | Soft equation of state |
| $c_s^2 = 1/3$ (maximum) | $c_s^2 = 0$ (minimum) |
| Gluonic degrees of freedom frozen | Gluons are the dominant degrees of freedom |
| Violent explosion with sudden hadronization | Long lived mixed QGP+H (Maxwell) |
| $T_{\text{eff}} = T_0 + m_{\langle u_t \rangle}^2$ | $T_\pi \simeq T_K \simeq T_p$ |
| $R_{\text{out}} \simeq R_{\text{side}}$ | $R_{\text{out}} \gg R_{\text{side}}$ |
| Hadron synthesis: Quark Combinatorics | $g \to s \bar{s}, c \bar{c}$ |
| $\frac{\Omega}{\bar{\Omega}} = \frac{[p/p]}{[K/K]}^3$ | Strangeness suppression factor |
| $\frac{\Omega_{ccc}/\Omega_{cc}}{[p/p][D/D]}^3$ | $J/\psi$ suppression |
| $\langle p_t \rangle$ of $J/\psi$ increases with $E_t$ | $\langle p_t \rangle$ of $J/\psi$ first increases then decreases with $E_t$ |

Table 3: Quark Matter (QM) versus Quark Gluon Plasma (QGP) formation: Simple steps

| Quark Matter | Quark Gluon Plasma |
|--------------|-------------------|
| 1 Constituent quarks are created from the bombarding energy | Quarks and gluons are created from the first collisions |
| 2 initial energy density $\approx 1$ GeV/fm$^3$ | $\approx 3-4$ GeV/fm$^3$ |
| 3 Hard equation of state, 3d expansion | Soft equation of state, 1d expansion |
| 4 Sudden hadronization, quark combinatorics | Slow hadronization, dominated by gluons |
| 5 Kinetic and chemical freeze-out overlaps | Kinetic and chemical freeze-out well separated |