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EXPECTATIONS FOR NEW STATES OF MATTER

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ABSTRACT

This review of quark matter and its possible formation in very high energy heavy ion collisions is written as an introduction to the specialized Conference of 1983, held at Brookhaven National Laboratory. It surveys the situation as it appeared after the specialized Workshop of 1982, (Bielefeld Interdisciplinary Centre) with hints at recent developments to be presented in greater detail during the specialized Conference.

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1. INTRODUCTION

Hadrons are made of quarks interacting through the colour field. This statement covers calculations which can be performed in a perturbative way in the framework of quantum chromodynamics for interactions at very short distance, deep within the range defined by hadronic sizes¹. This statement also covers longer-range effects, whereby vacuum polarization forces quarks to remain confined within systems globally neutral with respect to colour². While in the former case recent successes with short-distance (large transfers) processes justify optimism, in the latter case difficulties still appear to be overwhelming. For this very reason, it would be extremely worthwhile to extend our study of hadron systems beyond the low quark density and low temperature (or mean energy density) conditions which prevail in actual hadrons. Indeed, we have at present many reasons for thinking that, at very high density and/or very high temperature, the nature of the QCD vacuum is modified. This allows colour sources (quarks and gluons) to propagate freely over extended volumes where such conditions would prevail³. This is what is meant by deconfinement, and it would correspond to a new state of matter, referred to as "quark matter" or "quark gluon plasma". The conditions which one is led to consider correspond to a quark density of the order of 5 per f^3 [as opposed to 0.5 in (cold) nuclear matter], at low temperature, or to a temperature of the order of 200 to 300 MeV (the latter being twice the "limiting" Hagedorn temperature") at low quark density. Such conditions should have prevailed in the early Universe about 10^{-5} sec after the Big Bang. The temperature of the primordial Universe should have indeed fallen as $T \approx 0.5 \tau^{-1/2}$ with T in MeV and τ in seconds.

It seems reasonable to expect that the relevant energy density could be reached over volumes of linear dimensions of a few fermi in heavy ion

collisions, provided that the incident energy would exceed 200 GeV/nucleon, which corresponds to typically 100 times the energy so far used for heavy ion experimentation⁴. This could, however, be within the reach of present proton synchrotrons (such as the CERN SPS), provided that they are equipped with intense ion sources. Within three years, one may thus hope to obtain some valuable pieces of information before a more specialized machine could allow for some thorough investigation⁵. At present, information is limited to too low an energy (a few GeV/nucleon) for heavy ion collisions, to probably too small ions (α - α collisions) at high energy (ISR) and, when considering heavy ion collisions and very high energies, to too few cosmic ray events. While no definite conclusion can be reached, present information should not be undermined, since it provides definite support for present estimates of the energy density reached in high-energy heavy ion collisions and also several encouraging hints, as will be discussed later.

2. A RAPID SURVEY

With such a convergence of theoretical interest and experimental possibilities, it was deemed appropriate to convene a Workshop which would be able to review these questions in some depth. This was done at Bielefeld in the spring of 1982 and the proceedings⁶ now offer a primer where the reader can assess for himself problems and promises. The purpose of this paper is to summarize the situation as it appeared after the Bielefeld Workshop, in order to provide an introduction for the Brookhaven Conference, which now approaches these questions again in a thorough way, 16 months later. In so doing I shall mention, though only briefly, some of the new developments which will be discussed at much greater length during the Conference, and go through a data sample providing new and encouraging pieces of evidence. Several new results indeed contribute to making the question of nuclear matter in heavy ion collisions still more challenging and interesting than it appeared a year ago.

It was clear after the Bielefeld Workshop that an interplay between experimental and theoretical analysis was needed, in particular when considering fluctuations in heavy ion collisions, and one of the very positive elements which appeared at the Workshop was that experimentalists were not at all frightened by the very large expected multiplicities (several hundred pions). This remains a very strong motivation for moving ahead, and the SPS used as an ^{16}O accelerator (in 1986?) could provide a first fruitful look. On the other hand, over the past year, the SPS used as a $p\bar{p}$ collider has provided several encouraging results and in particular ample evidence that protons (antiprotons) behave as broad band beams of quarks and gluons acting, to a large extent, incoherently of one another, when studying interactions at short distances^{7,8}. The

relative simplicity of the proton as a probe thus appears as of rather little interest. For such purposes, a nucleus at such energy would just be a more intense beam of quarks and gluons, and nucleus-nucleus collisions provide the proper way to study multiple quark interactions. In so doing, the recent collider results, later reviewed in Section 3, provide strong encouragement for moving ahead to much higher CM energy ($\sqrt{s_{NN}} \geq 200$ GeV, say) than that previously considered as minimal ($\sqrt{s_{NN}} \geq 20$ GeV).

The situation after the Bielefeld Workshop could be summarized through a list of questions and answers. The questions were:

- (i) Is there a phase transition between hadronic matter (nucleons and pions) and quark matter (a quark gluon plasma) at high density and (or) temperature?
- (ii) If such a transition exists, what are the critical values?
- (iii) Could such conditions be reached in heavy ion collisions, assuming that collisions with centre of mass energy (at the nucleon-nucleon level) in excess of, say, 20 GeV are considered?
- (iv) Could specific signals be associated with such a transition, granting the fact that it must correspond to a very transient phenomenon?
- (v) If there are a priori interesting signals, could they be seen against the large expected background with present techniques?

