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RELATIVISTIC HEAVY ION COLLISIONS - IN SEARCH OF THE
QUARK-GLUON PLASMA *)

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ABSTRACT

According to quantum chromodynamics, colour should no longer be confined within hadrons at high enough temperature and/or quark density. Conditions for this to occur are such that there is a good hope of reaching them in heavy ion collisions, when the incident energy is of the order of a few hundreds of GeV per nucleon. CERN had an exploratory programme with oxygen ions in 1986 and sulphur ions in 1987, and there is much interest in new developments which could lead to a lead beam in the early Nineties. There is also an important ion programme going on at BNL.

Present results are reviewed. All the information which will eventually come from the two past runs at CERN is not yet available in view of the complexity of the final states. High enough energy densities seem to have been reached. One predicted signal has been observed and it has resisted so far many attacks trying to interpret it through standard means. They continue.

This is a general review, written for non-specialist readers.

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1 - IN SEARCH OF THE QUARK-GLUON PLASMA

Nuclear physicists have long searched for a new state of nuclear matter, a state which speculatively could have been reached at high enough density, once the influence of the short-range repulsive core, which so greatly limits the compressability of nuclear matter, had been overcome. Despite extensive searches nothing of this type has been observed but, in the framework of quantum chromodynamics (QCD) /1/, we now understand why. QCD tells us what this new state of matter should be: a plasma of quarks and gluons, within which colour would flow freely instead of being confined to hadronic dimensions corresponding to distances of the order of 10^{-15} m, as is the case under normal conditions. QCD also tells us about the conditions required to reach such a state, which should appear at high enough temperature and/or high enough quark density. One is talking about temperatures in excess of 200 MeV ($\sim 10^{10}$ K) at low quark density, and about densities in excess of five times the nucleon density (which is 0.15 GeV/fm^3) at low temperature. While such conditions could be reached in heavy ion collisions with incident energies of the order of a few hundred GeV per nucleon, such incident energies are a hundred times larger than those which were available for previous investigations at the Bevalac, Saturne II and Dubna. One thus understands why no sign of such a new state of matter has been spotted during past investigations.

At CERN, the old Linac (LINAC I) has been equipped with an ion source /2/, and fully-stripped ions (oxygen in 1986 and sulphur in 1987) could be accelerated through the PS-SPS complex up to 200 GeV/nucleon. The use of the old Linac does not allow the acceleration of heavier ions. However, the construction of a new injection system would make it possible to go up to lead with a similar energy per nucleon. This is being seriously considered. It would be possible to achieve this in the early Nineties, but funds still have to be appropriated /3/.

The 1986 oxygen run gave data at 60 GeV/A and 200 GeV/A to four major experiments and several emulsion experiments. The major experiments used sophisticated detectors built to a very large extent out of recycled equipment previously used in experiments at CERN and at the Bevalac, mainly. The 1987 200 GeV/A sulphur run gave data to six major experiments. These experiments are briefly presented in Appendix A /4/.

At Brookhaven, the AGS, in association with a preaccelerator complex for heavy ions, has also been used in a programme which now involves two major experiments with a third one under construction. The energy is lower (14.5 GeV/A), but the hope is to compensate for lower energies by the high quark density resulting from full stopping, thus also reaching the required conditions. Silicon ions have been accelerated and gold ions should be available by 1991-1992 /5/. At such energies the stopping power in head-on collisions is practically full, whereas it is at most of the order of 50% at 200 GeV/A. These experiments are also briefly presented in Appendix A.

At present, the CERN programme involves about 400 physicists and the Brookhaven one about 150 physicists /4/.

What motivates such a great deal of enthusiasm is, of course, the hope of finding evidence for a hitherto unknown state of matter and of studying some of its properties. Predictions from QCD, though not yet very precise, are specific enough to justify the present hope. This is also a question of general interest. Our Universe should indeed have gone through a quark-plasma phase up to 10^{-5} s after the Big Bang, and this has important consequences for our views about baryon genesis in the early Universe, about the relative abundance of the light elements, and also about the overall baryon density in our present Universe. A short introduction to these questions can be found in Appendix B.

The experimental effort of the past four years has already paid some important dividends /6/. There is now evidence that the stopping power is as high as one could hope for at 200 GeV/nucleon, and high enough to yield energy densities of the magnitude required (1 to 3 GeV/fm³), at least in frequent central collisions /7/. There are some puzzling and striking effects and in particular one: the quenching of J/ψ production in collisions with high multiplicity. This effect has so far denied any explanation other than the formation of a blob of quark-gluon plasma /8,9/, but attacks continue and it is too early to consider the case as settled. The data collected in 1986 and 1987 have not yet yielded all the information which they contain. Analyzing events with 500 particles or so in the final state is a real challenge, in particular when looking for photons, e^+e^- pairs or V's associated with strange particles. The early results, reviewed in this report, are in any case supporting a clear enthusiasm to continue, in particular with a lead beam.

As previously stated, CERN is seriously considering the possibility of accelerating lead ions. The necessary work could be completed in 1992, funds permitting. By that time Brookhaven should have a gold beam accelerated in the AGS. The main longer-term project at Brookhaven is, of course, RHIC, a heavy ion collider to be installed in the Isabelle tunnel. The heaviest ions would be accelerated up to 100 GeV/A. If properly funded, RHIC could be operational in the mid-Nineties /5/.

In the more distant future at CERN, if the LHC, a 17 TeV proton-proton collider, is built alongside LEP in the LEP tunnel, it could use lead ions from the source operational at that time. One would have lead-lead collisions with beams of 3.2 TeV/A.

We do not know about physics at high quark-gluon density when the relevant volume justifies a thermodynamical approach. It is a challenge to learn about it. The difficulties speak for themselves. Here we review what has been learned and discuss some of the topical questions which one hopes to answer soon, as new pieces of information become available.

2 - QCD AND THE QUARK-GLUON PLASMA /10/

At present, quantum chromodynamics is a well-established theory which has already had many clear quantitative successes when confronted with data at high momentum transfers (> 10 GeV, say) or, in other words, when probing at very small distances ($< 10^{-17}$ m) /1/. QCD is a gauge theory like QED, but it is based on the non-Abelian SU(3) gauge group instead of the Abelian U(1) gauge symmetry of QED. It is a theory of quarks (of spin $\frac{1}{2}$) and of massless vector fields, the gluons. The gluons are the eight gauge fields of the theory. The gauged quantity is called "colour". Quarks exist in three varieties of colours, while gluons exist in eight and are directly coupled among themselves, unlike photons, which couple only through electron loops.

