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QUARK MATTER, FACTS AND HOPE^{*)}

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ABSTRACT

The aim is to study nuclear matter under extreme conditions. The hope is that conditions reached in present relativistic heavy ion collisions are adequate for the formation of a quark-gluon plasma where colour would no longer be confined to hadronic dimensions. The situation prior to the "Quark Matter '88" Conference is reviewed. The questions of topical interest are discussed, illustrated by results already available.

*) Opening talk, "Quark Matter '88", Lenox, Massachusetts, U.S.A., 26-30 September 1988.

INTRODUCTION

It is a privilege for me to give the opening talk at "Quark Matter '88". This is a privilege of which I was also strongly aware five years ago, when I was asked to give the opening talk at "Quark Matter '83" at Brookhaven.

The situation has changed a great deal since! Yet one may say that the present situation meets the hopes and expectations expressed in 1983. The exploratory programmes at CERN and Brookhaven have had a very successful start. Many data were already presented at "Quark Matter '87" in Nordkirchen, after the results of the first runs had been partially analyzed. Many more results will be presented now.

In 1983 we certainly already had some data. However, they were deemed to correspond to too low energies for heavy enough ions (Bevalac, Dubna, Saturne), to too small ions when the energy was high enough ($\alpha\alpha$ collisions at the CERN ISR), or were too few to be statistically reliable for heavy enough ions at very high energies (cosmic ray events).

We now have many solid experimental results with energies and ion sizes which already appear adequate enough to probe new ground. There are some puzzling and exciting results which are at the origin of passionate debates. There is therefore much enthusiasm to continue with this research, which is a very fruitful interface between particle physics and nuclear physics. This is particle physics at very high quark density, which is something new. This is nuclear physics when partonic degrees of freedom become fully relevant, which is also something new. There is a theory for all that - quantum chromodynamics - which can thus be probed in a new domain, where challenging questions occur.

The situation as it appears before the conference is reviewed. It is analyzed within the limits of information which has already been made publicly available.

We can look forward to exciting new results and enlightening discussions at this Conference. It is an exciting time for this budding field of investigation.

1. QUARK MATTER

In the framework of quantum chromodynamics, colour should no longer be confined at high enough temperature and/or high enough quark density¹. One is talking about temperatures in excess of 200 MeV at low quark density (quark chemical potential) or of densities well in excess of five times the nuclear density (which is 0.15 GeV/fm^3) at low temperature.

This is a big issue in QCD. One indeed expects the deconfinement of colour to occur under such extreme conditions. Quarks should no longer be bound into colourless hadrons of 10^{-15} m , but should freely roam over the whole volume where such conditions hold. This is also a big issue in astrophysics and cosmology. The Universe should have been a quark-gluon plasma until its temperature fell below 200 MeV. This was the case until 10^{-5} sec after the Big Bang. The way hadronization proceeded, with or without inhomogeneities, could have had much influence on baryon genesis and then nuclear synthesis. Under conditions which no longer appear untenable, one could perhaps raise the baryon density of the Universe up to the critical value, without upsetting in an unacceptable way the abundance ratios of the light elements².

The required conditions should be within experimental reach. Relativistic heavy ion collisions could raise the energy/quark density to a level such that a quark-gluon plasma could be formed³. In 1986, the first exploratory runs took place using oxygen ion beams of 60 GeV/A and 200 GeV/A at CERN, and of 15 GeV/A at Brookhaven. Silicon ions were also accelerated at BNL. Many of the results obtained were presented at "Quark Matter '87"⁴. By that time, however, the collected data had not been fully analyzed. Indeed, the study of events where up to 500 charged particles are produced requires a great deal of care and patience!

The present-day experimental situation, with several major experiments having run or being still at the completion stage, and a number of completed emulsion experiments, is reviewed at this conference by P. Braun-Munzinger⁵.

The run of 1987, in particular the 200 GeV/A sulphur run at CERN, has already yielded results, some of which will be presented here for the first time. These results have mainly consolidated the earlier ones obtained with oxygen ions and strengthen the conclusions drawn. In 1988, a proton reference run took place at CERN.

At present, an optimist would say:

- 1) When one looks "outside", namely at the many pions produced in the collisions, everything observed seems compatible with what could be expected from the formation of a quark-gluon plasma.
- ii) When one looks "inside", and in particular at J/ψ production, which has to take place at an early stage deep inside the colliding nuclei, things do look as if a quark-gluon plasma has been formed.

However, the only definite and more cautious statement that one can presently make is that many interesting and sometimes puzzling features have been found and there is therefore much enthusiasm to continue with this research.

Indeed, it is clear that one has not yet looked hard enough. The data collected so far should contain many pieces of information which have not yet been extracted. This is particularly the case when considering prompt photon radiation and, more generally, particle identification.

QCD is the theory of strong interactions. When it can be used in a perturbative way, for instance in calculating jet yields in hadronic interactions, it has been immensely successful. Figure 1 shows the angular distribution of hadronic jets as observed at the $p\bar{p}$ collider. This is illustrated by two of the now famous "Lego plots", showing a two-jet event and a three-jet event respectively. This is the Rutherford experiment of this decade⁶.

