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HEAVY-ION COLLISION PHENOMENOLOGY

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Abstract

This review serves as a tentative summary to the session on heavy-ion collisions, where several topical points were discussed in detail, through a series of talks.

1) Invited Contribution to the Heavy-Ion Session, 25th International Conference on High-Energy Physics, Singapore

1. INTRODUCTION

The purpose of heavy-ion collisions, as recently studied, mainly at CERN and at BNL, is to reach very high-energy (and quark) densities over the volume of the colliding ions. The projectile ions are still only moderate in size, with oxygen and sulfur runs at CERN and oxygen and silicon runs at BNL. In view of the rapidity dependence of the observed effects, and the limited acceptance of many experiments, it pays to start with a symmetric system, hence the emphasis put on sulfur–sulfur collisions at CERN. This is one more of the reasons which calls for the use of higher mass projectiles. The BNL programme will be extended to gold in '92. At CERN, the construction of a dedicated injector, now approved, will make lead–lead collisions possible in '94.

With high-energy (and quark) densities, we are after a new state of matter, a quark–gluon plasma within which colour is no longer confined. Expected conditions are such that it should be within reach with present facilities [1].

I shall discuss in turn:

i) the theoretical guide-lines;
ii) the promising signals;
iii) where we are at present;
iv) how to continue.

2. IN SEARCH OF QUARK MATTER

Exploratory runs started in '86, at BNL and at CERN. They quickly brought interesting results. These results were presented and extensively discussed at Quark Matter '87 (Nordkirschen), Quark Matter '88 (Lenox), and Quark Matter '90 (Menton) [2].

Nuclear physicists have long searched for a new state of nuclear matter at higher density, which could be reached once the repulsive core of the nuclear force has been overcome. In the framework of QCD we now know what it should be, namely a quark–gluon plasma. It should be the stable state of matter at high temperature or/and high density. One may say that:

i) Its existence is a big issue in QCD since it affects the long-range behaviour where the theory is still poorly explored, and in particular the expected confining property. It also touches the interesting features of a field theory at high temperature.

ii) Its existence is also a big issue in astrophysics. The core of neutron stars could be in the plasma phase.

iii) It is also a big issue in cosmology. The early Universe is expected to have been a quark–gluon plasma up to 10^{-5} s after the Big Bang, hadronization proceeding when the temperature was much below the nucleon mass ($T \sim 0.2 m_{\mathrm{p}}$). Baryonic density fluctuations resulting from such conditions could help raise the maximum value of the baryonic density up to 0.3 times the critical density, while a limiting value of 0.2 was usually admitted to follow from the observed helium abundance. With large density fluctuations a higher fraction of the primordial neutrons could be lost before nucleosynthesis can start.

The parameters of the expected phase transition between hadronic matter and quark matter can be estimated from lattice gauge theory and Bag Model calculations [1,2]. It is usually agreed that quark matter corresponds to the stable phase for $T \gtrsim 200$ MeV, at low quark density (actually quark chemical potential), or for $\rho \gtrsim 5\rho_{\mathrm{N}}$ at low temperature, where ρ_{N}, the nuclear density, is of the order of 0.15 GeV/fm^3.

Such conditions could be reached in heavy-ion collisions at 200 GeV/A (CERN programme). While the BNL energy is much lower (15 GeV/A), the corresponding higher stopping power could also help achieve adequate conditions.

We have to admit that we know very little about standard hadronic collisions under such conditions. This is a new ground to explore even when hadrons do not lose their identity.

The aim is therefore to study matter at very high energy and quark densities. The hope is, of course, to find evidence for a phase transition and, beyond it, for the quark–gluon plasma.

When the CERN and BNL programmes started in '86 there were two important questions to answer [1]:

i) Can one achieve, in that way, interesting enough conditions, with energy densities at the level of 2 GeV/fm^3, or more.

ii) Can one study at all what happens with typically 500 secondaries produced in such collisions.

The answer was a double yes [2] and therefore a strong encouragement to continue the programme with heavier ions.

Lattice gauge theory calculations offer the best present guide-lines when trying to obtain the properties of the phase transition. Progress has however been slow. One did not anticipate, at first, the computer power which would be needed to extract meaningful results. Yet big steps forward could be possible and the present situation is reviewed by Ukawa [3]. To illustrate the effort involved one may say that from 1980 to 1990 the typical number of 'flop units' per project has increased from 10^{11} to 10^{17}. This gain by a factor of 10^6 corresponds to a big increase in computer power, available both from new commercial computers and from dedicated projects. It also corresponds to the organization of large collaborations which have replaced the many individual groups computing independently in the early period [1].