The non-Abelian character of the theory, and the direct coupling among gluons which results from it, lead to asymptotic freedom. The effective coupling constant squared, α_s , the equivalent of the fine structure constant in QED, decreases logarithmically with increasing momentum transfers, whereas the opposite occurs in QED and with a much larger energy scale. QCD can then be used in a perturbative way at large transfers (in practice at distances less than 10^{-17} m) and spectacular successes have been recorded. However, the effective coupling becomes large at small transfers, or when the distance being probed approaches that typical of hadronic size (10^{-15} m). Strong coupling calculations have then to be performed. The workable approach consists of studying the theory on the lattice. Some interesting results have already been obtained, but computer power imposes strong limitations. We do not yet quantitatively understand how quarks become bound into hadrons. Detailed quantitative studies appear to require an extra factor 100 in computer power from what is presently available with the CRAY II generation or dedicated computers of similar power. This increase in computer power is needed to include the effect of light quark loops, so far neglected in the so-called quenched approximation calculations /11/.

The strong coupling character of QCD at large distances ($> 10^{-16}$ m, say) leads to colour confinement. One may say that the direct coupling among gluons, which imposes the rise of α_s at large distance, prevents the colour field from extending into the vacuum. To use an analogy, one may say that the vacuum behaves like a superconductor with respect to the colour field, preventing it from penetration away from colour sources. The situation we meet here is very different from the one which prevails in QED, where the electromagnetic field freely extends into the vacuum with a resulting r^{-1} potential away from a source. This is illustrated by Fig. 1.

Fig. 1: The field configuration between two sources. (a) The QED case, $V(r) \sim r^{-1}$. (b) The QCD case, $V(r) \sim r$.

If one attempts to separate two colour sources (a quark and an antiquark, say, as is the case when giving a strong kick to a meson), the colour field between the two sources is limited to

a thin filament, about 1 fm across. The effective potential is thus linear in r . It costs about 1 GeV/fm to pull the two sources apart. When one insists and keeps giving bigger kicks, as happens when quarks are shot aside in very high energy collisions like those studied at the CERN $p\bar{p}$ collider, nothing prevents the energy thus stored in the colour flux tubes dragged by each individual colour source from materializing into π mesons with mass energy of only 0.14 GeV. Instead of eventually obtaining a quark-antiquark pair, one obtains a string of π mesons. If a quark were to be given a huge momentum kick, the π mesons would come out in a jet in the direction of the kick, each pion taking a certain fraction of the momentum first given to the quark or the gluon. This is called a hadronic jet.

Such hadronic jets have already been well studied at the CERN $p\bar{p}$ collider /12/. Figure 2 shows some of the now famous lego plots giving the angular distribution of the transverse energy observed in a $p\bar{p}$ collision.

Fig. 2: Jets in hadronic collisions. (a) Two-jet system. (b) Three-jet system.

These spectacular jets correspond to quarks, antiquarks and gluons (partons) which are shot aside during the two-body collisions. These scattered partons may carry a good fraction of the energy of the incident hadron to which they belonged. One then clearly "sees" the primordial collision at the quark-gluon level. This is the Rutherford experiment of the present decade, relevant to hadron structure at distances smaller than 10^{-17} m. The experimental results are in beautiful agreement with predictions from QCD /1,12/. Figure 1a shows a two-jet system resulting from the hard collision of two partons (quarks, antiquarks or gluons). Figure 1b shows a three-jet system obtained when an extra hard gluon has also been radiated during the collision. The probability of seeing three well-separated jets is lower by a factor α_s (at the 10% level, say).

The annihilation of an electron-positron pair at high energy also leads to a quark-antiquark system in the final state, which appears as a two-jet system. Indeed, e^+e^- collider physics also contributed a great deal to our present knowledge about jets /13/. Jets will be the typical final state at LEP.

This is physics at short distances ($< 10^{-17}$ m), where QCD can be used in a perturbative way. At larger distances the colour force becomes strong and binds quarks into hadrons. The hadrons which we know are indeed the simplest quark systems (three quarks for a baryon and a quark-antiquark pair for a meson) which are globally neutral under colour. Hadrons can therefore freely propagate through the vacuum.

At present, we can parametrize the colour potential rather simply. At small distances it has the Coulombic r^{-1} form, up to logarithmic terms. At large distances it eventually increases linearly with r . Such a potential binds a quark-antiquark pair and provides a meaningful approach to heavy quark systems (c quarks with $m_c \sim 1.5$ GeV, b quarks with $m_b \sim 5$ GeV), since they remain non-relativistic in the solution of the Schrödinger equation. One can thus calculate the position of a series of levels for quarkonium (a bound system of a quark and an antiquark). This applies very well to the $c\bar{c}$ charmonium states (J/ψ family) and to the $b\bar{b}$ bottomonium states (T family), which are simply the quark cousins of positronium in QED. Here also agreement with experiment is quite spectacular /13/. This is the "hydrogen atom" problem of QCD.

We have thus described the binding of a quark-antiquark pair in the vacuum. A heavy quark-antiquark pair orbits non-relativistically in the QCD potential with prescribed energy levels. For light quarks ($\pi, \rho, f, \dots$) we cannot calculate accurately yet, but the physics should be the same. Let us now study the system in a medium which is dense with colour sources. In much the same way as in QED, the potential will be screened at large distances. Instead of increasing as r (QCD) or decreasing to zero as r^{-1} (QED), it will decrease exponentially to zero with a scale corresponding to the Debye radius. The quark-antiquark system may then cease to be bound. Particles cannot form in a dense quark-gluon plasma. At high enough density, hadrons should thus melt into a quark-gluon plasma phase.

The same occurs at high temperatures. A high temperature implies a high gluon density (and, to a lesser extent, a high quark-antiquark density) and therefore a strong colour screening. The density increases according to the Stefan-Boltzmann law $\epsilon \sim T^4$. Hadrons should therefore also melt into a quark-gluon plasma at high enough temperature.

One may also look at such a process from the field configurations of Fig. 1. As the temperature increases, field configurations extending away into the vacuum are no longer strongly suppressed by the low Boltzmann factor which applies at low temperature. The field eventually freely extends into the vacuum. The potential changes from its r behaviour to a r^{-1} behaviour. Since gluons carry colour, screening eventually imposes an even sharper fall-off at large distances.

These heuristic considerations, which lead us to expect that at high enough temperature and/or high enough quark density the hadron phase disappears to be replaced by a quark-gluon plasma phase, are supported by QCD calculations on the lattice [11]. So far calculations have been possible only for low quark density (zero chemical potential). The deconfinement temperature is of the order of 200 MeV, and in a pure gauge SU(3) theory (with no quark), one has a first-order transition. Combining these results with phenomenological considerations based on the bag model, one can draw the phase diagram of Fig. 3, on which one has placed two trajectories.

Fig. 3: QCD phase diagram. Separation of a hadron gas from a quark-gluon plasma. The two trajectories correspond to heavy ion collisions (I) and the early Universe (II) respectively. The fuzzy zone stands for a possible separate phase transition with chiral symmetry breaking.