Figure 1: A success of perturbative QCD; jet production in hadronic collision. CERN $p\bar{p}$ collider results with Lego plots of two-jet and three-jet events.

However, despite all the information already available from lattice gauge theory, we do not yet fully understand how quarks and gluons bind themselves into hadrons and the mechanism(s) of colour confinement. At present, hadronization has to be merely parametrized. This is a key question where experimental information is very much needed.

Of particular interest experimentally is the question of glueballs which calls for a big effort in hadron spectroscopy. Of particular interest also, in the framework of the Conference, is the existence of a deconfined phase, which the theory leads us to expect at high enough temperature and/or quark density³.

The QCD potential between two coloured sources has an r^{-1} behaviour (up to logarithmic terms) at short distances. This is the Coulombic part expected when perturbation theory can apply. It has an r behaviour at larger distances ($> 10^{-16}\text{m}$). This is the still parametrized confining form, which also comes out in lattice gauge theory calculations. This potential can be fruitfully used to study the dynamics of heavy quark systems which remain non-relativistic in that potential. Levels can be calculated, and much success is met with quarkonia ($c\bar{c}$, $b\bar{b}$ bound and resonance states)¹. This is the hydrogen problem of QCD.

Crystal Ball

Figure 2: A success of QCD in its parametrized confining regime. The low-energy levels of charmonium as they are determined experimentally from photon emission and can be calculated in potential theory.

Figure 2 shows as an example the low-energy level structure of charmonium with the corresponding photon emission lines. It is important to probe QCD beyond these successes. Its behaviour at high energy and/or quark density is a great challenge.

At high enough colour source density, the binding property of the potential should disappear. Debye screening should eventually lead to an exponential fall-off of the potential and such heavy quark systems should no longer be bound⁷. It follows that resonances formed at the early stage of the reaction, in particular the J/ψ , should no longer be found if a quark-gluon plasma is formed. As the temperature increases beyond the deconfinement value T_c , binding is no longer possible. Instead of J/ψ 's, one should see a few more charmed mesons in the final state.

The most reliable information about the deconfinement parameters comes from lattice gauge theory calculations. Such calculations in principle provide information on anything which can be derived from the free energy. One may say that their implying a phase transition is probably their most important outcome at present. There was a great deal of enthusiasm for the lattice approach in 1982³. Lots of difficulties were met, and shortcomings were noted and partly overcome⁸. It is clear that one is still severely limited by computer power and that an extra gain by a factor 100 is probably needed before the effects of light quark loops can be properly taken into account. Present algorithms also work only in the low-density limit, and there is thus no information about transitions at appreciable values of the quark chemical potential.

The situation as of a year ago was reviewed by F. Karsch at Nordkirchen⁸. Figure 3 illustrates some of the key results. Figure 3a shows the behaviour of ϵ/T^4 as a function of T (related to the parameter $\beta = 6/g^2$ in the lattice approach). Here ϵ is the energy density and T the temperature. One sees clearly a sharp phase transition in the pure gauge SU(3) case, with a large latent heat. Indeed, the thawing of colour degrees of freedom as one goes from the meson gas phase to the quark-gluon plasma phase corresponds to an increase by an order of magnitude of ϵ/T^4 ! The critical temperature can be determined from the simultaneous calculation of the string tension or of the rho meson mass. This is how one actually relates T to $\beta = 6/g^2$. The critical temperature is of the order of 200 MeV, which corresponds to a needed energy density for plasma formation of the order of $\epsilon \approx 2 \text{ GeV/fm}^3$. Figure 3b shows the behaviour of ϵ/T^4 and p/T^4 in a calculation with two light quark species. The phase transition is again clearly seen. However, the behaviour of the pressure shows that there are important collective plasma excitations. In the case of pure gauge SU(3), the transition is known to be of first order, provided that the mean field approach applies⁹. With light quarks, the transition seems to maintain its first-order character.

Figure 3: Phase transition in lattice gauge theory (F. Karsch, Nordkirchen).

3a: ϵ/T^4 versus $\beta = 6/g^2$ for pure gauge SU(3). Also shown are the lowest-order (upper) and order g^2 (lower) lines in weak coupling perturbative theory for the plasma phase.

3b: ϵ/T^4 and $3p/T^4$ versus β for SU(3) with two light quark species. Lines are drawn to guide the eye (F. Karsch, Nordkirchen).

Lattice calculations have developed greatly over the past year, mainly thanks to extensive calculations on Cray-type computers and on the dedicated computers built in Rome and at Columbia. At this Conference we shall hear about the present situation from A. Mueller and A. Ukawa^{10,11}. It seems that, while a rather sharp transition is still there, the corresponding jump in ϵ/T^4 is less than meets the eye in Fig. 3b. There is also a gradual rise before (after) T_c in the hadronic (plasma) phase.

One may sketch the expected behaviours of systems in the phase diagram of Fig. 4, where the hadron and quark-gluon plasma phases are separated according to temperature and quark density. Two trajectories are shown. They correspond respectively to heavy ion collisions (I) and to the evolution of the early Universe (II). The separation between the two phases is indicated by a shaded

area, since there could be two successive transitions. As the temperature increases, quarks could be freed while keeping a mass. This could be associated with the presence of a $\langle q\bar{q} \rangle$ condensate. Eventually this condensate would disappear. Chiral symmetry would be restored and the actual quark-gluon plasma formed. Present lattice results indicate that at low density (zero quark chemical potential), the two transitions seem to occur simultaneously, as seen from the behaviour of their respective order parameters. There could, however, be two successive transitions at high quark density.