With 'teraflop' capability, as now envisaged for the relatively near future, the number of flop units could be extended to 10^9, with an extra gain by a factor of 10^3. Recent calculations [3,4] correspond to typically 10^4 hours of Cray YMP or the equivalent of it.

Calculations have long been limited to pure gauge where, in SU(3), it is known that the transition is first order, with a critical temperature of the order of 200 MeV. The calculation of the critical temperature results from a simultaneous calculation of the ρ mass, both values being expressed in terms of the lattice parameters. Calculations now include dynamical quarks. With four flavours, all of rather small and identical mass, the transition is found to be also of first order, but with a critical temperature of about 100 MeV. The latent heat is also rather small, the quantity ε/T^4 rising both before and after the jump associated with the phase transition. With two flavours, the transition seems to be of second order, but could still be of first order, and with a critical temperature of 150 MeV [3]. With two light quarks and a heavier one the transition looks like first order. All these questions have still to be examined in detail [3]. Despite the fact that all present calculations refer to zero value of the quark chemical potential, this can be considered as good news. Adding quark degrees of fredom seems merely to increase the colour screening provided by the gluons in a pure gauge calculation; but much work is still needed. Indeed one should distinguish the first-order *deconfinement* transition which is found for heavy quarks, or the pure gauge case, from the first-order

chiral symmetry restoration which is found for light quarks (with a number of flavours $N_f > 2$). It is not yet clear whether the latter case corresponds to the actual situation [4] and whether the two transitions correspond to the same process.

Precision [with at present $(16)^3 \times 8$ lattices] will increase. One will be able to study changes associated with variations of the quark masses. There are gains to expect from an increase in computer power. There are perhaps more difficult but more efficient gains to be obtained from better algorithms.

One has gained confidence in the existence of a phase transition, with parameters of the order of those first estimated [1]. There is also a fair amount of optimism to go from pure gauge QCD, to which one has long been limited, to full QCD.

These changes with N_f and quark masses may seem peculiar. However, as shown by Shuryak [4], the chiral symmetry restoration transition can be considered as a liquid–gas transition for instantons. The 'liquid' state appears for enough flavour (N_f) light-quark lines only, as they connect instantons to anti-instantons in a complicated enough way.

Indeed, an instanton can be considered as the vertex producing a quark–antiquark pair of each light flavour, as long emphasized by 't Hooft.

3. THE SIGNALS

A reference to the Cheshire cat of 'Alice in Wonderland' has often been made. One cannot see the cat but only its grin, after it has disappeared. The plasma blows itself out almost immediately after it has been formed. Yet a certain number of promising signals have been proposed [1,2]. What is the present situation:

i) *Transverse energy and particle rapidity densities*

One looks for particularly large values and important fluctuations. Extensive results have been obtained by Experiments E802, NA34, NA35, WA80, and a large number of emulsion experiments [2].

One finds particularly high values of dE_T/dy and dn/dy which bear witness to large energy densities being reached. However, nothing very peculiar is found. This is not so surprising, even if something very special happens, since the many pions produced are great averagers.

ii) *Peculiar photon radiation, or low-mass lepton-pair production*

This would, in principle, be the best way to measure the temperature reached and the volume over which this temperature was effective [1,5]. Background problems speak for themselves. Nothing conclusive has been reported yet.

iii) *Enhanced strangeness production*

A high-temperature plasma should give through chemical equilibrium a large number of $s\bar{s}$ pairs and the more so when it is produced with a high ud chemical potential [6]. Results have mainly come from Experiments E802 and E810 at BNL, and NA34, NA35, and WA85 at CERN. This is the latest of the clearly ascertained effects. Strangeness production is definitely enhanced in reactions selected for their high transverse energy. The relative enhancement with respect to lower E_T reactions is typically a factor of 2 [7].

