IN SEARCH OF QUARK MATTER - THE NEW ROUND OF TESTS*

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ABSTRACT

Heavy ion collisions at very high energy offer conditions such that a quark gluon plasma could be formed. Specific signals are used to probe what is actually happening. The first round of tests, with small to medium size ions, is now completed. New rounds of tests using the heaviest ions and, later on, much higher energies, will take place over the coming years. The present situation is assessed with a look at the information which the new round of tests should bring.

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In Search of Quark Matter - The New Round of Tests

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1. INTRODUCTION

Nuclear physicists have long searched for a new state of nuclear matter which could be reached once the repulsive core of the nuclear force would have been overcome through compression or heating. We now know what this new state is likely to be. According to Quantum Chromodynamics it should be a plasma of quarks and gluons. The coloured bearing constituents would freely circulate in a hot vacuum which would no longer be opaque to colour. They would be deconfined.

It is possible to quote the values of the key global parameters, such as the temperature and the baryon chemical potential, beyond which this new state of matter should prevail. For zero chemical potential the temperature should be in excess of 150 to 200 MeV. This corresponds to our reading energy densities of the order of 2 GeV/fm³.

The conditions required for deconfinement should have been those prevailing in the early universe before it was 10 to 20 microseconds old and therefore before its temperature had fallen accordingly below 150 MeV. The energy density required for deconfinement is an order of magnitude above that of nuclear matter.

Having required conditions which can thus be rather precisely formulated, the question is how to reach such conditions experimentally. The only tool at hand is the collision of heavy ions at very high energy. Even during the very short collision time, scattering among their constituents should generate much entropy and a rapid evolution through rescattering and cascading could

lead to a very hot and possibly thermalized system, extending over the volume of the colliding ions. This system will evolve into a hot hadron gas from which the particles which are seen in the final state will eventually freeze out and escape.

It was in the early eighties that it was realized that there was a good hope to reach at least the needed energy density with collisions of ions accelerated in existing machines, and that the foreseen experimental conditions, with hundreds of secondaries produced in a typical collision, appeared as manageable [1]. This eventually generated an exploratory programme which started in the mid eighties at the Brookhaven AGS and the CERN SPS. An interesting feature of these ventures is that they brought together in roughly equal numbers particle physicists and nuclear physicists thus bridging the gap which had appeared between the two communities in the late fifties.

The first good news was that the stopping power was as high as one could expect. The looked for energy density was thus well in reach. Specific signals were soon indicating that there was something special to nucleus-nucleus collisions [2]. This fueled enthusiasm for a more ambitious programme. This is now history. At present, we are at a particularly interesting point.

A first round of experiments performed with small to medium size ions (up to Sulfur/Silicon) could be carried since 1986. One had to be modest at first. This research became possible only insofar as the experimental programme could rely on already existing machines and often on the use of recycled detectors. The center of mass energy per nucleon-nucleon collision thus reached was 5 GeV at BNL (AGS) and 20 GeV at CERN (SPS). The results obtained led to the conclusion that, at least at the SPS, the energy density which was looked for appears to be at hand. Some specific (and predicted!) signals came up in a dramatic way. They showed that a nucleus-nucleus collision cannot be considered as a mere superposition of nucleon-nucleon collisions. The energy deposited and the size of the system make possible the manifestation of particular effects. These particular signals are now precious handles to study in far greater details what is happening. We can therefore look with confidence and enthusiasm at the new rounds of experiments which will involve heavier ions and eventually much higher energies.

We can first look forward to the period extending from now to 1999. The BNL AGS already accelerates close to the heaviest possible ions up to 4 GeV per nucleon and the CERN SPS will soon accelerate close to the heaviest ions up to 17 GeV per nucleon. We thus go from Sulfur-Lead collisions to Lead-Lead collisions.