It was realized several years ago that such conditions (an energy density of a few GeV/fm^3 over the volume of a whole incident ion) could be reached in heavy ion collisions at present accelerators³. It was also realized that the typical final state conditions (with several hundred particles produced) could be manageable³. There was nothing but enthusiasm for the development of experimental programmes.

Figure 4: The QCD phase diagram with a hadronic phase and a quark-gluon plasma phase. The two trajectories illustrate the expected behaviour in relativistic heavy ion collisions and in the early Universe respectively.

Figure 5 shows one of the spectacular events observed with the streamer chamber of NA35¹². It is beautiful but very complex. The amazing thing is that such events are manageable. Indeed, we now know that the early optimism of 1982-1983 was justified. We may thus stress that:

- i) Despite their great complexity, events are manageable.
- ii) One should be patient when waiting for all the information which should eventually become available. Events are very complicated. This is particularly the case, in such a streamer chamber experiment, when looking for

information about the production of strange particles (V's seen among the very many tracks). It took quite some time to extract them, which is understandable!

While we have good reasons to expect that a quark-gluon plasma might be formed in central heavy ion collisions at such energies, we must also realize that the plasma blows itself out almost as quickly as it is formed. The expected lifetime is at the level of a few fermi/c. We still have much to learn about the dynamics of hadronic matter or of such a plasma, and all the more so since reaction rates, in particular for strangeness excitation, become a key issue. The present situation will be reviewed at this Conference by G. Bertsch¹³ and G. Pethick¹⁴.

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

Figure 5: A streamer chamber event, NA35.

2. SIGNATURES FOR THE QUARK-GLUON PLASMA

When looking for signatures, one may think of the Cheshire cat in "Alice in Wonderland". Once the cat has disappeared we are left with only the grin to look at. We hope that the grin will be sufficient to learn about the key properties of this new form of matter.

One may, of course, look for very peculiar features which could only be associated with a plasma of very high density. Among the objects searched for in this way one may mention strangelets, hadron bags of many quarks including many strange quarks, which might thus be stable¹⁵. However, one may not be so lucky.

There is still a long list of questions, the answers to which should provide very interesting information. Most of these questions have not change for several years³, and it looks like we have to round up the usual list of suspects. However, we do know more about them than a few years ago, and some new suspects have shown up.

i) Is the energy deposition high enough?

This has much to do with the stopping power of a target nucleus at very high energy. We now know that the energy deposition (i.e., the energy available for excitation) is as high as one could hope it to be. It should be high enough, at least in central collisions.

ii) Are there any collective excitation effects?

One may wonder whether a nucleus-nucleus collision is not merely the superposition of many nucleon-nucleon collisions. We now know that there is something besides that. The formation of a blob of very high density (a few GeV/fm³) is becoming a fact.

iii) Are there anomalous effects in dE_t/dy , dn/dy ,?

Here E_t is the transverse energy, n the multiplicity and y the rapidity. Anomalous phase space (rapidity) distributions would naturally signal something new from usual nucleon-nucleon collisions. At present there is nothing peculiar to report despite intensive searches; however, so far one has only looked at pions in the final state, when it is known that they are great averagers. They eventually come out (freeze out) after many interactions and in large numbers.

iv) Is there a peculiar photon radiation?

Photons could tell us about the interior of the quark-gluon plasma, and their distribution could give evidence for anomalously high temperatures. The question of photon radiation is still unsettled. We shall hear more about it at the Conference¹⁶, but no definite conclusion seems to be at hand.

v) Is strangeness production enhanced?

An enhanced production of strange particles has long been advocated as a signature for the formation of a quark-gluon plasma¹⁷. A high temperature and a high chemical potential for non-strange quarks both favour the production of $s\bar{s}$ pairs and eventually of strange particles, as strange

quarks drop out of equilibrium relatively easily. However, there are other ways to produce strange particles and a dense hadronic medium could be enough.

Experimental evidence for an enhanced production of strange particles will be one of the big issues at this Conference¹⁸. The production rates of K^+ and Λ particles is typically twice as large as expected from the mere superposition of nucleon-nucleon collisions. Whether this signals the formation of a quark-gluon plasma is however still unclear. In order to draw a conclusion, one would have to have a much tighter control of the strangeness production rate as a function of time. The clearest experimental test would be an anomalously large production of antihyperons which standard hadronic reactions are very unlikely to produce in large numbers. We will probably be left with too little information to draw a conclusion now, but this Conference is likely to open up exciting perspectives on strangeness production.

vi) Is J/ψ suppression an unambiguous signal?