The first one corresponds to what should happen during a heavy ion collision at high energy. One starts with a system with a nuclear quark density at zero temperature. The system is compressed, heated, and turns into a quark-gluon plasma phase. It eventually hadronizes as it expands and cools down.

The second one corresponds to what should have happened in the early Universe $\sim 10^{-5}$ s after the Big Bang. The early Universe at very low quark density (as compared to nuclear matter!) but very high temperatures goes through a phase transition and hadronizes.

The phase diagram is separated into two zones by a still grey area. This has to do with the fact that one may have actually two successive transitions. As the temperature (density) increases, all hadrons may melt but for $q\bar{q}$ bound states, which act as Goldstone bosons and

provide the quarks with an effective mass. This corresponds to a breaking of chiral symmetry. It may happen before the actual quark-gluon plasma is formed and chiral symmetry restored. Calculations on the lattice indicate that at low quark density (where they have been made), the two transitions appear to occur at the same time /11/. This could, however, not be the case for a cold system at high quark density. The two transitions could succeed each other.

There is a big difference in energy density between the two phases, since many degrees of freedom are frozen when quarks, antiquarks and gluons hadronize. For a hadron gas $\epsilon = \pi^2/10T^4$ whereas for a quark-gluon plasma $\epsilon = 37\pi^2/30T^4$. There is a factor 12 between the two. If the transition is first order, this implies a very large latent heat. The transition may, however, be more gradual. In any case, reaching the quark-gluon plasma phase implies very large energy densities, in excess of 2 GeV/fm^3 .

3 - THE SIGNATURES LOOKED FOR

The existence of a quark-gluon plasma at high enough temperature and/or quark density is a very important question in QCD. It is a question about which precise predictions cannot yet be made from the theory because of the very severe computational difficulties which are encountered. Yet it appears that conditions for its formation could be met if a large enough fraction of the incident energy available in a heavy ion collision at high energy is properly used. Hints from experiment then become all the more interesting. As we have previously said, the existence of a quark-gluon plasma is also very interesting in astrophysics and cosmology. This could be the central core of neutron stars, affecting their cooling behaviour. This should have been the state of the early Universe up to 10^{-5} s after the Big Bang, with important consequences for hadron formation (Appendix B).

By 1982, at the Bielefeld meeting /1/ which brought together about 150 high-energy and nuclear physicists, theorists and experimentalists, it was realized that medium-size ions, accelerated up to 200 GeV/A in the CERN PS-SPS complex, could already provide interesting enough initial state conditions. It was also realized, and this was also extremely important, that the typical final state conditions, with 500 or so particles produced, could be manageable. This was the initial spark. The original enthusiasm was supported by discussions at "Quark Matter '83" at Brookhaven, "Quark Matter '84" in Helsinki and "Quark Matter '85" in Asilomar. By the time of "Quark Matter '87" at Nordkirchen, the first data were available.

Obtaining evidence for the formation of a quark-gluon plasma is not an easy task. The plasma blows itself out almost as fast as it is formed, and the most that one can hope to see is the remains of its very short appearance. It reminds one of the smile on the face of the Cheshire cat in "Alice in Wonderland" - only the smile remains after the cat is gone. Hadronization occurs much, much faster than in the early Universe. It is as if the Hubble constant were 10^{17} times what it was 10^{-5} s after the Big Bang.

Yet there are some promising signatures which may be likened to the cat's grin.

i) Anomalous distribution

One may see very anomalous distributions of particle density dN/dy and of transverse energy density dE_T/dy . The quantity y is here the rapidity $y = \frac{1}{2} \ln ((E+P_L)/(E-P_L))$, where E and P_L are the particle energy and longitudinal momentum respectively. A blob of quark-gluon plasma, produced most likely at small centre-of-mass rapidity, could release its latent heat with a sizeable entropy increase. This would give an anomalously large particle density or particles at such rapidity with anomalously large transverse energy. Nothing like that has been seen so far, but one has mainly looked at pions in the final state, where pions are great averagers.

ii) Anomalous formation zone

One may see peculiar effects in hadron interferometry. This is a generalization of the Hanbury-Brown-Twiss effect well known in star interferometry. It allows one to measure the size of a source which cannot be resolved by optical means. Applied to equal-sign pions (π^- in practice), this already provides a measurement of the size of the blob of matter from which the eventually observed pions originated, as it was at the time when the pions ceased to interact (freeze out). As discussed later, a peculiar effect has been found (NA35) with a source 8 fm across. This is very interesting, but cannot yet lead to any definite conclusion as far as the formation of a quark-gluon plasma is concerned.

Fig. 6: The prominent rôle of geometry.

(d) $d\sigma/dE_{ZDC}$ as a function of E_{ZDC} , the energy deposited in the zero degree (forward) calorimeter for oxygen collisions with carbon, copper, silver and gold nuclei (WA80).

There is a very good correlation between the amount of transverse energy collected by the detector surveying the central region and the amount of energy collected by the forward calorimeter. The larger the former, the smaller the latter is, and vice versa. This is shown in Fig. 6e (NA35) with a strong, clear correlation.

Fig. 6: The prominent rôle of geometry.

(e) Relation between E_T and E_{ZDC} for the detectors of NA35, for oxygen collisions with gold nuclei.

The observation of a large amount of transverse energy is associated with that of a large multiplicity. Each secondary carries on average roughly the same amount of transverse energy, whatever the global transverse energy is. This is shown in Figs. 7a (NA34) and 7b (WA80, NA34). There is no sign of "hotter" pions at large E_T . All the collisions, even the most violent ones, thus look to a first and good approximation like superpositions of nucleus-nucleus collisions.

a)

b)

Fig. 7: The transverse energy of the secondaries.

(a) The mean transverse energy per charged particle as a function of the global transverse energy (NA34).

(b) Relation between the charged multiplicity and the transverse energy for oxygen collisions with tungsten nuclei (WA80, NA34).

One also sees that these violent collisions, with large excitation energies, can be just as well triggered either by selecting events with large transverse energy, events with low forward energy, or again events with high multiplicity. The three selection triggers play identical rôles - this is very useful to know.

During these collisions the target nucleus is completely shattered. Its nucleons all fly apart, though with relatively modest transverse energy. On the one hand, one has the deposition of a large amount of excitation energy, and on the other, a complete destruction of the target. This is illustrated by Fig. 8a which shows the observed rapidity distribution for the baryons (WA80) together with the result of a calculation which neglects the spectator nucleons. There is a big discrepancy in the target fragmentation region. Figure 8b (WA80) shows the rapidity distribution of baryons for 200 GeV/A oxygen collisions with carbon, copper, silver and gold nuclei, and the same for proton-nucleus interactions at the same

energy. For gold, the number of shattered nucleons in the target fragmentation region increases by a factor ten between proton- and oxygen-induced reactions. One sees about 100 shattered nucleons.

Fig. 8: The shattering of the target nucleus.