The answers which could then be formulated, and which still stand today, were respectively⁶:

- For (i): almost certainly one and maybe two, the second one corresponding to the restoration of chiral symmetry, with $T_{ch} \geq T_c$.
- For (ii): the relevant energy density should be of the order of 1 to 2 GeV/fm³, or, if considering temperatures, at the level of 200 to 300 MeV. These values should be compared to an energy density of 0.15 GeV/fm³ in nuclear matter and to the Hagedorn "limiting" temperature of 140 MeV.
- For (iii): almost certainly yes, either in the fragmentation region or in the central region⁹⁻¹¹. The required energy density could be reached, say, a few percent of the times in U-U collisions at 200 GeV/nucleon, when the impact parameter would be small enough.
- For (iv): Several signals look promising, when studying large fluctuations on an event-to-event basis: photons, lepton pairs, hyperons in the fragmentation region
- For (v): The answer was yes.

The history of a blob of hadronic matter undergoing a transition to quark matter during a heavy ion collision can be pictured schematically in the phase diagram of Fig. 1. While there is, as previously stated, some uncertainty as

to the precise location of the separation curve between the hadron matter phase and the quark matter phase, the relation between the critical temperature and the chemical potential is correctly displayed. Through the reaction, one has first a compression and then a large increase in temperature in the fragmentation region before the quark gluon plasma returns to the hadronic phase. In the central region, the quark density remains low while the temperature soars and eventually decreases^{12,13}.

FIGURE 1

Time evolution of a system undergoing a transition between hadron matter and quark matter. The values of the critical parameters are indicative only.

The critical parameters as they appear in Fig. 1 can be readily obtained in a simple two-phase approach¹². At low baryon density we have, on the low temperature side, a pion gas, and on the high temperature side, a quark gluon plasma. In the latter case, the equation of state involves the bag constant B corresponding to the external pressure imposed by the vacuum. The critical temperature is thus expressed in terms of B *) and one finds:

$$T_c \approx 0.72 B^{1/4} \approx 140 \text{ MeV} \quad (2.1)$$

At high baryon density we have on the low density side a degenerate Fermi gas of nucleons and on the high density side, a quark plasma. In this case,

*) The value of B cannot be considered as fully settled yet.

the critical conditions (at low temperature) correspond to a particular density which is again expressed in terms of B , namely:

$$d_c = 2(3\pi^2)^{-1/4} B^{3/4} \approx 5 d_0 \quad (2.2)$$

with $d_0 = 0.15 \text{ fm}^{-3}$ for the standard nuclear density.

In both cases, the latent heat per unit volume (if the transition turns out to be of first order) is equal to $2B^{1/2}$. The critical values (2.1) and (2.2) are those which appear in Fig. 1 with the phase transition curve "interpolating" in between.

It is reasonable to assume the existence of two distinct phases³. At high density, the nuclear bags should merge into one another, with a resulting unique big blob of quark matter. At high temperature, the colour field can expand into the vacuum, since the corresponding high-energy configurations are only weakly damped in the partition function. As the colour field expands its range sideways, it no longer confines. While this may even appear inevitable, the nature of the phase transition is, however, not specified. It does not have to be of first order; it could well be gradual and take the form of a percolation into a blob of quark gluon plasma.

At present, gauge theory calculations on the lattice provide a unique but promising way to follow a system through the transition. This represents in itself a very important facet of present studies on quark matter, and we discuss it separately in Section 4.

We first remain at a general level and, granting the fact that a phase transition exists, with critical parameters of the order of those given by (2.1) and (2.2), we consider if such conditions have any chance of being realized in heavy ion collisions.

One first requires that a large amount of energy be transferred to transverse degrees of freedom. An important fraction of the kinetic energy of the incident particles should eventually be found concentrated over a particular domain where the comoving energy density should be large enough. This will eventually manifest itself in a large transverse energy density in terms of rapidity⁹ and also in a large particle density.

This energy being available on transverse degrees of freedom, the reaching of a high temperature over an extended domain still requires rescattering among the relevant constituents (quarks and gluons) in order to have some thermalization. If rescattering can proceed for a long enough time, one eventually reaches chemical equilibrium with, as a result, a fair amount of strange quark-antiquark pairs¹⁴.

In both cases, (transverse energy excitation and multiple scattering), one expects a sizeable increase with A (the atomic number) and with E (the

incident energy), granting the fact that we assume in any case that $E_{CM} \geq 10$ GeV per nucleon. We may indeed tentatively assume that the rapidity density increases linearly with A and therefore that the energy density per unit volume increases as $A^{1/3}$. At the same time, the rapidity density increases logarithmically with E_{CM} . At high energy, one may quite generally consider an incident proton as a broad band beam of quarks and gluons, insofar as hadron formation time far exceeds the transit time during which the two nuclei pass through each other. There is therefore a priori little difference between a proton and a nucleus. A nucleus is simply a more intense flux of quarks and gluons, which can flare up on impact at different points simultaneously. One should take benefit from it.