J/ψ suppression may be our present smoking gun when searching for the quark-gluon plasma. We already mentioned that the J/ψ could not be formed if the gluon-gluon collisions from which it mainly originates occur within a blob of quark-gluon plasma. Two clear predictions were made. Satz and Matsui argued that J/ψ production should be suppressed in reactions where a quark-gluon plasma would be formed¹⁹. Such reactions are triggered upon requiring a large amount of transverse energy. Karsch and Petronzio have argued that this suppression should no longer be effective at large transverse momentum²⁰. Both features have been found by NA38¹². The J/ψ suppression is measured relative to the Drell-Yan background. The early results of 1987⁴ are now complemented by more extensive results combining oxygen and sulphur data²¹. It is clear that the two expected signatures are beautifully met by the data. Can one draw a conclusion?

We shall hear a lot about that at this Conference. The beautiful experimental results of NA38 have been at the origin of passionate discussions and much theoretical work has been triggered by them. Many attempts to explain the results by standard hadronic processes have been made. The question will be reviewed by J.P. Blaizot, and it was recently also reviewed by H. Satz⁷. There is no clear answer yet, but the Conference will definitely bear witness to the lively aspect of this field of research, with puzzling results, challenging questions and passionate debate. Whatever way one looks at it, present experi-

mental evidence calls for a system of very high density ($> 2 \text{ GeV/fm}^3$) with a long enough lifetime (a few fermi/c) and partonic effects (gluon radiation) over nuclear dimensions. This is definitely something new.

3. THE GLOBAL FEATURES OF HEAVY ION COLLISIONS

The first aim is to obtain large excitation energies. In doing so, it pays to use heavy ions. The excitation energy eventually leads to a large transverse energy flow E_T and to a large multiplicity n . We now have ample experimental information to say that the heavier the ions, the higher E_T is and the higher n is. This is illustrated by Fig. 6, which puts together results on $d\sigma/dE_T$ (NA34 and NA35), $d\sigma/dn$ (WA80) and dn/dy (WA80) obtained with different target nuclei and different ion beams¹². Also shown is an emulsion result²² showing the multiplicity pseudorapidity distribution for oxygen and proton collisions in emulsion.

Figure 6: Transverse energy differential cross-sections (NA34 and NA35), multiplicity differential cross-section (WA80) and multiplicity rapidity distributions (WA80 and KLM Emulsion Collaboration) for different targets. See Fig. 8 for sulphur-tungsten collisions.

One sees that in such collisions a large amount of energy is deposited, the more so the heavier the ions are, and this eventually leads to the production of many secondary particles, mainly pions.

The next question is whether or not this energy deposition is high enough in comparison with our expectations. The answer is yes. To a good first approximation, the energy deposited corresponds to that expected if each of the incident nucleons were to interact with the target independently of their fellow nucleons in the incident ion. This is illustrated by Fig. 7 which shows how the

transverse energy differential cross-section can be obtained by folding the transverse energy distribution of individual nucleon-nucleus collisions up to the maximum number of nucleons in the projectile (16 for oxygen). This is shown with CERN results at 200 GeV/A (NA35) and Brookhaven results at 14.5 GeV/A (E802).

Figure 7: The transverse energy differential cross-section and its analysis as a folded distribution of independent nucleon-nucleus collisions. 200 GeV/A oxygen-gold collisions (NA35) and 14.5 GeV/A oxygen-gold and oxygen-copper collisions (E802).

The low E_T part of the distribution corresponds to glancing collisions, where only a few nucleons enter the target. The large E_T limit corresponds to the maximum, reached in head-on collisions where the incident ion fully penetrates the target at maximum thickness. The weight associated with each type of collision can be calculated according to the impact parameter.

One should not overstress the validity of this simple approach, according to which each incident nucleon would "do its job" independently of the others, according to what it typically does in a proton-nucleus collision at the same energy²³. Nevertheless, it provides a good guideline. At 14.5 GeV/A (Brookhaven)

there is practically full stopping and, in head-on collisions, all the incident kinetic energy is available for excitation. At 200 GeV/A (CERN), the maximum excitation energy corresponds to about 65% of its ultimate value, defined as that which one would observe if the incident ion and the tube which it bores in the target nucleus were to make a unique isotropic fireball. This, however, applies to oxygen. For sulphur it is only about 60%. A word of warning is appropriate concerning these analyses. Many experiments are sensitive only to a certain range of the rapidity distribution, while increasing E_T or making the collision more central shifts the peak of the rapidity distribution to lower lab rapidity values. An analysis of the stopping power thus requires information over the full rapidity range!

The transverse energy differential cross-section can in any case be looked at as a question of geometry. Averaging over impact parameters, one can reproduce rather well the data from models successful at describing nucleon-nucleon and nucleon-nucleus interactions. At the same time one obtains, fairly successfully, $d\sigma/dE_T$, particularly in the central rapidity region, where most of the transverse energy is found, and $d\sigma/dE_{ZDC}$, where ZDC corresponds to the energy flow observed in the forward cone (in a "zero degree" calorimeter), not having been trapped for target excitation. This question was already well documented a year ago⁴. More recent results have consolidated the picture. The power of geometry is impressive. That way, one can see that oxygen is larger than carbon, the incident ion never being "fully stopped", with only a vanishingly small energy in the forward calorimeter in an oxygen-carbon collision. One can also see that tungsten is not spherical by the anomalous way in which $d\sigma/dE_T$ falls at large E_T .