We can next look forward further to the period extending beyond 2000, when the dedicated RHIC machine at BNL will collide head on the heaviest ions, accelerated up to 100 GeV per nucleon, and when the CERN LHC will collide head on the heaviest ions accelerated up to 2.7 TeV per nucleon. The special Lead source now built for the SPS can be readily used to feed the LHC with Lead ions and experiments on Lead-Lead collisions could start as soon as the machine is ready.

The key problem in such studies is that the dense and hot system which is formed through the collision of two heavy ions immediately blows itself apart as it expands and cools. Since we are after a phase transition between a quark

gluon plasma and hadronic matter, there is nothing like volume and time before the final freeze out. And there is little of both! During the first period we shall gain much in volume and also in time since we shall be dealing with a larger system. During the second period, extending beyond 2000, we shall further gain in volume and in time since the system formed will be hotter and denser to start with. It will therefore stay for a longer time under the special conditions associated with a quark gluon plasma while expanding much before freeze out. The "chemical" conditions will also be different. With fixed target experiments we have always access to a baryon rich system. The highest energy densities correspond to an important stopping power and therefore to a high baryon density at central rapidity. On the other hand, in the future collider experiments, the central rapidity region, where the energy density is also expected to be the largest, will correspond to a baryon poor system. This baryon poor system is more similar to the conditions which prevailed in the early universe. It is also more similar to those which can be studied through present computational means, whether perturbative or non perturbative on the lattice.

The present overview of the situation, as now possible at the end of the first exploratory period, is the occasion to assess the gains to be expected during the new periods.

2. THE QUARK GLUON PLASMA WHICH WE ARE AFTER

Quantum Chromodynamics has already proved itself to be a very reliable and powerful theory when dealing with quark interactions at short distances. It however operates on a very complicated vacuum. The long range behaviour of QCD leads indeed to an a priori surprising property of the vacuum [3]. It is opaque to the colour carried by the quarks and the gluons and therefore forces quarks to be confined into colour neutral hadrons. The QCD vacuum shows properties which are similar to those of a superconductor. In particular, it has a critical temperature beyond which it becomes transparent to colour. When calculable, with specific approximations for the quark sector of the theory, this temperature is found to be of the order of 150 to 200 MeV. It should be within reach and indeed now is! This is not the case for the electroweak critical temperature which is of the order of 200 GeV.

We can naively consider a system consisting of a set of hadrons in the vacuum and compress it. The hadrons are initially too far apart to interact. As the density increases they start interacting among themselves. We thus go from a dilute to a dense hadronic gas. With increasing compression the hadrons eventually overlap and should merge among one another. The small vacuum bubbles separately associated with each individual hadron should eventually fuse into one big bubble within which quarks would freely move over distances much larger than those offered by the hadrons in which they were first confined. This is shown in Figure 1. Since in high energy collisions new particles are created out of the collision energy, we reach the same conclusions if the initial dilute hadron gas is heated up instead of being merely

compressed. In heavy ion collision we have a complicated mixture of compression and heating.

Fig. 1 : Artist view of the compression or heating up of a hadronic gas into a quark gluon plasma.

Fig. 2 : Lattice Gauge calculation of the thermodynamic properties of a hadronic gas turning into a quark gluon plasma.

This is this thermal evolution which one can actually follow with QCD thermodynamics as approximated on the lattice. Following methods initiated by K. Wilson and first implemented on fast computers by M. Creutz, one can calculate the QCD partition function and, from it, the thermodynamical parameters. Computer calculations show a behaviour of the energy density and of the pressure as a function of temperature with a sharp rise of the former (in the two light flavour case), which one can associate with a first order transition. One thus goes from conditions which correspond to a typical hadron gas, at low temperatures, to those corresponding to a typical quark-gluon plasma, at high temperature, as the pressure has followed its more gentle rise with temperature. This is shown in Figure 2 [4]. The critical temperature at which the sharp rise of the energy density occurs can then be calculated in terms of some other measured quantity also calculated on the lattice (such as the rho meson mass or the string tension). There is general agreement that the transition should take place at 150 to 200 MeV and it may well be of a first order type.