One year ago⁶, estimates of the energy density were based on the calculation of R. Anishetty et al.¹⁰, which incorporated available information about particle production translated in terms of local clustering of energy, and also on the hydrodynamical approach of J. Björken¹¹. It was concluded that for $E_{CM} \geq 10$ GeV/nucleon ($E_{lab} \geq 200$ GeV/nucleon, say), U-U collisions could give energy densities of the order of 2 GeV/fm^3 in the fragmentation region and (though with less certainty) about the same amount in the central region. Under similar conditions, an O-Pb collisions could give energy densities still in excess of 1 GeV/fm^3 . These values refer, of course, to particularly violent processes where the impact parameter is small ($r < 1 \text{ fm}$, say), which have a typical probability at the few per cent level.

One could thus approach this question with much optimism, the energy density expected being neatly above that associated with critical conditions.

A year later, new estimates have been made, with a more detailed analysis of the compression process. One may say that the values now mentioned, while centred on the estimate of 1982, show some important scattering. On the relatively low side, one finds the estimate of Kajantie et al.¹⁵, while on the relatively high side, one finds that of Gyulassy et al.¹⁶. One may thus quote energy densities at the level of 1 to 4 GeV/fm^3 in the fragmentation region and at the level of 2 to 10 GeV/fm^3 in the central region, the higher values in the latter case referring to very high energy ($E_{CM} \geq 100 \text{ GeV/nucleon}$, say), thus benefiting from the increase of the central rapidity density with incident energy. The present situation is reviewed by L. McLerran⁰. While one may certainly remain as optimistic as in 1982, one has to face the possibility that the values reached in the fragmentation region could be a little on the low side; this is in particular the case for the compression factor (quark density) which could be reached¹⁵.

One should say, however, that such estimates correspond to mean values when large fluctuations could take place, and some cosmic ray events indeed indicate

large fluctuations, though at very high energy. Optimism should thus prevail, though with an urgent need to know more about fluctuations. Large fluctuations in rapidity density is a question for which an interplay between theory and experiment is very much needed.

The energy density should rapidly decrease with time as the system expands. Typically¹³

$$\frac{dE}{dz} \sim A \frac{(dE/dy)_{pp}}{\pi R^2} \quad \frac{dy}{dz} \sim \frac{0.5 A^{1/3}}{t} \text{ (GeV/fm}^3\text{)} \quad (2.3)$$

where z is the beam axis and t is the expansion time, measured in Fermi. One usually considers one Fermi as the width of the domain over which one should define the initial energy density. In the centre of mass system, this distance corresponds to the extension of the wee partons, which strongly interact and define the maximum Lorentz contraction of the colliding nuclei. Recent studies give an expansion time which seems to be adequate for reaching kinetic equilibrium (some thermalization)¹⁵⁻¹⁷. One does, however, need better three-dimension simulation [(2.3) is a one-dimension formula!] in order to determine the expansion time better. The study of expansion through a first-order transition (if it occurs) shows interesting effects¹⁸. The key question is that of entropy generation as the quark gluon plasma returns to the hadronic phase. It could be small with a plasma deflagration resulting in large hadron momenta using the latent heat release¹⁸.

While $E_{CM} \gtrsim 10$ GeV/nucleon seems adequate to reach the required energy density, the collider and cosmic ray results recently obtained do show that much should be gained operating at much higher energies, $E_{CM} \gtrsim 100$ GeV/nucleon. This is what should be aimed at when considering a specialized machine, notwithstanding the very great interest of (first generation) SPS experiments⁶.

The reader's attention is drawn to Ref. 6) for a discussion of signals and of signal-over-background ratios. The situation has not changed qualitatively. Present prospects are reviewed in detail by M. Gyulassy⁰; this paper turns rather to a data sampling, picking up some new results which all have some bearing one way or another on high-energy heavy ion collisions.

3. A DATA SAMPLING SINCE THE BIELEFELD WORKSHOP

It is clear that with nucleus-nucleus collisions, one hopes to reach large values of dE/dy or $(1/\sigma)(d\sigma/dy)$, the inclusive particle yield. Even though α 's are small nuclei, a sizeable increase should be observed between $\alpha\alpha$ and pp collisions¹⁹. This was already known in 1981, and Fig. 2a shows the inclusive π^- yields in $\alpha\alpha$ and pp collisions at $\sqrt{s_{NN}} = 31$ GeV (ISR), as measured by experiment R418²⁰. The rapidity density is typically 1.8 times

higher in the central region. This corresponds, to a large extent, to several nucleon-nucleon collisions taking place during the same α - α collision, thus increasing the global particle yield at wide angle. This is a *necessary* condition in order to reach high-energy densities. Increasing A should help. Figure 2b, which corresponds to the recent 1983 run, shows the effects gradually building up, with a ratio now of 1.5 between the positive and negative yields in $\alpha\alpha$ and pp collisions at the same value of $\sqrt{s_{NN}}$.

FIGURE 2
Inclusive charged particle yields. Ratios of the rapidity distribution: a) between $\alpha\alpha$ and pp at $\sqrt{s_{NN}} = 31$ GeV (1981).

FIGURE 2
Inclusive charged particle yields. Ratios of the
rapidity distribution: b) between $\alpha\alpha$ and dd at
 $\sqrt{s_{NN}} = 31$ GeV (1983).