Models have been refined. The status of the Lund FRITIOF model will be reviewed by B. Anderson²⁴ and the status of the dual parton models will be reviewed by J. Ranft²⁵. While different in their original starting points, all the models have strongly converged in their incorporation of a lot of hadron phenomenology and in their finer tuning to an increasing set of data. As we shall hear from T. Awes²⁶, model builders have recently made a valuable effort to compare their tools. These models provide the much-needed interface between data and a conclusion about the physics.

Figure 8 illustrates the power of present geometrical models with $d\sigma/dE_T$ measured over two different rapidity ranges. This recent result of NA34 on sulphur-tungsten collisions is also the first one where E_T is measured over the full phase space $-0.1 < \eta < 5.5$.

Figure 8: $d\sigma/dE_T$ in sulphur-tungsten collisions at 200 GeV/A over two rapidity intervals $-0.1 < \eta < 2.9$ (squares) and $-0.1 < \eta < 5.5$ (triangles) and geometrical model fit (NA34).

Having acknowledged the presence of a large amount of excitation energy, which is as high as one could expect, one may ask how it is distributed in phase space and among secondaries. Figure 9 illustrates two important properties. There is first a very strong correlation between the transverse energy observed in the central rapidity region and the forward energy measured in a forward calorimeter; the larger the former, the smaller the latter, and vice versa. Here results from NA35 beautifully illustrate this point. There is also a very strong correlation between the amount of transverse energy measured and the number of (charged) secondary particles. This is illustrated here by results from NA34, showing that the mean energy per charged particle is almost independent of the global transverse energy. There is no obvious sign of "hotter" pions. The mean number of secondaries increases according to the transverse energy.

Figure 9: 9a: Correlation between the transverse energy observed in the NA35 acceptance and the forward energy flux in the projectile fragmentation cone. Oxygen-gold collisions at 200 GeV/A.

9b: Average E_T per charged particle as a function of transverse energy in the $-0.1 < \eta < 2.9$ range. NA34 result. Oxygen-tungsten collisions at 200 GeV/A.

These correlations are very useful experimentally. They mean that, in the search for events with large excitation energy, one can either trigger on a large amount of E_T in the central rapidity region, or on a small amount of energy in a forward calorimeter, or again on a large multiplicity. This is practically equivalent.

It may sound disappointing that the E_T and $y(\eta)$ distributions of pions do not show anything really special. However, pions are great averagers. They interact before freezing out at a relatively late stage. More specific information could still come from the p_T and $y(\eta)$ distributions for K, p, Λ , $\bar{\Lambda}$... in the present data. We wish to know more about them.

While particle production models are successful at reproducing the multiplicity in the central rapidity region, where one sees most of the many secondary pions associated with the excitation energy, they fail in the target fragmentation region since they do not yet take into account the break-up of the target nucleus. This is illustrated by Fig. 10. The low lab rapidity distribution observed by WA80 is much larger than the expectation from the Lund model, which applies only to the primary nucleon-nucleon collisions. The number of such fragments increases with target size and is much larger in oxygen collisions than in proton collisions. The target nucleus is completely shattered. There is no actual "spectator" nucleon in the collision.

Figure 10: The target nucleus is completely shattered (WA80).

10a: Pseudorapidity distribution showing a large excess in the target fragmentation region which is not reproduced by a model calculation taking only "participating" nucleons into account.

10b: Average number of baryons per event as a function of pseudorapidity. Oxygen and proton collisions at 200 GeV/A.

During a heavy ion collision, there is thus a great flare of pions associated with a large amount of transverse energy. At the same time, the target nucleus is completely destroyed. This implies some complicated cascading effects which have not yet been studied in detail.

At this stage, one may conclude that:

- i) There is a large amount of excitation energy.
- ii) The stopping power is as high as one could hope.
- iii) The excitation energy and the multiplicity are strongly correlated.
- iv) The final state of a nucleus-nucleus collision does look, to a first approximation, like a superposition of nucleon-nucleus collisions, according to geometry.

This might sound like boring news. However, one should stress that:

- i) This is only a first look.
- ii) The energy density inferred by the data appears to be high enough.

The aim was indeed to reach an energy density in excess of 2 GeV/fm^3 , over a sizeable volume. It is well known that the relation between the energy density ϵ and the transverse energy rapidity density dE_T/dy , or any other indicator, presents some ambiguity²⁷. Nevertheless, all estimates show that, in the rather frequent central collisions, energy densities at the level of 2 to 3 GeV/fm^3 are reached, which is very good news. The remaining question is whether there is enough time for some thermalization. This depends on the lifetime, and therefore also on the size of the high density system produced. In connection with that, one may remark that, going from oxygen to sulphur on a heavy target, the maximum value of E_T increases experimentally by 1.7 only²⁸. We do not get a full factor two. The transverse size of the excited system increases by a factor 1.6. There is therefore little gain in ϵ , but a good gain in size and hence in lifetime. This is the reason for going to a lead beam, despite a limited expected gain in mean energy density (1.5, say). At present, the energy density reached is most probably enough. It is the size and lifetime that then appear crucial for the formation of a quark-gluon plasma.