The most significant effects are those associated with Λ and $\bar{\Lambda}$ production (NA35 and WA85) and with the $\bar{\Xi}/\Xi$ (and $\bar{\Lambda}/\Lambda$) ratios (WA85). We shall come back to that later.

iv) *Are peculiar systems formed?*

Among the most dramatic ones, one may quote many-quark systems and in par-

ticular strangelets. Nothing has been seen so far.

v) *Are there peculiar collective effects?*

They could be seen through the formation of systems of anomalously large size, detected through $\pi\pi$ or KK interferometry. The meson–meson correlations are then analysed in terms of radius parameters, measuring the fireball size at freeze-out time, when the observed mesons are formed. The NA35 Collaboration reported an increase in size by a factor of 2 for $\pi^-\pi^-$ produced in central collisions in its early oxygen run [2]. The situation is still unsettled and calls for high-statistics analyses.

vii) *Is J/ψ production suppressed?*

This possible signal, associated with the colour screening of the plasma, has long been proposed [8]. A suppression by a factor of 2 in high-E_T reactions has since been reported by NA38 [2]. The analysis has been refined [9]. The effect matches all expectations, namely:

a) relative suppression in high-E_T reactions;
b) no suppression at large p_T;
c) scaling according to energy density, namely $E_T/A^{2/3}$.

We thus see that, whilst some looked-for and most-important pieces of information, such as the prompt photon yield, the $\bar{\Xi}/\bar{\Lambda}$ ratio, etc., are still lacking, two clear new effects have now been ascertained. They both correspond to a change by a factor of 2, in reactions with a large amount of transverse energy, where a quark–gluon plasma blob could have been formed:

a) J/ψ production is suppressed by a factor 2;
b) strangeness production is enhanced by a factor 2.

This is already a good score! However, while these expected effects have been found, one should admit that they could also result from more standard mechanisms. A careful analysis has to be done to see whether or not they can be considered as bona fide signatures of the formation of a quark–gluon plasma.

In the case of J/ψ suppression one can argue that central high-E_T collisions are those for which absorption, and in particular that of the produced J/ψ, is particularly large [10,11].

In the case of strangeness production one can argue that, in dense nuclear matter, secondary collisions can generate more strange particles whilst they are unlikely to suppress some of them (K^+, Λ) because of lower cross-sections.

Debates have been impassioned, in particular at Lenox (J/ψ) and at Menton (strangeness). It seems now clear that one should consider both effects simultaneously when advocating a particular model. The situation may then become clearer. Information on ψ' and on antihyperon formation would greatly help. This should be available soon.

4. ASSESSING THE SIGNALS

Particle densities and transverse-energy densities are now well documented [2]. At first sight a nucleus–nucleus collision looks like a superposition of nucleon–nucleon collisions according to geometry. Models are very successful at reproducing the observed distributions. One can indeed use the observed spectra to analyse the shape of the colliding nuclei and check, for instance, that tungsten and uranium nuclei are not spherical. However, all this may *a priori* look like boring news. It did to some extent in '87. But then, the great piece of news was that the stopping power was high, indeed as high as