(a) Pseudorapidity distribution of the baryons as observed in the fragmentation region (acceptance cut) and as calculated neglecting spectator nucleons, oxygen on gold (WA80).
(b) Pseudorapidity distribution of the baryons in oxygen and proton collisions on carbon, copper, silver and gold nuclei (WA80).

One may conclude at this stage that there is a lot of excitation energy in such collisions, in particular in the rather frequent central ones. Is the energy density high enough?

In order to estimate it, one often uses a method proposed by Björken, considering a slab of matter with cross-section πR^2 , R being the radius of the projectile, and of width d , a time τ_0 after collision. The rapidity distribution within this slab is therefore $\Delta y = d/\tau_0$. An energy density ϵ corresponds to a global excitation energy of $\epsilon \pi R^2 d$ for the slab. One may say that R is both the radius of the incident nucleus and that of the hole bored in the target nucleus, which is in practice larger. The excitation energy eventually results in Δn particles with mean transverse energy $\langle E_T \rangle$ seen within Δy . One therefore writes

$$\epsilon = \frac{\Delta n}{\Delta y} \langle E_T \rangle \frac{1}{\pi R^2 \tau_0}$$

All quantities are known except for τ_0 . The value to use is a formation time, which is of the order of 1 fm/c, but which cannot be specified precisely. From the observed value of dn/dy in oxygen-gold collisions, one may say that energy densities of up to 1 to 3 GeV/fm³ can be reached. This seems to be high enough. A similar estimate is derived from hydrodynamical calculations /21/. Studying the expansion of a hot hadronic pion-nucleon gas, with energy eventually given to the particles escaping its surface, one reaches similar conclusions.

One may conclude at this stage that:

- a) Oxygen collisions at 200 GeV/A on heavy targets lead to a large excitation energy in the centre of mass, which results in a good approximation to that expected from the mere superposition of the nucleon-nucleus collisions which take place.
- b) The estimate of the energy density which one can derive from the experimental results should be high enough to lead to the formation of a blob of quark-gluon plasma.

ii) The hadronization process

Granting the fact that a blob with very high energy density is formed, one so far only sees the numerous pions which take away most of that energy in the aftermath of the collision. There are so many pions produced that one can make $\pi^+\pi^-$ interferometry, thus generalizing the Hambury-Brown-Twiss method in order to measure the size of the blob at freeze-out time, when the pions cease to interact among themselves as the blob expands /22/. The momentum correlation between a pair of pions, with centre-of-mass momentum components Q_T and Q_L is expressed as:

$$C(Q_L, Q_T) = 1 + \lambda e^{-\frac{Q_T^2 R_T^2}{2}} e^{-\frac{Q_L^2 Q_T^2}{2}}$$

where R_L and R_T are the longitudinal and transverse radii of the blob at freeze-out time and λ a coherence parameter ($\lambda = 1$ for a fully chaotic system). Figure 9a shows the $\pi^+\pi^-$ Q_T correlation measured by NA35 separating the fragmentation region ($1 < y < 2$) from the central region ($2 < y < 3$) and also the lack of correlations expected in a hadronization model (FRITIOF), treating independently the different nucleon-nucleon collisions. In the fragmentation region NA35 find $R_T = 4.3 \pm 0.6$ f, $R_L = 2.6 \pm 0.6$ f and $\lambda = 0.34 \pm 0.08$, whereas in the central region they find $R_T = 8.1 \pm 1.6$, $R_L = 5.6 \pm 1.0$ and $\lambda = 0.77 \pm 0.19$. The transverse momentum distribution of the π^- 's in the central region is also very different from the distribution measured in pp collisions. It shows a concave structure with a rather sharp forward peak.

There is thus evidence for the freeze-out of a pion blob with dimension much larger than the incident oxygen ion (more than twice its size). The sharper p_T distribution can be associated with the extension of the source, much larger than that expected from the superposition of nucleon-nucleon collisions. The concave shape can also be interpreted as resulting from the collective flow within the blob which pushes pions at larger transverse momenta /21/.

There is in any case a new effect. In the central region, hadronization proceeds from some collective excitation. However, this is not yet evidence for the formation of a blob of quark-gluon plasma! One may only say that there is formation of a blob with large energy density (1-3 GeV/fm³) /21/.

The conclusion is clear. Ion collisions lead to a large excitation energy, seen either through the transverse energy flow or through the number of secondaries produced. It mainly affects the central region. Is this transverse energy large or small compared to what could be expected?

Figure 6a (NA35) shows a comparison between the transverse energy distribution in oxygen-lead at 200 GeV/A and the expectations obtained in folding 16 times results on proton-gold interactions at the same energy. The relative weights of the different terms are calculated according to geometry (impact parameters). One sees that the maximum transverse energy observed corresponds to neither less nor more than that expected when all incident nucleons are doing their job. The incident nucleons do not screen one another in any appreciable way.

Fig. 6: The prominent rôle of geometry.

(a) $d\sigma/dE_T$ as a function of E_T for oxygen-lead collisions and the 16-fold convolution of proton-gold collisions (NA35).

(b) $d\sigma/dx$ as a function of $x = E_T/E_T^{\max}$ for oxygen collisions with aluminium, copper, silver and gold nuclei (NA35). Close to 50% of the incident kinetic energy can be transferred to excitation energy, close to 100% at BNL (14.5 GeV/A).

The stopping power is therefore as high as one could expect - it is not full, though. At 200 GeV/A the target does not fully stop the incoming ion. The maximum transverse energy observed corresponds to about a half of what could be obtained if all the incident kinetic energy were to be absorbed. This is shown in Fig. 6b (NA35), which also shows how heavy targets are, as expected, more efficient than lighter ones. Similar studies at BNL, with 14.5 GeV/A incident ions /15/, shows that there the incident ion can be fully stopped. The maximum transverse energy observed corresponds to full absorption of the incident kinetic energy, all of which is good news.

Figure 6c (WA80) shows how well the geometrical picture works. An AA' collision deposits as much transverse energy as a pA' collision when the impact parameter distribution - the geometry - is used to obtain the hit probability. The same calculation gives the amount of energy still observed in the forward direction, not used to excite transverse degrees of freedom. The data, like those shown in Fig. 6d (WA80), agree with expectations. Calculations there are based on the Lund (FRITIOF) model. While one may say that the agreement is not perfect, the main trends and orders of magnitude are very well reproduced. One notices in Fig. 6d that a gold nucleus can almost "stop" an oxygen nucleus, with a sizeable probability for the observation of only a small amount of energy in a forward calorimeter; a carbon nucleus, however, cannot do so and the probability for less than 1000 GeV (the equivalent of five undisturbed nucleons) in the forward calorimeter is zero. One sees the power of geometry. Indeed one can even notice in this way that a tungsten nucleus is not spherical (NA34)!