As an aside, one should stress that the linear relation between ϵ and dE_T/dy ²⁷ applies only to relatively flat rapidity distributions so that a rapidity interval can be unambiguously associated with a velocity spread. One should not see a spike (fluctuation) in a rapidity distribution as a sign of a particularly high energy density! This may or may not be the question.

Wild fluctuations in rapidity density are, however, worth searching for as a sign of something special. Nothing striking has been reported so far, but it is due to the fact that nothing very prominent occurs and that the proper method was not readily applied. An efficient way of looking for fluctuations beyond random ones is based on intermittency²⁹. We shall hear a lot about its new application²⁸. One indeed finds rapidity fluctuations (in multiplicity) over small intervals which are not of a random type. However, they seem to affect equally all hadronization processes and point to the fact that there is a whole range of time scales for hadronization. One cannot simply say that it takes about one fermi/c to make a hadron according to its own clock, as tacitly assumed in all past hadronization models. With a wide range of time scales one can have important fluctuations over almost arbitrarily small rapidity intervals, which random pile-ups of standard clusters, typically two units wide in rapidity, cannot reproduce.

While such intermittency fluctuations are very interesting and will force models to adapt, it does not seem that they are more important in heavy ion collisions than in any other processes. A more careful look is worthwhile, however, and it will soon become part of the standard systematic tests.

4. SPECIAL FEATURES IN HEAVY ION COLLISIONS

There are features already ascertained which show that there is much more in heavy ion collisions than the mere superposition of nucleon-nucleon collisions. The first special feature is the result of $\pi^-\pi^-$ interferometry. It is a generalization of the Hanbury-Brown and Twiss method, using the Bose nature of the pion to probe the size of the volume at freeze-out, namely the volume beyond which pions cease to interact appreciably. The $\pi^-\pi^-$ phase space correlation is presently being analyzed in terms of a three-parameter fit

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

Here Q_L and Q_T are the relative momenta of the two identical pions in the longitudinal and transverse directions. The source is thus described with two geometrical parameters R_L and R_T only, corresponding respectively to its longitudinal and transverse radii. A unique, chaotic parameter λ , which varies between 0 (full coherence) and 1 (complete chaos) describes its properties.

Figure 11: $\pi^-\pi^-$ interferometry results of NA35. Correlations in Q_T for different rapidity intervals and absence of correlations in Monte Carlo FRITIOF "data" with no Bose statistics effect included.

Figure 11 shows the results obtained by NA35 with oxygen-gold collisions at 200 GeV/A¹². They are particularly striking. There is a strong positive correlation in phase space at low Q which gives rather standard parameter values away from the central rapidity region, namely $R_T = 4.3 \pm 0.6$ f, $R_L = 2.6 \pm 0.6$ f, $\lambda = 0.34 \pm 0.08$, for $1 < y < 2$, but peculiar ones, namely $R_T = 8.1 \pm 1.6$, $R_L = 5.6 \pm 1.0$ and $\lambda = 0.77 \pm 0.19$ in the central rapidity region, for $2 < y < 3$. Read at face value, this shows that, in the central region, pions originate (freeze out) from an inflated fireball 2.5 times the size of the incident oxygen ion, which is highly chaotic (thermalized).

There is a probably correlated peculiarity in the transverse momentum distribution. It is shown in Fig. 12, comparing π^- p_T distributions in oxygen-gold and proton-proton collisions at the same energy. In the former case one notices a sharp spike at low p_T , a behaviour which could be associated with the anomalously large size of the source. One also notices a tail at large p_T . This is certainly due in part to the Cronin effect. It can also be analyzed in terms of a collective flow³⁰. The widening of the p_T distribution at large p_T is also observed for π^0 's (WA80)¹². The analysis in terms of a collective flow is particularly interesting, since it shows that, even from the point of view of a purely hadronic system, the spectrum and the source size ($\pi\pi$ interferometry) impose an energy density which is initially very large, of the order of 2 GeV/fm³.

Figure 12: Transverse momentum distribution of π^- in pp and oxygen-gold collisions. Results of NA35.

While these results cannot yet be claimed as evidence for the formation of a blob of quark-gluon plasma, it seems impossible to escape the conclusion that a large "spherical" chaotic system, stemming from a very high energy density, appears in the central rapidity region. This is new.

It would be very nice to have similar interference data for other particles, but this is not yet for this Conference. π^- are plentiful and easy to distinguish from other particles! Yet hadron interferometry has already shown itself to be a very powerful tool, with big news at stake.

One should remark that, with increased statistics, this generalization of the Hanbury-Brown and Twiss analysis could be even richer in its probing of the production mechanism. The three-parameter fit used is only a first approximation. The topic is ripe for an increase in sophistication³¹, and conclusions could therefore still be premature.

The question of prompt photons has long been on the hunting list. A blob of quark-gluon plasma should radiate. Photons should escape and their spectrum should indicate the temperature. But looking for prompt photons is difficult! We do not yet have any definitive information. Nevertheless, NA34 claim that their photon distribution has a shape which is compatible with known hadronic sources over the $0.125 < p_T < 1.4$ GeV/c range, and WA80 claims a γ/π^0 ratio of 0.1 around 1 GeV/c increasing to 0.3 at about 2.5 GeV/c³². There is no open conflict at this stage, but certainly an embarrassing situation. The question of prompt photons is a burning one, and it is unlikely that this Conference will see the situation clarified. Patience must be shown - prompt photons are hard to get at. The same applies to strangeness excitation, but here the Conference is likely to bring forward new and clear results.