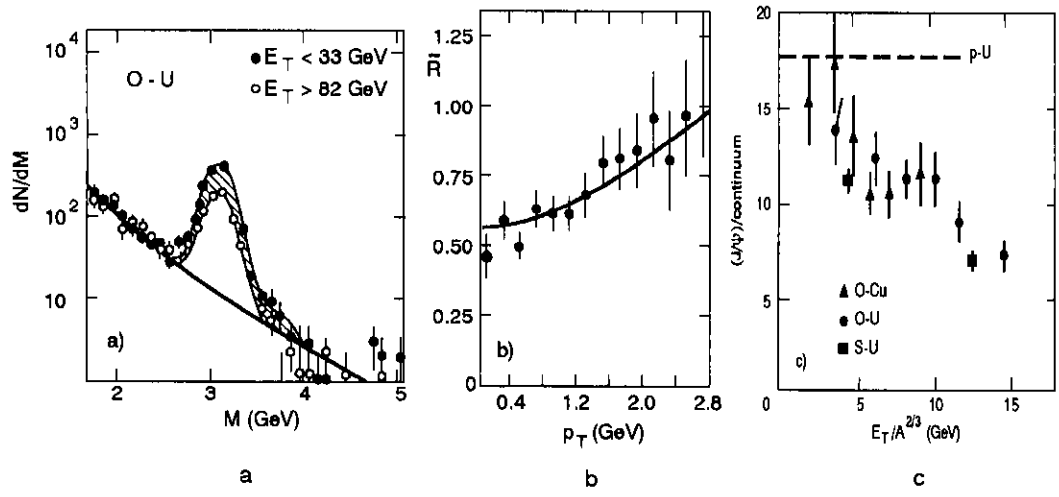

Figure 1: A summary of the effects associated with J/ψ suppression. a) The J/ψ signals for $E_{\mathrm{T}} < 33\,\mathrm{GeV}$ and $E_{\mathrm{T}} > 82\,\mathrm{GeV}$ normalized to the same Drell–Yan background b) The p_{T} dependence of the J/ψ suppression ratio in oxygen-uranium collisions at 200 GeV/A together with theoretical expectations (Ref. 35). c) J/ψ to contiuum ratio as a function of $E_{\mathrm{T}}/\mathrm{A}^{2/3}$. Results from NA38.

one could hope for, and, therefore, that the excitation energy, and as a result the energy density reached, was high. Even at 200 GeV/A the maximum excitation energy (end of the E_{T} spectrum) is about 60% of that expected from full stopping of the impinging nuclei.

Estimates of the energy density reached remain a little ambiguous. There seems to be a consensus that they give $\sim$ 2 GeV/fm^3. This is what one was aiming at. The particle and transverse-energy rapidity distributions, which are closely correlated, show that conditions suitable for the formation of a quark–gluon plasma should be achieved.

Figure 1 summarizes the situation with respect to J/ψ suppression, with its three positive scores [8,9]. Is it one of the looked-for signatures?

An explanation based on absorption has to circumvent the disappearance of the suppression effect at large p_{T} ($p_{\mathrm{T}} \gtrsim$ 2 GeV/c). This is done by arguing that the p_{T} distribution in ion–ion collisions is much wider than in proton–proton collisions. This, in turn, may result from multiple gluon scattering before a χ is formed through gluon–gluon fusion. The formation of a χ is an important source of ψ's through $\chi \rightarrow \psi\gamma$ decay. A large absorption will then give an overall strong suppression at low p_{T} but no net result at large p_{T} [11]. This is also a possible scenario.

One may, of course, remark that the strong absorption needed requires a very high density and that the multiple-gluon collisions, also needed, imply some colour transparency of very dense nuclear matter. On both counts one is also close to a quark–gluon plasma, the issue then being thermalization. However, playing on the J/ψ absorption cross-section, the high-density condition could perhaps be relaxed [10].

One realizes that in order to push the analysis, information about J/ψ production in proton–nucleus collisions is not as extensive as one would wish! Recent results from E772 [12] seem to indicate that the ratios of the p_{T} differential cross-sections in proton–lead and proton–carbon do not show the behaviour needed in the absorption scenario, namely a sizeable increase with p_{T}. Also the mean value of p_{T}^2 as a function

of the transverse energy, which increases for J/ψ production, does not seem to increase for Drell–Yan lepton-pair production (NA38), when it should do so in the absorption scenario. These results have recently been globally analysed [13]. Whilst one cannot yet come to a conclusion in view of their still limited accuracy, the production of J/ψ in proton–nucleus collisions does not seem to show any of the prominent features that would help to explain the observed effect in nucleus–nucleus collisions along rather standard lines. This is clearly a case for more statistics, both for proton–nucleus and nucleus–nucleus collisions. The behaviour at large p_T ($p_T > 3$ GeV/c) is also tantalizing. It should saturate at 1 in the plasma scenario. It should keep rising in the absorption one.

Strangeness enhancement was the new feature this year [2]. Some evidence for it was available at Quark Matter '88. It had come of age at Quark Matter '90 [14].

At present there are results from E802 (K,$\overline{\text{K}}$) and E810 (V's), from NA34 (K,$\overline{\text{K}}$), from NA35 (V's), NA38 (ϕ), and WA85 (V's, Ξ, and $\overline{\Xi}$) [7,9]. Strangeness enhancement is seen in many channels. The claim of an enhancement by typically a factor of 2 in reactions with large transverse energy is supported by the analysis of the rapidity and transverse-mass dependences.

The transverse-momentum distributions of the produced strange particles can all be fitted to a temperature of 200 MeV.