A very interesting, but still hardly studied effect which emerged from the 1980 run was the important increase in yield at large p_T . This is probably the mere generalization of the effect already observed at Fermilab in p -nucleus collisions²¹ (the Cronin effect), but further enhanced in nucleus-nucleus collisions¹⁹. At large p_T ($p_T > 3$ GeV/c), the inclusive pion yield becomes larger than $A^2 = 16$, which would correspond to independent parton-parton scattering. Such an increase beyond 16 can be interpreted in terms of multiple collisions²², a parton collecting transverse momentum through two successive collisions, say. The available data were, however, not clear enough to allow for any detailed study, let alone to provide definite evidence of the effect. Figure 3a puts together the results of R418 and R807 (charged particles) and those of R806 and R110 (neutral particles), as available in 1981¹⁹. Also shown (dashed curve) is the behaviour anticipated from the factorization of the proton-nucleus effect²¹. Figure 3b shows the global (neutral) transverse energy as now measured by R110²³. The $\alpha\alpha$ results are presented together with the pp results multiplied by 16. One sees that, at relatively low E_t ($E_t < 5$ GeV), where the cross-section is still big, $\alpha\alpha$ collisions are far more efficient than pp collisions at providing large amounts of transverse energy. With the results shown in Figs. 2a, 2b, 3a and 3b, one sees that the two conditions necessary for the formation of a quark gluon plasma, namely a large rapidity density and some

rescattering among constituents, appear to be satisfied, though one is still waiting for the analysis of the recent $\alpha\alpha$ data which should clarify the question of the high p_T behaviour of single particle yields. One should consult the contribution of W. Frati to that effect⁰. The relatively limited size of the α nuclei is, however, such that they may not yet be sufficient to allow one to the required conditions.

FIGURE 3
Large p_T (E_T) yields at wide angle: a) inclusive particle production as a function of p_T in $\alpha\alpha$ collisions.

The data of Fig. 3b are particularly encouraging. The enormously large yields at large E_T seen in this Figure correspond to the fact that in $\alpha\alpha$ collisions we may have the cumulative effects of two, three, and even four nucleon-nucleon collisions. This is spectacular, but not of immediate relevance here, in view of the smallness of the cross-section. The behaviour at lower E_T ($E_T < 5$ GeV) is more relevant.

FIGURE 3
Large p_T (E_T) yields at wide angle: b) global transverse energy distribution at wide angle ($\Delta y = \pm 1$) in $\alpha\alpha$ and pp collisions. The value found in pp collisions has been multiplied by 16 to show better the "anomalous" enhancement found in $\alpha\alpha$ collisions. Events/luminosity.

Our data sampling now moves to the recent cosmic ray results of the JACEE Collaboration²⁴. Among a hundred or so events with $Z > 6$ and $E > 1$ TeV/nucleon, one finds three spectacular ones. Figure 4 displays the pseudorapidity distribution for two of them (a Si-AgBr event at 4 TeV/nucleon, and a Ca C event at 100 TeV/nucleon) and the transverse momentum distribution of photons (from π^0 's) in the latter case. Observation of these events among such a limited data sample speak for a rather frequent type of configuration, yet it looks very peculiar by present standards. First, the rapidity density is very high, much larger than an independent interaction model would lead one to expect²⁵. Second, there are very wild fluctuations in the rapidity density which, if confirmed, would be something novel and peculiar⁹. Third, the density looks anomalously

large in the fragmentation region, as if something very special had happened in the blob associated with the fragmentation of the incident ions. Fourth, the p_T distribution in one event appears to be anomalously wide, with a mean value twice as high as usual⁹. The incident energy puts them in between the ISR (2 TeV) and SPS collider (150 TeV) energy ranges. Such events should then be accessible in heavy ion collisions with centre of mass energies of the order of 100 GeV to 200 GeV/nucleon. These impressive fluctuations, let alone in total multiplicity, offer a strong case for considering very high energies. The contributions of V. Jones and of T. Saito cover present information from cosmic ray results⁰.

FIGURE 4
 Two events observed by the JACEE Collaboration. Pseudorapidity distributions: a) Si AgBr at 4 TeV/nucleon; b) Ca C at 100 TeV/nucleon; c) p_T distributions of γ rays (from π^0) in the Ca C event.

Reaching such energies (100 to 200 GeV/nucleon per beam) would also take full benefit from the important rise in central density now verified with accuracy at the collider^{26,27}. Figure 5a shows the central pseudorapidity density at ISR and collider energies (UA5). The density rises by almost a factor two. From (2.3), this reflects itself in a corresponding rise in comoving energy density. Figure 5b shows the neutral pseudorapidity measured earlier in cosmic ray Emulsion Chamber experiments²⁸, at a similar energy ($E \sim 100$ TeV), together with a mere extrapolation of Fermilab results, with a constant central density.

FIGURE 5

Central (pseudo) rapidity density: a) charged pseudorapidity density as a function of centre of mass energy. Open dots - UA5 data at the ISR and SPS collider. Full dots - other ISR data.

(b)

FIGURE 5
Central (pseudo) rapidity density: b) electromagnetic energy density as measured in Emulsion Chamber at 100 TeV (full dots) and in emulsion at Fermilab (open dots) with extrapolation to higher energy.

Going to such energies would certainly allow one to reach very high energy densities in the central region (6 to 10 GeV/fm³) for heavy ion collisions¹⁶, and this would happen rather frequently (at the few per cent level). Secondary distributions show spectacular fluctuations in rapidity density. The UA5 experiment reports that at the few per mil level, one can find a cluster of 15 charged particles within 1/2 unit of pseudorapidity (five times the mean value), large fluctuations being found not only in high multiplicity events²⁸.