One should, however, not ignore several problems which have not been dealt with yet. All calculations refer indeed so far to a zero quark chemical potential. In practice, one can deal only with systems which have no net quark number. Those met in present practical conditions are very different ! The influence of strange quarks, or that of an extra quark species with a non vanishing mass, is also still the nature of conjectures and debates. Yet there is no doubt left that, beyond a certain temperature, quarks should be deconfined.

Full deconfinement should also be associated with the disappearance of the quark effective mass as it is met within hadrons. The freed light quarks should have but their very small mass. It is two orders of magnitude smaller than their effective mass, which is of the order of 300 MeV, and it is therefore practically zero. With quarks of practically zero mass there is chiral symmetry. Lattice calculations seem to indicate that deconfinement and chiral symmetry restoration occur at the same critical temperature, when they could have succeeded each other in the evolution of the system. This is shown in Figure 3. Such conclusions however again apply only to the case of vanishing quark chemical potential.

Fig. 3 : Deconfinement and chiral symmetry restoration in Lattice Gauge theory calculation. The lattice parameters have to be related to temperature through a different calculation of physical quantities.

There may be a long way between thermodynamical calculations dealing with wide and steady systems to those involving a very small volume under explosive conditions which are met in experiments with heavy ion collisions. Yet there is enough hope to study what occurs under the only possible experimental conditions which are at hand. At stake is securing evidence for a crucial property of QCD, namely deconfinement at high enough energy density and/or temperature. The astrophysical interest which includes baryon formation in the early universe and the interior of neutron stars cannot be overlooked.

If things occur as expected, one should have different successive phases in the observed events. They are the following, as shown in Figure 4 :

- (i) An initial phase during which many collisions occur at the parton level. A large number of energetic partons are formed. The system is still far from any equilibrium. A large amount of entropy is released.
- (ii) A thermalized phase, obtained through the many scattering of the many partons. The temperature is very high. The system is a quark-gluon plasma.
- (iii) A mixed phase, obtained as the plasma cools down with parts of it hadronizing as the temperature goes through its critical value.
- (iv) A thermalized dense hadronic gas from which hadrons eventually escape as their mean free path exceeds the size of the system. This is what is referred to as freeze out.

This being said we have two main problems to face. All the successive processes occur in a very short time. First, if we look only at the dominantly produced hadrons we merely integrate over the whole evolution. Even if we find evidence for a thermal hadronic phase, it should have averaged out the past history and hide evidence for the earlier plasma phase which we are looking for. Second, in any particular collision, only part of the full history may occur and different pieces of the colliding hadrons may also go through different histories at the same time. We may but see a very complicated mixture. Present experience is however such that there is no reason to be discouraged [5].

We can indeed look for signals associated only with phase (i). This corresponds to the production of charm and beauty and of high mass lepton pairs. Nothing like that occurs unless we deal with the very energetic partons which we expect in phase (i). At this stage there is nothing special separating

proton-proton collisions from nucleus-nucleus collisions but for the increased rescattering expected in the latter case. One should then consider in parallel proton-proton, proton-nucleus and nucleus-nucleus collisions to assess any yield seen. Comparing charm and beauty production to lepton pairs production, one may measure the respective effective quark-gluon ratios.

The separate study of this phase was not possible so far in view of the vanishingly small cross sections at the available collision energies. It is however a promising field of investigation at RHIC and the more so at the LHC. This is a phase during which we have confidence in what can be presently calculated with perturbative QCD.

We can now look for signals associated with phase (ii). One of them, as long advocated by Matsui and Satz, is the suppression of charmonium formation. In their views this results from the Debye screening effect of the plasma which forbids the binding of charmonium states until the constituents are too far apart to do so as they have travelled through the plasma in different directions. The constituents, which can be created only during the first stage of the collision eventually appear separately in heavy mesons.