In the plasma scenario [6] the enhancement of strangeness production results from the expected abundance of $s\bar{s}$ quarks. This should imply an important increase of the $\overline{\Xi}/\bar{\Lambda}$ ratio as compared with that measured in proton–nucleus and proton–proton reactions. However, no information is yet available on this most crucial test. Many of the observed $\bar{\Lambda}$ should then be daughters of $\overline{\Xi}$, with a resulting longer effective lifetime or a non-vanishing longitudinal polarization.

On the other hand, it is relatively easy to produce K^+ and Λ, and results on their enhanced yields are therefore not conclusive alone [14].

Most important, therefore, is the enhancement of the antihyperon yield. This is shown in Fig. 2, which puts together the NA35 results on Λ and $\bar{\Lambda}$ production in sulfur–sulfur collisions and the WA85 results on the relative $\bar{\Lambda}/\Lambda$ yield in sulfur–tungsten collisions. In the former case the production in high-multiplicity reactions is typically two times that expected from a superposition of nucleon–nucleon collisions, whereas nothing peculiar is found in proton–sulfur reactions. In the latter case there is an increase by a factor of 1.7 of both the Λ/h^- and $\bar{\Lambda}/h^-$ ratios between sulfur–tungsten and proton–tungsten. Here h^- stands for negatives, mostly π^-'s. At the same time, the ratio $\overline{\Xi}/\Xi$ for sulfur–tungsten is found to be 0.43 ± 0.07, whilst it is 0.27 ± 0.06 for proton–tungsten.

If supported by better statistics this last result would be very significant, with production of $\overline{\Xi}\Xi$ pairs becoming more important over nucleon excitation into Ξ, as expected from the hadronization of an $s\bar{s}$ rich system. Of course the $\overline{\Xi}/\bar{\Lambda}$ ratio should also be rather important [6]. With different acceptance limitations for Ξ and Λ, information is however not yet available.

The enhancement of ϕ production over $\rho\omega$ production has been reported by NA38 [9]. This may a priori be considered as one more example of strangeness enhancement. This would be the case if one would look at most of the ϕ produced. However, ascertaining vector mesons seen through their $\mu^+\mu^-$-pair decay among an overwhelming background is possible only to the extent that a rather high-p_T cut is applied, namely 1.3 GeV/c.

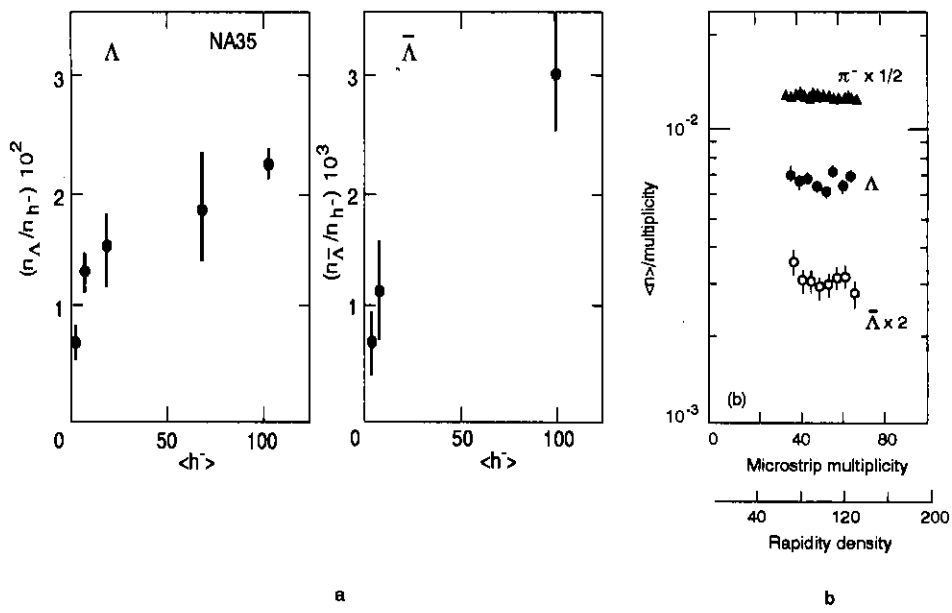

Figure 2: Hyperon and antihyperon yield normalized to negative production. a) Results from NA35 in sulfur–sulfur collisions. b) Results from WA85 in sulfur–tungsten collisions ($2.3 < y_{\rm lab} < 3.0$).