A year ago, at "Quark Matter '87", E802 came up with the striking result that the K^+ over π^+ ratio was $24 \pm 5\%$, with their central trigger¹². This was deemed very high but, as an average over their acceptance, it could still have been mostly due to the increase of the K^+/π^+ ratio with p_T , well known in pp collisions. This experiment has a powerful particle separation system and their scatter plots are of textbook quality, as shown in Fig. 13. Over the past year, the analysis has been refined and one now has $\pi^+(\pi^-)$ and $K^+(K^-)$ p_T distributions³². The K^+ and π^+ distributions are shown in Fig. 14. The m_T ($m_T^2 = p_T^2 + m^2$) distributions coincide. Near the maximum of the $d\sigma/dp_T$ distribution, the K^+/π^+ ratio is definitely about twice as high as in pp collisions at the same energy. This is a new effect.

At this Conference, we shall hear much more about these beautiful results^{18,33} and also about recent CERN results on Λ production (NA35) and on the $\bar{\Lambda}/\Lambda$ ratio (WA85). It seems that there is an excess of K^+ (E802) and Λ (NA35)

Figure 13: Particle separation in experiment E802.

Figure 14: Differential cross-section as a function of m_T for π^+ and K^+ . Silicon-gold collisions at 14.5 GeV/A, $1.3 < y < 1.6$. Result from E802.

as compared to what is expected from a mere superposition of nucleon-nucleon collisions, by a factor of two. However, it is not yet clear whether the separately reported K^+ and Λ enhancements can be put on the same footing, as one could naively do. We shall hear about their respective determination and characteristics.

One may of course remark that it is relatively easy to produce both K^+ and Λ strange particles in any dense hadronic medium and that, once produced, these particles may also escape relatively easily. The observed strangeness enhancement does not yet therefore provide evidence for the formation of a quark-gluon plasma. It calls at least for a very dense system with long enough a lifetime, so that strange particles can be produced copiously enough in pairs through hadron collisions. This is already an important new effect.

We are likely to be left with the conclusion that there is an excess of strangeness, but that its origin cannot be firmly associated with the formation of a quark-gluon plasma. How do we proceed further?

Information on antibaryon production would be easier to assess. An important excess of antihyperons would be very hard to trace to purely hadronic reactions. The WA85 experiment¹⁸ reports a value for the $\bar{\Lambda}/\Lambda$ ratio. In the central rapidity region, where it is measured, it looks normal, though one should stress that we have no pp data to compare it to! Do the excess of Λ 's of NA35 and the "normal" $\bar{\Lambda}/\Lambda$ ratio of WA85 indicate an excess of $\bar{\Lambda}$? This is certainly too far-fetched! We can look forward to interesting discussions, but we need more data. On the other hand, one should try to estimate better the strangeness production rates. They are certainly faster in a quark-gluon plasma than in a hadronic gas for mere threshold effects, but by how much? We still lack fully reliable values and we actually have to admit that we just do not know how hadronic reactions work at very high particle density.

The last but most important special feature is, of course, J/ψ suppression. This deserves a special mention.

5. J/ψ SUPPRESSION. IS IT THE SMOKING GUN?

The production of J/ψ (seen through its muon pair decay) is relatively suppressed as compared to the Drell-Yan background in events which are selected according to a large transverse energy. At "Quark Matter '87", NA38 already presented impressive results¹². This is shown in Fig. 15a, which gives the J/ψ signal and the Drell-Yan background in oxygen-uranium reactions at 200 GeV/A for $E_T < 28$ GeV and $E_T > 50$ GeV in the calorimeter respectively. The signal over background ratio is much larger in the former case than in the latter one. This is more clearly shown in Fig. 15b³⁴. Comparing data with $E_T < 33$ GeV to data with $E_T > 82$ GeV, the relative suppression effect is of the order of two.

Figure 15: 15a: J/ψ signals to Drell-Yan ratio as observed by NA38 for $E_T < 28$ GeV and $E_T > 50$ GeV in the calorimeter. Oxygen-uranium at 200 GeV/A.

15b: The J/ψ signals for $E_T < 33$ GeV and $E_T > 82$ GeV normalized to the same Drell-Yan background.

Reactions with large E_T , where a quark-gluon plasma is produced, have a much smaller yield of J/ψ relative to the Drell-Yan continuum. This effect was predicted¹⁹.

At the same time¹², it was found that this suppression effect disappears gradually as the p_T value of the J/ψ increases. This is shown in Fig. 16a, where one also sees that no such p_T dependence occurs for the Drell-Yan background. In Fig. 16b the p_T dependence of J/ψ suppression in oxygen-uranium collisions, actually the ratio $\bar{R}$ of the $E_T > 68$ GeV and the $E_T < 38$ GeV results, is shown as a function of p_T , together with expectations based on the formation of a quark-gluon plasma in the large E_T events³⁵. This effect was indeed predicted²⁰, large p_T J/ψ escaping the plasma before binding takes place.