Figure 6a shows the pseudorapidity distribution typical of such an event. The rate is such that it cannot be associated with large p_T jets, as will be discussed later. Indeed, the azimuthal distribution, as shown in Fig. 6b, appears to be isotropic.

Thus, at collider energies, $p\bar{p}$ collisions already show anomalously high fluctuation densities, which should correspond to very high comoving densities. Coming back to mean values, the very important increase in central mean density corresponds at least partly to the occurrence of a new kind of configuration, where large central densities are associated with large mean transverse momenta. Figure 7a hints at a dichotomic separation between two types of configuration, as has long been advocated from the analysis of Emulsion Chamber results²⁹. The lower n_Y (the Emulsion Chambers are sensitive to electromagnetic energy only) and lower $\langle p_T \rangle$ configurations would correspond to the mere extrapolation of typical Fermilab (ISR) configurations. The higher n_Y and higher $\langle p_T \rangle$ configurations would correspond to something new. Whilst such a dichotomic separation (Mirin and Açu events²⁹) is probably too strong, the recent collider results show a definite rise of $\langle p_T \rangle$ with dn/dy , the central rapidity density³⁰.

FIGURE 6
Pseudorapidity (6a) and azimuthal (6b) distributions for collider events selected according to the presence of a large number of particles ($N_{\text{max}} \geq 15$) within $1/2$ unit of $\text{Sh } \eta$. Such configurations reported by UA5 and Ref. 28) occur with a probability of a few per mil.

FIGURE 7

The correlation between high central density and large mean transverse momentum which becomes more pronounced with increasing energy:

a) separation between two classes of events in Emulsion Chamber results. See Refs. 28) and 31);

b) evidence for a correlation at collider energy, Ref. 29), and at ISR energy, Ref. 30).

This has now also been seen at the ISR with new and precise results³¹, though in a far less obvious way. This effect has been associated with the fact that, as one moves to very high energy ($E \sim 270$ GeV here), there are many low X partons which can incoherently scatter at wide angle, thus producing several mini-jets with, as a result, an increase in central multiplicity and an increase in $\langle p_T \rangle$ ³². This is undoubtedly a promising starting point for reaching very high temperatures through multiple rescattering in heavy ion collisions. The contributions of C. Rubbia and of G. Pancheri provide a status report of this process⁰. The occurrence of this effect is again a strong incentive to consider very high collision energies.

In such high density cases, the incident nucleons behave as broad band beams of partons (quarks and gluons), acting to some extent incoherently (semi-hard processes). Full incoherence in scattering occurs in large p_T collisions producing wide angle jets. While the association between high p_T phenomena and hadronic jets could be advocated long ago from the analysis of ISR results³³, the results of the collider obtained over the past year have made jets obvious to the naked eye (Fig. 8a). The jet yields, measured now at the collider³⁴ and at the ISR³⁵, are in good agreement with predictions based on QCD^{36,37,32}. The association of high p_T hadronic jets (short-range processes) with hard scattering among quarks and gluons, acting incoherently in the framework of perturbative QCD, does not leave any doubt.

Indeed, one is thus led also to expect that, in some cases, two partons from one incident particle should scatter against two partons from the other with, as a result, a clear four-jet event. Figure 9 shows the angular distribution of the transverse energy for such an event. One sees clearly two two-jet systems, each balancing its transverse momentum.

After this excursion to collider energy, we may now "go back to rest", to mention the EMC effect³⁸. The ratio of the structure functions (F_2) measured in iron and in deuterium, through the analysis of deep inelastic muon scattering, shows an excess at low X and a depletion at high X in the heavier case (iron) (Fig. 10a). This effect was later confirmed in the study of deep inelastic electron scattering at SLAC³⁸ (Fig. 10b). This clearly shows that, when probed at the quark level, a nucleus is not simply an assembly of nucleons, as if quarks were more free to wander around and interact inside a nucleus; a hint at some deconfinement when the quark density has a reasonable value³⁹. While it is too early to draw any conclusions, this makes it all the more interesting to look for a new state of matter, as expected to occur at high quark density and (or) high temperature.

FIGURE 8
Hadronic jets at high p_T at collider energy: a) angular (θ, ϕ) distribution of transverse energy in large E_T events, as now routinely observed by UA1 and UA2; b) jet yields at ISR and collider energy and predictions from QCD³⁵.

(a)

(b)

FIGURE 9
A four-jet event (as observed by UA1): a) single and double parton scattering;
b) angular distribution of the transverse energy.

FIGURE 10

The EMC effect (European Muon Collaboration):

- a) Ratio of $F_2(X)$ in iron and deuterium, as determined in deep inelastic muon scattering at CERN, Ref. 33);
- b) Ratio of $F_2(X)$ in iron and deuterium, as determined in deep inelastic electron scattering at SLAC, Ref. 38).

We shall conclude this data sampling here. Most of these results are rather new (Figs. 2b, 3b, 4, 5a, 6, 7b, 8, 9 and 10), and were not known at the time of the Bielefeld Workshop. They provide strong encouragement in our quest for evidence of a new form of matter. They are also a strong motivation for heavy ion collisions in an energy range which would bring us close to present collider energy.