Only under such conditions can one extract the associated peaks. One then finds a relative increase of the order of 1.5 between high-$E_{\rm T}$ and low-$E_{\rm T}$ reactions, and a relative increase by a factor of 3 between high-$E_{\rm T}$ sulfur–tungsten reactions and proton–tungsten reactions [9,15]. There is a clear effect, as shown in Fig. 3 [14]. However, its interpretation is still ambiguous. It is well known that the fragmentation of a jet gives relatively easily a leading strange particle (the $\rm K^+/\pi^+$ ratio increases sharply with $p_{\rm T}$) and the same should apply to a leading ϕ as compared with a leading ρ or ω. When keeping only those vector mesons produced at large $p_{\rm T}$ one biases oneself in favour of a jet production and fragmentation with a leading vector meson. The corresponding yields are small at these energies, but no one doubts that jets are produced and could be an important source of vector-meson production at large $p_{\rm T}$. The rise of the ϕ/ω ratio would then be seen as the result of the relative increase of the jet component with increasing observed transverse energy. Figure 3 shows the scaling behaviour which would then also be expected.

There should not be such a strong increase with $E_{\rm T}$ in proton-induced reactions. Indeed, in that case, there is at most one pair of jets to be expected, whereas in a nucleus-induced reaction several jet pairs can be produced at the same time.

It seems that NA38 could thus have seen the jet signal missed long ago by NA5, while first observing large-$E_{\rm T}$ reactions at a similar energy with a wide solid-angle calorimeter [16]. This jet mechanism again seems to be a tenable explanation for the effect, besides its also entering naturally into the debate between the quark–gluon scenario (large number of $\rm s\bar{s}$ pairs) and the rescattering one, with ϕ resulting from secondary collisions in the dense medium and then escaping too much absorption, when once formed, because of their small cross-section.

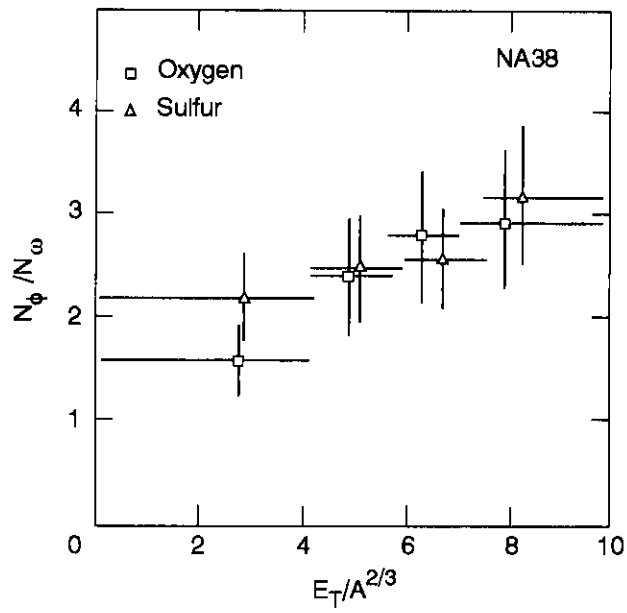

Figure 3: ϕ enhancement relative to ω, ρ and its dependence on the energy density (NA38). Shown is the oxygen and sulfur values normalized to the proton value.

5. THE PRESENT SITUATION

The present situation is definitely far different from what is was before '86 and the first round of experiments at CERN and BNL. Before that time, one had only:

i) heavy-ion collisions at too low energy (Bevalac);

ii) very energetic collisions but with too light ions ($\alpha\alpha$ at the ISR);

iii) very energetic heavy-ion collisions but with very little statistics (cosmic-ray studies).

One now has a rather good picture of the heavy-ion collision in the highly relativistic domain ($E \gg m$). The energy densities that can be reached appear to be in the proper range ($\varepsilon \geq 2$ GeV/fm^3). The events are manageable despite their very high multiplicities. Many specific questions are calling for an increase in integrated luminosity.

Two peculiar effects have been found. They were both expected. They stand out clearly, each one implying typically a factor of 2 effect between low-E_T reactions, where nothing very special is expected to occur, and high-E_T reactions, where a quark–gluon plasma could have been formed. They are, as we saw, J/ψ suppression (colour screening) and strangeness enhancement (chemical equilibrium).