Fig. 6: The prominent rôle of geometry.
(c) $d\sigma/dE_T$ as a function of E_T for oxygen collisions with carbon, copper, silver and gold nuclei and model calculation (FRITIOF) estimate (WA80).

silver and gold targets. Figure 5b (W80) shows the cross-section as a function of the number of charged particles seen for 200 GeV/A oxygen interactions with carbon, copper, silver and gold targets. In Fig. 5c (NA34) we see how one gains in the accessible range of transverse energy going from oxygen to sulphur (lead target).

Fig. 5: Transverse energy and multiplicity distributions.
 (a) $d\sigma/dE_T$ (barn/GeV) as a function of E_T for oxygen collisions with aluminium, copper, silver and gold nuclei (NA35).
 (b) Multiplicity distribution $d\sigma/dn$ as a function of n (charged) for oxygen collisions with carbon, copper, silver and gold nuclei (W80).
 (c) $d\sigma/dE_T$ (mb/GeV) as a function of E_T for oxygen and sulphur collisions with tungsten nuclei (NA34).

Most of the multiplicity (and of the transverse energy) is seen in the central rapidity region which corresponds, to a good approximation, to the centre of mass in each individual nucleon-nucleon collision. Figure 5d shows the pseudorapidity distribution (η) of the charged multiplicity ($\eta = \frac{1}{2} \ln(P+P_L/P-P_L) \approx \eta$) in oxygen collisions with carbon, copper, silver and gold nuclei (WA80). Such a multiplicity distribution in oxygen emulsion interactions is compared with that for proton emulsion interactions in Fig. 5e.

Fig. 5: Transverse energy and multiplicity distributions.
(d) Pseudorapidity distribution of the multiplicity $dN/d\eta$ as a function of η for oxygen collisions with carbon, copper, silver and gold nuclei (WA80).
(e) Pseudorapidity distribution of the multiplicity for oxygen and proton collisions in emulsions.

iii) Peculiar photon radiation

A quark-gluon plasma should be an intense source of radiation and the photon spectrum should be characteristic of the high temperature reached. One may look at prompt photons or, more reliably in practice, at electron-positron pairs. This is a priori very interesting, but no information is yet available. Experimentally, things are obviously very different; some information should become available.

iv) Strangeness enhancement

If a quark-gluon plasma is formed, one expects that its high temperature (> 200 MeV) should enhance the production of strange quarks /14/. The s/u ratio should be higher than in usual hadronic reactions where the K/π ratio can be related to the Boltzmann factor associated with the Hagedorn temperature, which is of the order of 140 MeV. The plasma contains a high gluon density and the gluons are flavour "blind", fragmenting in $s\bar{s}$ as in $u\bar{u}$ or $d\bar{d}$ pairs. If the plasma is formed at lower temperature but high quark density, the high number of primordial u and d quarks will favour the formation of $s\bar{s}$ pairs, with s quarks on lower levels than that of the $u(d)$ Fermi sea. The plasma is formed in an almost explosive state. The strange quark content is then frozen out of equilibrium as the system expands and cools. The $s, \bar{s}$ quarks are then available for the formation of a relatively large number of strange particles.

At present, results from E802 at Brookhaven (silicon-gold collisions at 14.5 GeV/A) /15/ show a K^+/π^+ ratio of $20 \pm 5\%$ for a muon p_T value of 0.4 GeV/c. This is very interesting, but this alone does not impose the formation of a quark-gluon plasma. Such a K^+ enhancement could also result from a dense pion and nucleon gas in rapid expansion, the produced K^+ 's dropping out of equilibrium. Results on $\bar{\Lambda}$ production would be far more specific /16/. There is no information available yet. It is very difficult to single out Λ 's in very high multiplicity events. Dedicated experiments (WA85 at CERN, E810 at Brookhaven) should eventually give definitive information. Some information should also come from NA35 and NA36 at CERN and E814 at Brookhaven.

v) Resonance Suppression

It has long been realized /1/ that the formation of a quark-gluon plasma has a quenching effect on resonance formation since it suppresses the binding between quarks. This applies most clearly to those resonances which cannot be formed easily through final state interactions among hadrons. Satz and Matsui have pointed out that J/ψ production could provide a particularly clear test /8/ and NA38 later observed a spectacular effect /9/. In collisions with large transverse energy, which are more likely to be associated with the formation of a quark-gluon plasma, the J/ψ signal, as seen in muon pairs, is suppressed by a factor two with respect to the Drell-Yan background, as compared with the situation met in collisions with small transverse energy, where the plasma is not expected to be formed.

The experimental effect is neat and clear. It seems quite difficult to explain it by any other means. Yet a final conclusion still requires many tests and more information about J/ψ production off nuclei. This effect is, of course, the source of much enthusiasm.

vi) New particles

We have considered tests corresponding to effects expected on rather general grounds. Since very high quark densities are achieved, one may, however, look for more exotic features. Of particular interest are hitherto unknown systems which may be formed, since present views do not forbid their existence, and be long-lived enough to be observed.

As we have previously said, all hadrons observed so far correspond to the smallest number of quarks which can be globally neutral under colour. More complicated systems could a priori exist, which could be as penetrating as a hadron and fragment into several baryons. Of special interest are quark systems containing a sizeable number of strange quarks, together with u and d quarks in a single hadron bag. They could then be metastable and even stable, because of the relatively high level of the u - d Fermi sea. Such strangelets /17,18/ would be seen as fragments with an anomalously low Z/A ratio. Under collision they would yield several strange particles; E814 at Brookhaven is looking for them.

It is clear that one would like to see correlations between several of these signatures. We shall come back to each of them as we survey the present results in more detail. As previously stated, more is expected to come out of the past CERN runs as the data analysis progresses. Generally speaking, one may say that it is now clear that the stopping power is at least as high as one could expect it to be and that the final states, despite their very high multiplicities, are manageable experimentally. Figure 4 shows an event observed in the Streamer Chamber of NA35. It is spectacular, but it is obvious that analyzing such events in order to extract detailed information is a real experimental challenge.

NA 35 $^{16}\text{O} + \text{Pb}$ SEPTEMBER 1986

Fig. 4: Heavy ion collision in the Streamer Chamber of NA35.

4 - A SURVEY OF PRESENT RESULTS

At the moment, results are available from experiments WA80, NA34, NA35 and NA38 at CERN /4/ and also from a number of emulsion experiments there /19/. We also have results from E802 at Brookhaven /15/. In this review, no attempt is made to show the most recent data, particularly those obtained with the 1987 sulphur run at CERN. Most of them are available only in a preliminary form anyway, and one should at least wait for "Quark Matter '88" in order to draw definite conclusions /20/. We prefer to use recent but published data in order to illustrate all the key questions. A very extensive and convenient compilation of these data is found in "Quark Matter '87" /6/. We shall give the relevant experimental number for each set of data presented, using Ref. /6/ as a master reference. At present one may say that the newer sulphur results have basically consolidated the former oxygen ones.