J/ψ suppression has been observed ! This is typically a "factor of two" effect when comparing reactions with high energy density to those with low energy density. This was already a well established effect back in 1988 [2] and it was one of the expected signals of plasma formation. However, once the effect had been observed, one could not stop attempts to explain it differently. We shall come back to this later. At present one may just say that J/ψ suppression is a wonderful signal to focus upon, studying it under various conditions to better assess its significance. One can now also study ψ' suppression and, with RHIC and the LHC, one will extend those studies to the Upsilon family. We can already say that through this signal we have evidence for the formation of a very dense system (an order of magnitude denser than nuclear matter) with some transparency to colour. We cannot yet distinguish phase (ii) from phase (iii) and (iv) but we have evidence for something new. This is a strong encouragement to continue.

Strangeness enhancement has long been advocated by Rafelski as evidence for phase (ii) [6]. Indeed frequent partonic collisions and/or a temperature of the order of 200 MeV (which should a priori correspond to a plasma phase) should enhance the strangeness content of the final state with not enough time to get back to equilibrium in a hadronic phase at lower temperature. Already back in 1989, strangeness enhancement had become certain. This is again typically a "factor of two" effect, comparing the relative amount of strange particles in reactions with high multiplicities to that found in reactions with low multiplicities. It may, however, well be a property of phase (iv) as well as of phase (ii) and (iii) and therefore cannot yet be clearly associated with phase (ii). This is, however, again a wonderful handle to probe further, studying in particular the production of strange antibaryons. It appears in any case as a very useful probe of thermalization leading to quark chemical equilibrium. Much should be learned in that case from the increase in volume associated with Lead beams.

The question of thermalization, at least in the final hadronic state, leads to the existence of a fireball from which hadrons would escape as they freeze out.

The size of this fireball can be measured with Hanbury-Brown-Twiss interferometry applied to identical particles. This is here that we find still an other "factor of two" effect, comparing the size at freeze out for identical pions to that of the impinging ion. The size found for kaons appears to be smaller than that for pions. Here again there is a great field for further investigations, with interferometry studies for different particles and under different conditions. This applies both to the coming increase in size and to the later increase in energy. The freeze out volume could then be over four orders of magnitude greater than the proton size.

We have not yet evidence for the succession of phases which we expect to take place. We have, however, already proven tools to investigate what takes place as the experimental conditions become better.

3. IGNITION CONDITION AND SIGNALS

As previously said, the first key question when it all started was : is the energy density reached in heavy ion collisions high enough ? Confidence came from the first round of experiments.

The energy density reached after phase (i) is given by the Björken formula. It is proportional to the rapidity density of transverse energy and inversely proportional to the incident ion area and to the formation time. The formation time corresponding to phase (i), whatever form it actually takes in detail, is taken as being of the order of 1 fm/c. The partons need some time to scatter and share their energy. We can make educated guesses on how the energy density varies with incident energy and ion size. It should at least increase logarithmically with energy (the rise of the rapidity plateau) but a more dramatic rise should be expected at the LHC, as production of minijets becomes overwhelming. The rise with the incident ion size should grow only very slowly as the result of rescattering effects. If one uses this to normalize everything to lead-lead collisions, one finds that the energy density should be 0.8 GeV/fm³ at the AGS (centre of mass energy of 4 GeV), 2.5 GeV/fm³ at the SPS (centre of mass energy of 17 GeV), 5.2 GeV/fm³ at RHIC (centre of mass energy of 200 GeV) and 9 GeV/fm³ at the LHC (centre of mass energy of 6000 GeV). The SPS conditions should therefore already be proper for the formation of a quark-gluon plasma. They should be great at RHIC and at the LHC. In the case of the AGS, one should bear in mind that the energy density is not the only relevant parameter. There is also the baryon density which is particularly high in that case.

Granting that the energy density is high enough, the key question which remains is the time available for thermalization. There is already some evidence that thermalization takes place under present conditions (AGS and SPS). Increasing the incident ion size (now) will improve conditions. Increasing the incident energy (later) will further help. We shall have a better control over thermalization using QCD in the first phase, with many minijets being produced as the reaction starts. The initial system being hotter, it will spend a longer time in the interesting state. As previously said, one should be able to disentangle baryon rich from baryon poor conditions.