The results of NA38 are clear and neat; they offer a beautiful new view of heavy ion collisions. No such effect is observed in proton-uranium collisions. One is inclined to salute the Portuguese members of NA38 (Portugal is the newest member of CERN) with the verse of Camoes:

"As armas e os barões assinalados
Que da ilustre praia Lusitana
Por mares nunca antes navegados...."

Figure 16: 16a: The p_T dependence of the ratio for the J/ψ signal for high and low E_T events and the absence of effects with the Drell-Yan background.

16b: The p_T dependence of the J/ψ suppression ratio in oxygen-uranium collisions at 200 GeV/A together with theoretical expectations (Ref. 35).

Is it the looked-for signal? More recently, the sulphur results have consolidated the earlier oxygen ones²¹. Figure 17 shows the $E_T/A^{2/3}$ dependence of the suppression effect combining results on oxygen-copper, oxygen-uranium and sulphur-uranium collisions³⁴. There is, as anticipated, a good scaling behaviour and the dependence seen in Fig. 17 agrees with expectations based on the formation of a quark-gluon plasma at large enough energy density³⁵.

Has the quark-gluon plasma thus been discovered? It is probably too early to draw any definite conclusion, but we shall hear passionate debates on this subject at this Conference³⁶. The experimental result has indeed triggered a very large amount of theoretical work, either trying to explain the observed effect by standard hadronic processes or trying to be more quantitative when following the quark-gluon plasma approach.

It is clear that a large value of E_T is likely to signal a collision with a small impact parameter where the J/ψ is produced deep inside nuclear matter. It therefore stands a greater chance of being absorbed than in a more peripheral collision³⁷. It was realized, however, that expected absorption effects are not enough. In order to reach the observed suppression effect, one has to argue that very dense hadronic matter has to be there long enough to provide enough absorption. Standard nuclear matter would not be sufficient. Yet one is also led to challenge the simple A^α parametrization used so far to express J/ψ production off nuclei. This is certainly no longer good enough.

Figure 17: J/ψ to continuum ratio as a function of $E_T/A^{2/3}$. Results from NA38.

The main shortcoming of the absorption approach is, however, that it does not explain the p_T dependence which comes out so naturally in the plasma approach. Another effect which was at first overlooked has recently been exploited in order to explain it. It is known that Drell-Yan and J/ψ production off nuclei show a wider p_T distribution than off protons. The quarks or gluons which annihilate respectively in these processes also radiate, and this radiation results in a p_T distribution which widens with the size of the target. Transposed to nucleus-nucleus collisions, this leads us to expect a much wider p_T distribution for the produced J/ψ than in a proton-proton collision at the same energy³⁸. One therefore depletes the J/ψ production at low p_T and strengthens it at large p_T . Completed with a strong absorption, all observed effects can thus be accounted for.

There remains a clear difference between this approach and the quark-gluon plasma one. In the former case, the ratio in [Fig. 16b](#) should eventually increase beyond 1 at large p_T , whereas it should saturate at 1 in the latter case. At present the data stop frustratingly short!

There is an alternative classical explanation for the observed J/ψ suppression and one can certainly look forward to interesting discussions. One may remark, nevertheless, that even in the "classical" approach, one has to

appeal to an anomalously high absorption which can result only from a very dense system with long enough a lifetime, and one has to appeal also to partonic degrees of freedom (gluon radiation) in nuclear matter. All this is new.

6. CONCLUSIONS

This Conference will offer the proper conclusions at this time. It will provide a clearer and richer experimental picture, with many new data reported. It will be a forum for lively discussions which will bear witness to the topical interest of this field of research.

One cannot fail to be very happy at the progress made over the past few years. One may say that seldom in particle physics have so short runs yielded so many interesting results. With the new data, the field has shifted gear. It has already been beautifully reviewed on several occasions over the past year³⁹, and its recent progress can thus be easily assessed.

At present one can say that:

- i) The energy density reached is high, and most probably high enough.
- ii) The events are manageable, despite their complexity. However, we have to be patient when trying to get the results.
- iii) There are already very puzzling and interesting results, in particular the large K^+/π^+ ratio (E802), the $\pi^+\pi^-$ interferometry findings (NA35) and, last but not least, J/ψ suppression (NA38).

Hence there is a great deal of enthusiasm to continue. There is a need for more statistics in some of the present experiments. There is also a need for experimentation with heavier ions at present energies. By 1992, Brookhaven should have ion beams extending in mass to gold. Funding permitting, there could also be by that time a lead beam at CERN, with acceleration of the lead ions in the PS-SPS complex. We all look forward to RHIC, with its 100 GeV/A colliding beams, and maybe later one could have lead colliding beams at 3.2 TeV/A in the CERN-LHC.

Looking at the near future, one may say that after the exploratory runs, we have reached a stage where luminosity becomes an important issue in some of the experiments. We would like to have more statistics, while at the same time imposing more severe selection criteria or studying particles ($\bar{\Lambda}$) which are not copiously produced.

At CERN, one may even ask the question: "Is sulphur always to be preferred to oxygen, granting the fact that there is a very sizeable loss in intensity?" Going from oxygen to sulphur, the gain in energy density is small. How important is the gain in volume and lifetime?

This Conference should help to answer such a question and also many others.

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