1) Excitation energy, multiplicity and energy density

The aim is to transform as much as possible of the incident kinetic energy into excitation energy. This excitation energy results in transverse energy E_T (the energy flow perpendicular to the incident direction) and in particles (mainly pions) being produced, with multiplicity n .

It is clear that the heavier the colliding ions, the larger the transverse energy and the larger the multiplicity. This is shown in Fig. 5. Figure 5a (NA35) shows the differential cross-section with respect to E_T for 200 GeV/A oxygen ions incident on aluminium, copper,

Fig. 13: The ratio between the J/ψ signal and the Drell-Yan background between high E_T and low E_T collisions as a function of p_T.

(a) On the J/ψ peak.

(b) Ratio between high E_T and low E_T collisions for the Drell-Yan background.

(c) The ratio as a function of p_T and expectation from the formation of a quark-gluon plasma.

The p_T dependence can be interpreted as being due to a widening of the p_T distribution of the J/ψ when produced in nuclear matter. The radiation of the gluons in nuclear matter during the annihilation process could give a wider distribution in large E_T (central) collisions than in the low E_T (peripheral) ones. Such a widening is indeed observed when comparing J/ψ

production off nuclei and off protons, and it can be used to explain the p_T effect observed, or at least a good part of it /25/. The production rate is depressed at low p_T and enhanced at large p_T , as compared to pp collisions. However, there is nothing to stop the high E_T /low E_T ratio from reaching values larger than 1 at large enough p_T . Will data at larger p_T go beyond 1, in contradistinction to the behaviour expected from the formation of a quark-gluon plasma /26/? This is a challenging question.

v) The question of strangeness

It has long been argued /14/ that the formation of a quark-gluon plasma should enhance strangeness production. A hot dense gluon gas is flavour-blind and the $s\bar{s}$ pairs formed can be frozen out of equilibrium in the fast expansion of the plasma. Their number may be strongly enhanced if the plasma is rich in u and d quarks, as expected when produced in 200 GeV/A reactions.

The signal, if present, can however be given other interpretations, at least in some cases. A hot blob of pions and nucleons should give K^+K^- pairs. The K^+ 's can drop out of equilibrium relatively easily, the K^- 's being absorbed by the nucleons. Λ 's may thus be formed, and they may also be formed in the fragmentation of nucleons into ΛK . There are therefore other ways of obtaining more K^+ 's, more Λ 's and fewer K^- 's. It seems that a neater signal would be $\bar{\Lambda}$ production, which requires a large number of $\bar{s}$ in order to be important, or a $\bar{s}/\Lambda$ ($\bar{s}/\Lambda$) ratio much larger than in proton-proton production, where it is at the few per cent level. A good fraction of the $\bar{\Lambda}$ observed would then have an apparent longer lifetime because of their $\bar{s}$ filiation, and they would show a longitudinal polarization, which they cannot get otherwise. No information is available yet.

E802 has reported a strong K^+ enhancement /15/ in silicon-gold collisions at 14.5 GeV/A. The spectrometer can separate out the different particles produced using momentum measurement and time of flight measurement. This is a textbook achievement (Fig. 14). The K^+/π^+ is reported to be $24 \pm 5\%$ with a K^-/π^- ratio of $4^{+4}_{-2}\%$. The former is definitely much larger, by a factor of order three, than in pp collisions at the same energy and p_T . This is a clear and new effect. Nevertheless, a hot hadronic pion-nucleon gas could also produce such an effect, with a large K^+ enhancement and a much weaker K^- enhancement. Despite the predicted strangeness enhancement, one cannot therefore claim evidence for the formation of quark-gluon plasma. One has to wait for the results of NA35, NA36 and in particular those of WA85, which should give us information about $\Lambda(\bar{\Lambda})$ production. An anomalously large yield of $\bar{\Lambda}$, with longitudinal polarization, would be a much less ambiguous signal that something totally new is happening.

Fig. 14: Particle identification of E802.

Fig. 9: The formation of a central blob with high energy density.

(a) $\pi^-\pi^-$ correlations measured by NA35 separating out the fragmentation region $1 < y < 2$ from the central region $2 < y < 3$. Centre-of-mass rapidity zero corresponds to this range in terms of laboratory rapidity.

(b) π^- transverse momentum spectrum in oxygen-gold central production (NA35) and in pp collision. There is a new concave structure.

(c) π^0 transverse momentum spectrum in oxygen-gold and proton-gold collisions (WA80).

The neutral pion spectrum observed by WA80 (Fig. 9c) also shows evidence for this concave structure. The spectrum is harder than that expected from a superposition of nucleon-nucleon collisions. This should be due at least partly (at $p_T > 1$ GeV/c) to the Cronin effect. Widening then results from multiple collisions within the nucleus, globally yielding the observed transverse momentum.

iii) The quest for further information

One would of course like to know if this new effect in pion production is associated with peculiar signals in photon production (the blob should radiate at high temperature before pions are eventually frozen out) and in strangeness production (collision among pions before freeze-out should give K^+K^- pairs with the K^+ 's dropping out of equilibrium much earlier; the $s\bar{s}$ content of the blob could be important with production of $\bar{\Lambda}$). Nothing is yet available, but prospects are encouraging. It is indeed possible, despite the very high multiplicity ($n \sim 500$), to reconstruct particles from their daughters (π^0 from $\gamma\gamma$, Λ from $p\pi^-$). This is shown in Fig. 10, where we see the π^0 signal reconstructed by WA80 and the Λ signal reconstructed by NA35.

Fig. 10: Reconstruction of particles through invariant mass distribution.

(a) $\pi^0(\gamma\gamma)$ WA80

(b) $\Lambda(p\pi^-)$ NA35

iv) The exciting new effect, J/ψ suppression

It has been predicted that the formation of a quark-gluon plasma should suppress J/ψ production /8/. NA38 has measured J/ψ production, the J/ψ being seen through its muon pair decay. The J/ψ peak appears over a Drell-Yan background resulting from quark-antiquark annihilation into lepton pairs. There is also a large muon background originating from π decay but it has dropped to practically zero on the J/ψ peak.

No absolute rate is yet available, but the J/ψ signal can be normalized to the Drell-Yan background. One expects the latter not to be modified by the nuclear environment, while the former should. Of course, this is not exact, since the EMC effect shows that quarks (and probably gluons) have different distributions in nucleons and in nuclei, but the effect observed is of such a magnitude that this should not be of great concern. Figure 11 shows the J/ψ signal and the Drell-Yan background in collisions where different amounts of transverse energy are required in the central calorimeter, $E_T < 28$ GeV in the former case and $E_T > 50$ GeV in the latter. One sees that the signal-over-background ratio is much lower in the latter case, when a quark-gluon plasma could have been formed, than in the former one, when its formation is very unlikely. The ψ' seen in the former case disappears in the latter, as expected. Comparing data with $E_T > 85$ GeV to data with $E_T < 34$ GeV, one finds that the ratio of the signal-to-background ratios is as low as 0.5 ± 0.1 . Figure 12 shows this ratio of ratios as a function of $E_T/A^{2/3}$, a crude measure of the energy density, for different targets and projectiles (NA38). It scales. No such E_T -dependent suppression effect is observed in proton-uranium collisions by NA38.