4. THE PHASE STRUCTURE OF QCD

We now turn to theoretical developments, with a brief survey of gauge theory calculation on the lattice, which provides the best evidence at present for the actual occurrence of a phase transition. The technique is now well known¹². The partition function reads

$$Z = \text{tr} \{ \exp^{-\beta H} \} \quad (4.1)$$

where $\beta = 1/T$. It is expressed in terms of a functional integral over the Lagrange density $\mathcal{L}$ which is periodic in (Euclidean) time with period $\beta = 1/T$:

$$Z(\beta, V) = \int [dA] \exp \int_0^\beta d\tau \int_V d^3x \mathcal{L}(A(\vec{x}, \tau)) \quad (4.2)$$

It is calculated on a lattice by Monte Carlo techniques⁴⁰. Results already obtained at the time of the Bielefeld Workshop for the pure SU(2) Yang-Mills case are displayed in Fig. 11. The energy density divided by T^4 shows a neat transition (now known to be a second-order one) as glueballs "thaw" into free gluons. The temperature is measured in terms of a quantity Λ_L which relates the effective coupling constant to the lattice spacing in the scaling limit. The specific heat divided by T^3 shows a peak associated with the sharp rise of the energy density. While the location of the transition is well determined in terms of T/Λ_L , the determination of Λ_L from the calculation of a physical quantity, such as the string tension (expressed as the long-distance force between static quarks), is at present much less precise. Nevertheless, one may say that the transition occurs at a temperature T_c of the order of 200 MeV. The SU(2) case long served as a test case in view of the relatively precise Monte Carlo calculations which were first able to be done in this (relatively simple) case.

Over the past year, expectations that a similar behaviour would hold for SU(3) Yang-Mills, with, in this case, a first-order transition¹², have been confirmed⁴¹ with a precise determination of T/Λ_L . The same applies when quarks are added in the quenched approximation, where one takes into account the action of the gauge field on the quarks but not the action of the quarks on the gauge field, thus neglecting quark loops also! The latent heat is, however, much increased as many more degrees of freedom are thawed (or frozen) during the phase transition. The overall behaviour of Σ/T^4 as a function of T/Λ_L is shown in Fig. 11¹².

Adding quarks leads one to consider the question of chiral symmetry restoration¹³. In the quark gluon plasma phase, quarks have only their (ultra-violet) small mass. They may lose their effective mass through the phase transition deconfining colour, but this may appear in two stages, with, as an intermediate step, quark-antiquark condensates remaining and providing for a spontaneous breaking of chiral symmetry which is restored only through the thawing of the condensates¹³. This could occur at a higher temperature (T_{ch}) than T_c . The present status of gauge theory calculation on the lattice will be the object of thorough discussions at this Conference. This is reviewed by J. Kogut⁰. More generally speaking, the lattice gauge theory approach to quantum chromodynamics has recently been presented in great detail in three thorough review articles⁴⁰. I merely itemize here some further important steps which took place recently, and were not discussed in any depth a year ago^{6,12}.

FIGURE 11
Phase transition in a pure SU(2) Yang-Mills theory; Ref. 12)
and references therein:
a) ratio of the energy density and the Stefan-Boltzmann limit
as a function of temperature;
b) the specific heat divided by T^3 as a function of temperature.

On the more formal side⁴², one finds that the deconfining condition in a gauge theory with symmetry $SU(N)$ corresponds to the breaking of a global $Z(N)$ symmetry [the centre of $SU(N)$], present even after gauge fixing. Under such a transformation, the gluon Lagrange density remains unchanged, but the quark action is modified. Breaking of this extra symmetry corresponds to deconfinement with a change in the free energy of a single static quark, which is related to the order parameter⁴³. The deconfining phase transition of the gauge theory belongs actually to the same universality class as that of a three-dimensional spin model with global symmetry $Z(N)$ ⁴⁴. The phase transition in $SU(2)$ is thus second order, and the phase transition in $SU(3)$ is then definitely first order.

While this may be considered as very good news, it appears that the presence of quarks creates a symmetry breaking effect which, in the spin system analogue, would correspond to an external magnetic field⁴⁵. The smaller the mass of the quark, the stronger is the effect, and one may be afraid that the symmetry would be lost anyway, and that the phase transition associated with its spontaneous breaking would disappear. The transition between hadron matter and a quark gluon plasma would thus not be as sharp as Fig. 12 would suggest, but would occur in a gradual way. The same predicament appears in simplified model studies^{46,47}, and $SU(3)$ pure gauge theory could thus have a first-order phase transition which would disappear when light quarks are considered, as they should be in any realistic approach. It also appears in present lattice gauge calculation as soon as $m_q < 4 T_c$, T_c being defined for infinite quark mass⁴⁷.

At present, one may say that the evidence for a first-order transition in $SU(3)$ Yang-Mills theory is well established, and that T/Λ_c is well determined, even if the value of Λ_c in terms of physical quantities is still not very precise. This is encouraging insofar as the expected values of the critical temperatures T_c and T_{ch} (chiral symmetry restoration) are within the range previously considered as accessible in heavy ion collisions. There remains, however, the puzzling fact that light quarks may spoil this sharp phenomenon; yet the role of the finite size of the lattice in actually contributing to this difficulty remains to be seen more clearly. One should also note that the hopping parameter expansion used (the hopping parameter is the lattice version of the coupling of the quark to the gauge field) becomes very ambiguous for low quark mass. It is therefore a mixture of good news when exploring the prospects of high-energy heavy ion collisions, but also of challenging questions for thorough discussion at this Conference, and more work later.