They both appear as first expected [8,6]. Nevertheless, they are now both at the origin of very exciting debates. In any case, one may say that there are special effects associated with dense hadronic matter. This readily brings up the question of rates in a quark–gluon plasma and in dense hadronic matter. Much work remains to be done in assessing them. Even in the latter case one is exploring new grounds!

At present, an optimist would say

i) When one looks 'outside', namely at the many pions produced in a nucleus–nucleus collision, everything seen is compatible with what could be expected, but nothing very special appears.

ii) When one looks 'inside' (in particular J/ψ suppression) it does seem as if a quark–gluon plasma had been formed.

But the only conclusion that one can safely draw is that something new and special is happening. It is at the origin of lively debates and it is providing much enthusiasm to continue along these lines.

Certainly each new feature found could *a posteriori* be 'explained' following more standard lines.

However, whichever way one tries to explain the observed results, one can hardly escape the conclusion that a system of high density has been formed ($\sim$ 2 GeV/fm^3 say), that it had a long enough lifetime to allow for rescattering (a few fm/c), and that some rescattering at the constituent level occurred, which means that the system formed is transparent to colour. This is certainly something new. However, this is not yet a quark–gluon plasma. One cannot yet claim that some thermalization and full chemical equilibrium takes place. In the case of strangeness enhancement, for instance, the $s\bar{s}$ fragmentation of gluons would have produced the same result even if gluons do not scatter enough to be thermalized. A dense quark and gluon system is all that is needed.

Information on photon (low-mass lepton pairs) yields could settle the issue. More information on $\overline{\Xi}$ and $\bar{\Lambda}$ production would also be very useful to assess the $s\bar{s}$ density.

Since one is after a phase transition, size is a key parameter. Granting the fact that the stopping power is good and that the energy density which can be reached is high enough, there is a very strong case to increase the size of the ion projectile.

6. OUTLOOK

One can increase the volume of the colliding ions and go all the way to, say, lead–lead collisions. As previously said there is a strong case to do so. This will be possible at BNL in '92 (15 GeV/A) and at CERN in '94 (160 GeV/A).

The energy density is not expected to increase much. The excitation energy goes up with the size (and energy) of the incident ion but it gets distributed over a larger volume. It is estimated to increase as $A^{1/6}$ only, which, from sulfur to lead, represents a gain by a factor of only 1.25. The size, however, is increasing much more: the gain is a factor of 1.85 in radius.

The reaction rates that are at play in the formation of the quark–gluon plasma are clearly increasing with the energy density, which one can thus hardly enhance, with the relevant cross-sections, which are fixed, and with the available length, which is the parameter that one can play with.

Granting the fact that multiplicities are manageable, lead–lead collisions are therefore very interesting.

Increasing the energy by as large a factor as possible with RHIC, with heavy-ion collisions up to 200 GeV/A in the centre of mass, should lead to an increase in energy density, which can be safely expected on the grounds of the rise of the central rapidity plateau. However, the key new feature will be that this very high energy density will now be reached in a baryon-poor region as opposed to the baryon-rich region presently obtained even in the CERN programme. Conditions will be different and in that case similar to those in the early Universe.

Later on, lead–lead collisions could be studied up to 7 TeV/A in the centre of mass at the LHC. The new dedicated lead injector could be used for feeding the LHC as it will soon be feeding the PS–SPS complex. In this case one may contemplate the continuation of the present heavy-ion programme, reaching still higher energy densities