Fig. 11: J/ψ production and Drell-Yan background in oxygen-uranium collisions (NA38).

(a) $E_T < 28$ GeV

(b) $E_T > 50$ GeV.

Fig. 12: The E_T dependence of J/ψ suppression in oxygen-copper, oxygen-uranium and sulphur-uranium collisions (NA38).

The observed suppression effect strongly depends on the transverse momentum. Figure 13 shows the ratio of ratios (J/ψ signal to Drell-Yan background between high and low E_T collisions) as a function of p_T . There is a strong J/ψ suppression at low p_T and no suppression at large p_T . This is again in agreement with predictions [8,23]. Is it the quark-gluon plasma smoking gun?

The J/ψ is produced mainly through gluon-gluon collisions, giving a χ state which eventually decays into J/ψ and γ . If not formed in such a primordial way, it has no chance of being produced in the final state. The observation of a clear and neat suppression (a factor two!) in collisions with large E_T , likely to be associated with a quark-gluon plasma so much in line with predictions, has generated much excitement. Is it evidence for the formation of a quark-gluon plasma? It is still too early to say. Many attempts have been made to interpret the observed effect in terms of already-known hadron physics [24]. Although none has yet fully succeeded, some have had partial success. The attacks continue.

One may of course say that large E_T collisions are central ones in which the J/ψ is produced deep inside nuclear matter. It may thus be more easily absorbed than in a more peripheral collision with low E_T . The amount of absorption needed seems, however, much too high in view of the magnitude of the observed effect and of the estimated J/ψ hadron cross-section. One also thus discovers that far more should be known about J/ψ production in proton-nucleus collisions. An A dependence, parametrized as A^α , with $\alpha \approx 0.95$, is probably much too crude an approximation. In any case, one would need an absorbing blob of very high density, living long enough to absorb the J/ψ much more efficiently than nuclear matter. This is already an important new effect.

5 - CONCLUSIONS

It is most impressive that two relatively short runs could yield so many results /27/. They have shown that it is possible to study such reactions despite their very high multiplicity.

The excitation energy has been found to be as high as expectations and high enough to be promising. There is already one exciting signal, J/ψ suppression, which is at the origin of lively debates.

There is obviously a great deal of enthusiasm to continue. Some experiments (in particular NA38) do require more luminosity. One has to focus on relatively rare events at the end of the E_T on multiplicity distribution. There is certainly a case for a new sulphur run, which could take place in 1990 after the start of LEP in 1989. There is also a very good case for developing a lead source and extending the present study to lead-induced reactions. Going from oxygen to sulphur meant an expected increase by a factor 1.3 in the accessible energy density - going from oxygen to lead would give instead a factor 2.8, hence typically 5 GeV/fm³. The looked-for signals should thus appear in a much clearer way.

Finding evidence for the formation of a quark-gluon plasma is a very important question in QCD. It is also a very topical question in astrophysics /28/.

Discussions with many colleagues at CERN and Brookhaven are gratefully acknowledged.

APPENDIX A

The main experiments at CERN and Brookhaven in 1987-1988.

CERN

WA80 (Gutbrod et al.)	Forward and mid-rapidity calorimeter, π^0 wall detector and plastic ball. Some results already available.
WA85 (Quercigh et al.)	Ω' spectrometer ($\Lambda, \bar{\Lambda}$), analysis in progress.
NA34 (Spech et al.)	Large angle calorimetry, lepton pair capability and large angle spectrometer. Some results already available.
NA35 (Stock et al.)	Streamer chamber and mid-rapidity calorimeter. Some results already available.
NA36 (Gruhn et al.)	TPC, analysis in progress.
WA38 (Kluberg et al.)	Muon pair and calorimeter. Some results already available.

BNL

E802 (Hansen/Nagamiya et al.)	Particle spectra with multiplicity and calorimeter triggers. Some results already available.
E810 (Lindenbaum et al.)	TPC and multiparticle spectrometer, at building stage.
E814 (Braun-Munzinger et al.)	Forward spectra and full calorimetry, running ready.

APPENDIX B

The temperature in the early Universe falls as the inverse square root of time $T \sim t^{-1/2}$. At the beginning there is a small excess of fermions with respect to the antifermions. After complete annihilation, when the temperature falls below 1 MeV, (one second after the Big Bang), the ratio of protons and electrons to photons is of the order of 10^{-9} .

The u and d quarks (and eventually protons and neutrons) are kept in thermal equilibrium by neutrino collisions down to $T \sim 3$ MeV (10^{-1} s after the Big Bang). There is no longer any neutron regeneration when the electrons and positrons disappear at $T \sim 1$ MeV. The neutrons start to disappear with a lifetime of 1000s. At 1s the p/n ratio is of the order of 5. Since the temperature is then low enough for nuclei to form, some neutrons are eventually stabilized in helium. However, this requires the intermediate formation of deuterium while the intense γ radiation destroys the deuterium nuclei as quickly as they are formed, right up to the time the temperature has dropped to $T \sim 0.1$ MeV, 100s after the Big Bang. By that time the p/n ratio has increased to seven. This gives the observed He/H mass ratio of 1/3.

This ratio is sensitive to the γ/q ratio. Decreasing it stabilizes more deuterium and increases the He/H mass ratio. This limits the mass density which can be associated with baryons to less than 20% of the critical density, in rough agreement with the observed hadronic matter (shining and dark) density.

There are strong arguments for a density equal to the critical one, since the evolution equation is a very strong amplifier of any discrepancy, and it would therefore be puzzling to have today a density rather close (factor < 10) to the critical density, and yet different from it. In inflationary theories the density has also to be equal to the critical one. If this is the case, where is the still-missing contribution to the energy density?

In the standard approach, associating it with hitherto unobserved baryonic matter leads to a conflict with the He/H mass ratio for the reason already given: too much deuterium being formed to be destroyed by the γ radiation.

However, we know now that a quark-gluon plasma should have existed up to 10^{-5} s, when the temperature fell below 200 MeV. The hadronization of the plasma could have led to large anisotropy in the principal baryon density, with proton-rich clumps and neutrons easily escaping such clumps, being neutral. The formation time for deuterium could thus be longer and a higher baryon density would become possible. This is a challenging topical question /27,28/.