In any case, it is the nature of the phase transition which is open, whether it remains of first order as in the case of the Yang-Mills sector, turns to second order, or smooths itself away as a liquid gas transition beyond the

critical point; it is not the existence of two distinct phases reached in the limits of low and high energy density respectively.

FIGURE 12

Phase transition in $SU(3)$. A sketch of the energy density divided by T^4 as a function of temperature in the pure Yang-Mills case (lower curve) and adding quarks in the quenched approximation (upper curve). First-order transition (in this case) would correspond to a large latent heat, Ref. 12. Hypothetical Monte Carlo result.

5. CONCLUDING REMARKS

The question of quark matter formation in heavy ion collisions has been very much alive since the Bielefeld Workshop, which provided a thorough status report a little over a year ago.

One does expect, from our present understanding of quantum chromodynamics, that hadronic matter as known at low temperature and nuclear density should transform itself into a quark-gluon plasma at high temperature or at high density, where colour would no longer be confined over the volume in which the special conditions would prevail, and where chiral symmetry would be restored, quarks losing their constituent (effective) mass. The conditions considered are such that they should be reached in heavy ion collision, provided that high enough energy is used [that corresponding typically to the SPS (Fermilab) in a fixed target mode or to the CERN-ISR in a collider mode]. The question of

experimental observation was much debated during the Bielefeld Workshop⁴⁸, and will be further discussed at this Conference. On the other hand, recent CERN collider data and cosmic ray data provide a strong incentive for considering heavy ion collisions at much higher energy. In any case, the time is ripe for a successful interplay between theoretical studies and experimentation, a crucial point being the analysis and the understanding of fluctuations in particle density.

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REFERENCES

- 0) "Quark Matter '83", eds. T. Ludlam and H. Wegner, Nucl. Phys. A, to be published.
- 1) For a detailed presentation of perturbative quantum chromodynamics, see: Perturbative Quantum Chromodynamics, Physics Reports reprint Vol. 5, (North-Holland, Amsterdam, 1983).
- 2) For a general survey of these questions, see: Non-linear and Collective Phenomena in Quantum Physics, Physics Reports reprint Volume, eds. J.L. Gervais and M. Jacob (WSPC, Singapore, 1983).
- 3) E.V. Shuryak, Phys. Reports 61 (1980) No. 2.
- 4) See, for instance: Proceedings of the 5th High Energy Heavy Ion Study, Berkeley 1981 (LBL 12652).
- 5) It seems reasonable to expect that oxygen ions could be accelerated up to 200 GeV/nucleon in the CERN SPS by 1985-86. The ion source is presently being built. See H. Haseroth in Ref. 6).
- 6) Quark Matter Formation and Heavy Ion Collisions, Proceedings of the Bielefeld Workshop 1982, eds. M. Jacob and H. Satz (WSPC, Singapore, 1983); One may also consult: Phys. Reports 88 (1982) No. 4, eds. M. Jacob and J. Tran Thanh Van.
- 7) See, for instance: 3rd Topical Workshop on $p\bar{p}$ Collider Physics, Rome 1983, eds. G. Bacci and G. Salvini; CERN report 83-04.
- 8) M. Jacob, Collider Physics, Present and Prospects, SLAC Topical Conference 1983.

- 9) The fragmentation region is the region of phase space close to the incident hadrons, within 2 units of rapidity, say. In between the two fragmentation regions, one has the central region extending over two units of rapidity for an incident energy of 200 GeV/nucleon. For a definition of the kinematical variables relevant to particle production in high-energy collisions, see:
D. Horn, Phys. Reports 4 (1972) 1, and L. Foa, Phys. Reports 22 (1975) No. 1.
- 10) For the 1982 estimates of the energy density, see:
L. McLerran, in Ref. 6);
R. Anishetty, P. Koehler and L. McLerran, Phys. Rev. D22 (1980) 2793.
- 11) J.D. Björken, Highly Relativistic Nucleus-Nucleus Collisions: the Central Region, FNAL-PUB-82-44 THY (1982);
K. Kajantie, in Ref. 6).
- 12) H. Satz, New States of Matter, International Conference on Nucleus-Nucleus Collisions, Michigan State University, 1982.
- 13) G. Baym, in Ref. 6).
- 14) J. Rafelski and B. Müller, Phys. Rev. Lett. 48 (1982) 1066;
T. Biro and J. Zimanyi, Phys. Lett. 113B (1982) 6.
- 15) K. Kajantie, R. Raitio and V. Ruuskanen, Nucl. Phys. B152 (1983) 222;
K. Kajantie and R. Raitio, Phys. Lett. 121B (1983) 415.
- 16) M. Gyulassy and A. Matsui, preprint LBL-15947 (1983).
- 17) I am very grateful to L. McLerran for information on that point.
- 18) L. Van Hove, CERN preprint TH.3592 (1983);
M. Gyulassy, K. Kajantie and L. McLerran, preprint LBL-16277 (1983).
- 19) M. Jacob, A Comparison Between $\alpha\alpha$ and pp Interactions at ISR Energy, 5th High Energy Heavy Ion Study, Berkeley 1981, ed. L. Schroeder, LBL-12652;
M. Faessler, Phys. Reports, in preparation;
M. Jacob, ISR Physics Present and Prospects, Topical Conference on Forward Collider Physics, Madison 1981, in: AIP Conference Proceedings No. 85 (1982).
- 20) Experimental results presented in Section 3 are referred to according to CERN experiment number. The Grey Book, "Experiments at CERN in 1982", should provide the reader with any needed piece of information.
- 21) J. Cronin et al., Phys. Rev. D11 (1975) 3105;
D. Antreasyan et al., Phys. Rev. D19 (1979) 764.
- 22) P.M. Fishbane et al., Phys. Rev. D16 (1977) 122;
D. Treleani and G. Wilk, Nuovo Cimento 60A (1980) 201.
- 23) M. Faessler, Presentation to the CERN-ISRC (September 1983).
- 24) T.H. Burnett et al., Phys. Rev. Lett. 50 (1983) 2062;
The JACEE Collaboration, in: Proceedings of the International Cosmic Ray Conference, Bangalore 1983, (HE3-33).
- 25) A. Białas and W. Czyz, Workshop on Future Relativistic Heavy Ion Experiments, GSI Darmstadt, 1980.