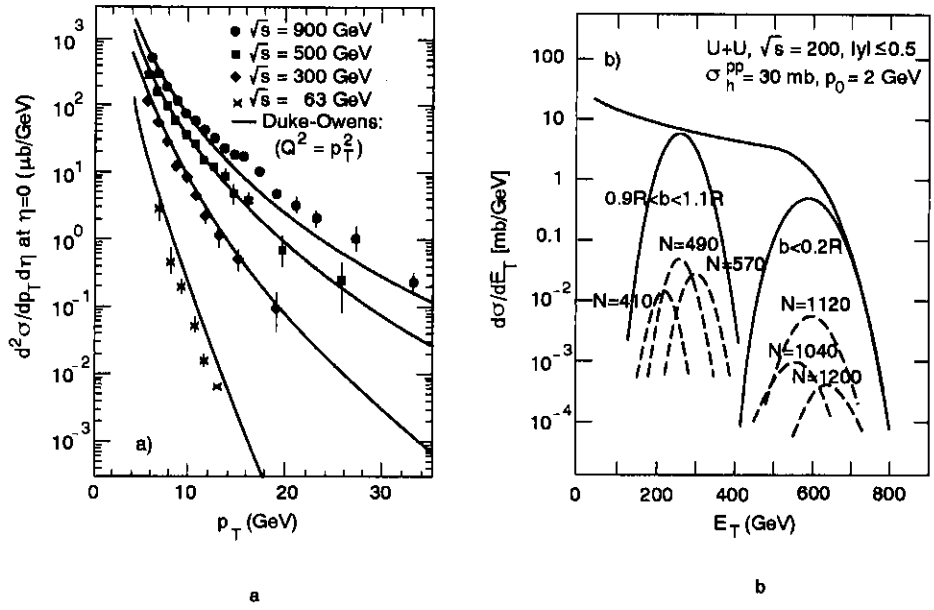

Figure 4: Minijets at the origin of quark–gluon plasma formation at RHIC energy. a) The inclusive jet yield and QCD prediction. b) The transverse-energy yield in UU collision expected from minijets down to 2 GeV/c.

in a baryon-poor region, but also there, there is the question of particle production in very intense electromagnetic fields. The colliding lead ions will provide an intense source for $\gamma\gamma$ collisions in the TeV range. This is very interesting for other reasons, namely new particle search.

When considering RHIC collisions (and of course LHC ones) an interesting mechanism to create the quark–gluon plasma is offered by mini-jet formation. There is a very large number of partons (and in particular low-x gluons), which can scatter independently of one another and provide a final state with many gluons scattered at wide angles. These gluons are so dense that they will rescatter and this could provide efficiently a partly thermalized plasma. The present situation is summarized in Fig. 4. We see (Fig. 4a) the mini-jet yield as observed over the ISR–SPS energy range (UA1) [17] and leading-log calculations in QCD which provide a good description down to the p_{T} value of 3 GeV/c [18]. Extending the calculation down to 2 GeV/c and taking into account multiple scattering during ion–ion collisions, one obtains a very high amount of transverse energy from these mini-jets alone (Fig. 4b). The distribution expected for UU collisions extends up to 700 GeV [19]. At 20 GeV of centre-of-mass collision energy, where one is now with the SPS programme, one expects that only 5% of the total transverse energy originate from clear mini-jets (taking a cut-off value at 2 GeV/c). This ratio should increase to 50% at RHIC. It should be close to 1 at LHC energy, but here one also comes up against the question of low-x parton density with it still unknown behaviour. One will, in any case, certainly find a very high gluon density. It will be so high that rescattering (thermalization) should occur.

Whilst we may contemplate with great expectation this future programme (perhaps '96 for RHIC and '98 for the LHC), one may come back to the present results and ask again the question 'Has the quark–gluon plasma been found?'

The key point is however not so much finding it but measuring its properties. Something new is happening. The question should then be reformulated as 'What are

the properties of the peculiar system which shows up in these collisions?' The density is high. The lifetime is decent. Constituents freely wonder through it. Yet one cannot say at present whether it is anything close to a thermalized system.

One clearly needs a more detailed look at hyperon and antihyperon yields, some information on photon and low-mass lepton-pair production, more detailed results on interferometry, etc.

An important gain is expected when going from sulfur to lead.

Even with present beams many experiments are statistics limited, in particular those on J/ψ suppression and interferometry.

It is clear that information on proton–nucleus collisions is not extensive enough to analyse, in depth, nucleus–nucleus collisions. This should be improved upon. Whilst it is now clear that it is better to work at as high a c.m. energy as possible (200 GeV/A as opposed to 60 GeV/A in the CERN programme), experiments at different energies would help spotting threshold effects.

The field of heavy-ion collisions is one which has now quickly come of age. It offers challenging problems where both theoretical and experimental insight are needed to continue.

It is a pleasure to thank E. Shuryak and S. Nagamiya for inviting me to give this review. I am indebted to F. Karsch, E. Quercigh, H. Satz and E. Shuryak for informative discussions.

A more detailed review of these questions is available in the plenary report of W. Willis at this Conference. This report can be considered as the continuation of my report 'Quark matter, facts and hopes' at the Lenox Conference. The stimulation of Quark Matter '90 is acknowledged.

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