APPENDIX C

Some peculiar effects observed in $p\bar{p}$ collider interactions are similar to those expected from the formation of a quark-gluon plasma. This is particularly the case for the increase of $\langle p_T \rangle$ as a function of dn/dy , seen by UA1 and CDF. This is also the case for the relatively large E/A ratio reported by UA5 /12/. These collider results have even been discussed in terms of quark-gluon plasma formation! However, it is appropriate to stress the difference. At collider energies, many low x (fractional momentum) partons (mainly gluons) can independently hadronize as minijets /29/. This leads to events with both larger $\langle p_T \rangle$ and larger energy density, and to events with a larger strangeness content (the $s\bar{s}$ being the leading fragments of flavour-blind gluons) than those seen at lower energy. A droplet of quark-gluon plasma with important transverse flow could produce similar results. However, it seems pointless to speak about a quark-gluon plasma for a system so small that thermalization is not even partially possible. On the other hand, minijet production provides a natural explanation of a predicted effect. This occurs only at very high energy, when low x gluons have energies in excess of a few GeV, and can then scatter incoherently from one another.

The quark-gluon plasma searched for in heavy ion collisions should appear at a much lower energy (lower by a factor ten). It should extend over a certain volume ($\gg 1 \text{ fm}^3$) with a great deal of rescattering among partons, so that one can speak of some thermalization. On the other hand, at RHIC energy, minijets should be an efficient means of producing transverse energy and "igniting" the quark-gluon plasma /30/.

REFERENCES

- /1/ For a detailed introduction to QCD, one may consult "Perturbative Quantum Chromodynamics", Physics Reports reprint volume 5 (North Holland, 1982), editor M. Jacob.
For a detailed introduction to the quark-gluon plasma and QCD, one may consult "Quark Matter Formation and Heavy Ion Collisions", editors M. Jacob and H. Satz (World Scientific, 1982). See also:
SHURYAK, E., Physics Reports 61 (1980) 71, and:
Proceedings of "Quark Matter '83" (Brookhaven), "Quark Matter '84" (Helsinki) and "Quark Matter '85" (Asilomar).
- /2/ This ion source has been developed by R. Geller, in Grenoble, for GSI Darmstadt. It is of the electron cyclotron resonance type, and can provide a beam of 100 μ A of O^{6+} . After acceleration in the LINAC and full stripping, one obtains a 10 μ A beam at 12 MeV/A at the entrance of the PS-SPS complex.
- /3/ For a review of the CERN programme prospects and study, see:
DARRIULAT, P., Proceedings of "Quark Matter '87", Z. Phys. C38 (1988) 325, and the London-McCubbin-Stock report to the SPSC (1988).
- /4/ "Experiments at CERN", 1987 and 1988.
- /5/ For a review of the Brookhaven programme and projects, see:
LUDLAM, T.W. and SAMIOS, N.P., "Quark Matter '88", op.cit., 353.
- /6/ For a detailed presentation of the experimental and theoretical situation at the end of 1987, see:
Proceedings of the "Quark Matter '87", Z. Phys. 38 (1988) Number 1/2.
- /7/ The energy density reached can be related to the particle density and the transverse energy density observed. Detailed results have been obtained by WA80, NA34 and NA35. They are reported in Ref. /6/. The sulphur run, with results in 1988, has confirmed those obtained in 1987 with oxygen.
- /8/ MATSUI, T. and SATZ, H., Phys. Lett. B178 (1986) 416;
KARSCH, F. and PETRONZIO, R., Phys. Lett. B199 (1987) 499.
- /9/ NA38, "Quark Matter '87", Z. Phys. C38 (1988) 177.
- /10/ The particle physicist reader familiar with QCD may skip Section 2 altogether. The reader willing to learn more can consult Ref. /1/.
- /11/ See the reports by KARSCH, F., Z. Phys. C38 (1988) 147 and
KAJANTIE, K., Z. Phys. C38 (1988) 157.
- /12/ For a review, see:
JACOB, M., Rapporteur talk, XXII International Conference on High-Energy Physics, Leipzig (1984);
JACOB, M., Cargèse Summer School 1987 (Plenum Press).
- /13/ For a review of jets, and more generally of physics in e^+e^- annihilation at high energy, see:
WU, S.L., Physics Reports 107 (1984) 59.
- /14/ RAFELSKI, J. and MULLER, B., Phys. Rev. Lett. 48 (1982) 1066;
KOCH, P. et al., Z. Phys. A324 (1986) 453;
RAFELSKI, J., Physics Reports 88 (1982) 331, editors M. Jacob and J. Tran Thanh Van.
- /15/ MIAKE, Y., et al., Z. Phys. C38 (1988) 135;
TANNENBAUM, M.J., report BNL 41608 (1988);
NAGAMIYA, S., Columbia preprint R1390 (1988).
- /16/ JACOB, M. and RAFELSKI, J., Phys. Lett. B190 (1988) 173;
JACOB, M., Z. Phys. C38 (1988) 273.
- /17/ FARHI, E. and JAFFE, R.L., Phys. Rev. D30 (1984) 2379.

- /18/ GREINER, C., et al., Phys. Rev. Lett. 58 (1987) 1825.
- /19/ OTTERLUND, I., Z. Phys. C38 (1988) 65.
- /20/ Proceedings of "Quark Matter '88", Lenox, Massachusetts, September 1988, to be published in Nucl. Phys. A.
- /21/ LEE, K.S. and HEINZ, U., Regensburg preprint TPR-88-16 (1988).
- /22/ KOPYLOV, G.I., Phys. Lett. 50B (1974) 472;
GYULASSY, M., et al., Phys. Rev. C20 (1979) 2267;
HAMBURY-BROWN, R. and TWISS, R.G., Nature 178 (1956) 1046.
- /23/ For a review of the present situation, see:
SATZ, H., Bielefeld preprint BI.TP 88/10, Invited talk at the Third Conference on Nucleus-Nucleus Collisions, St. Malo, France (1988).
- /24/ GAVIN, S., et al., Phys. Lett. B207 (1988) 257;
FTACNIK, J., et al., Phys. Lett. B207 (1988) 194.
- /25/ HÜFNER, J., et al., Heidelberg preprint 1988, to be published in Phys. Lett. B.
- /26/ KARSCH, F. and PETRONZIO, R., Z. Phys. C37 (1988) 627.
- /27/ For a recent review, see:
VAN HOVE, L., Summary talk, Bombay Conference on Heavy Ion Collisions, 1988.
- /28/ OLINTO, A.V., Z. Phys. C38 (1988) 303;
ALCOCK, C.R., Contribution to the Bombay Conference on Heavy Ion Collisions, 1988;
REEVES, H., Varenna Summer School on "Confrontation Between Theories and Experiments in Cosmology" (1987).
- /29/ JACOB, M., Cargèse Summer School 1981 (Plenum Press).
- /30/ KAJANTIE, K., et al., Helsinki preprint HUTFT-87-35 (1987).