- 26) UA5 Collaboration, K. Alpgard et al., Phys. Lett. 107B (1981) 315;
UA1 Collaboration, G. Arnison et al., Phys. Lett. 123B (1983) 103.
- 27) For a survey of large cross-section phenomena at the collider, see:
Proceedings of the 3rd $p\bar{p}$ Collider Workshop, Rome 1983, eds. C. Bacci and
G. Salvini; CERN report 83-04 (1983);
M. Jacob, in: Proceedings of the SLAC Topical Conference, 1983; CERN preprint
TH.3693 (1983).
- 28) J. Rushbrooke, Contribution to the Berkeley Workshop (1983), UA5.
- 29) C. Lattes, Y. Fujimoto and S. Hasegawa, Phys. Reports 65 (1980) No. 2.
- 30) UA1 Collaboration, G. Arnison et al., Phys. Lett. 118B (1982) 167.
- 31) A. Breakstone, Contribution to the International Conference on High Energy
Physics, Brighton 1983, R420.
- 32) R. Horgan and M. Jacob, Physics at Collider Energy, CERN School of Physics
1980, CERN report 81-04 (1981).
- 33) M. Jacob and P.V. Landshoff, Phys. Reports 48 (1978) No. 4;
P. Darriulat, Ann. Rev. Nucl. Part. Sci. 30 (1980) 159; Physica Scripta 19
(1979), eds. K. Hansen and P. Hoyer.
- 34) UA2 Collaboration, M. Banner et al., Phys. Lett. 118B (1982) 203, and
P. Bagnaia et al., CERN report EP-83-94 (1983);
UA1, G. Arnison et al., Phys. Lett. 123B (1983) 115, and
J. Saas, Rome Workshop, op. cit in Ref. 27).
- 35) T. Akeson et al., CERN report Ep-83-130 (1983), R807.
- 36) R. Horgan and M. Jacob, Nucl. Phys. B179 (1981) 441.
- 37) R. Field, La Jolla Summer Institute, 1978; AIP Conference Proceedings No. 53
(1979).
- 38) J.J. Aubert et al., Phys. Lett. 123B (1983) 275;
A. Bodek et al., Phys. Rev. Lett. 50 (1983) 1431.
- 39) We would thus take the attitude that some percolation among nucleons takes
place, as discussed for instance by G. Baym, Physica 96A (1979) 131, and not
that one observes quarks trapped on pionic degrees of freedom, as discussed
by C.H. Llewellyn Smith, to be published, and by M. Ericson and
A. Thomas, CERN preprint TH. 3553 (1983). At present, the situation is
certainly not settled. The subject is reviewed by J. Vary in Ref. 0).
- 40) M. Creutz, L. Jacobs and C. Rebbi, Phys. Reports 95 (1983) No. 4;
J. Kogut, Rev. Mod. Phys. 55 (1983) 775;
J.-M. Drouffe and B. Zuber, Phys. Reports, in print.
- 41) T. Celik, J. Engels and H. Satz, preprints BI-TP 83/04 and BI-TP 83/07;
J. Kogut, H. Matsuoka, M. Stone, A.W. Wyld, S. Shenker, J. Shigemitsu and
D.K. Sinclair, preprint ILL-TH-83/9 (1983).
- 42) I should like to thank P. Hasenfratz for a very informative discussion on
this question.

- 43) L. McLerran and B. Svetisky, Phys. Rev. D24 (1983) 450; Phys. Lett. B98 (1980) 195;
J. Kuti, K. Szlachanyi and J. Polonyi, Phys. Lett. B98 (1980) 199.
- 44) J. Polonyi and K. Szlachanyi, Phys. Lett. 110B (1982) 395;
L.G. Jaffe and B. Svetisky, Phys. Rev. D26 (1982) 903; Nucl. Phys. B210 (1982) 423.
- 45) T. Banks and A. Ukawa, Tokyo preprint INS 465 (1983).
- 46) T. DeGrand and C. DeTar, preprint COLO-HEP 66 (1983).
- 47) P. Hasenfratz, F. Karsch and I.O. Stamatescu, CERN preprint TH.3636 (1983);
T. Celik et al., preprint BI-TP 83/15 (1983).
- 48) Reports of the specialized working groups at the Bielefeld Workshop, in Ref. 6).