One may illustrate what takes place in the early stage (phase (i)) through the result of a parton cascade calculation [7]. The gluon density increases very fast, overshooting its equilibrium density in less than one fermi. The quark density remains, however, significantly below its equilibrium density for a long time. This of course results from the larger coupling of gluons. One thus reaches very quickly a very hot system in which gluons predominate. This is shown in Figure 5.

Let us now go to the other end of the time scale and consider the produced hadrons. The increase with incident ion size at the AGS is associated with an increase of the K/π ratio [8]. It is now known to go up gradually by over a factor of two from proton-proton collisions to Gold-Gold collisions. This can be interpreted as the result of thermalization achieved eventually as the size increases. A thermal system at a temperature of 150 to 200 MeV favours indeed far more kaons as compared to pions than the typical result of a proton-proton reaction. We have to keep in mind that what matters is the transverse mass and not the mass. The kaons are then not much discriminated against the lighter pions.

Fig. 5 : Parton cascade in the early phase. Gluon and quark densities scaled to their equilibrium value. Extreme energy case.

Fig. 6 : The AGS K/π ratio as a function of ion size.

It is clear that at the energy of the AGS all that was previously said about gluon thermalization in the early stage of the reaction does not apply at all. Nevertheless the system manages to show what looks as a thermalized outcome, which is related to the big ion size. The strangeness enhancement signal turns out in that case to be a very good tool to assess thermalization. This is shown in Figure 6.

We see from such a result all that we can hope to get from Lead-Lead collisions at the LHC, namely thermalization all the way from a rather early stage to the later stage. This is the conditions which we are after in the transitions from phase (ii) to (iii) and then to (iv).

Now, how to study that evolution ? There are numerous signals. The question is always to understand what they individually mean ? Let us illustrate that with two examples.

It has always been a puzzle that hadron spectra observed in proton-proton collisions appear to show a thermal behaviour. This has been efficiently

exploited by Hagedorn at predicting many yields. Yet we are at a loss trying to find what could be thermal in proton-proton collisions. The Landau model has but a historical interest. What about transverse momentum distributions in nucleus-nucleus collisions ? They again look thermal but the mean transverse momentum, which should "measure" the temperature is higher than in the proton-proton case. It actually rises quickly with the energy rapidly density to eventually saturate as if a new fixed temperature would be reached in collision where a quark-gluon plasma had a chance to be formed [9]. One could interpret that single feature as evidence for a first order phase transition with pion emitted at the same critical temperature whatever the energy density would be. This is illustrated by Figure 7. However, one knows that many other effects can be called upon to explain the observed rise followed by an apparent stability. One of them is transverse flow which certainly deserves further studies. Part of what we may be tempted to associate with a higher temperature could result from a collective sideways flow.

Fig. 7 : The mean transverse momentum of photon (from π^0) as a function of the particle rapidity density.

Fig. 8 : The muon pair mass spectrum with resonance contributions and any other contributions on top of known sources (full line).

The second example is the lepton pair mass spectrum. There are many origins for lepton pairs and some of them, such as the well understood Drell-Yan process, can be used for normalization. This being said, proton-nucleus and nucleus-nucleus reactions show a dramatic difference [10]. There is a definite excess in between the rho-omega region and the J/ψ region. This is shown in Figure 8. It is as if something were shining more brilliantly over a wide mass range during a nucleus-nucleus collision. Should a quark-gluon plasma shine more than a hadron gas ? Nothing is obvious. This newly seen signal is in any case a new interesting tool for further study. The next step is clearly to try to determine its temperature through a transverse mass distribution. Its observation, now possible, illustrates the improvement in experimental power since these studies started in the mid eighties.

4. THE THREE BY NOW CLASSICAL EFFECTS

We start with J/ψ suppression. The J/ψ signal is normalized to the Drell-Yan continuum which is now well under control. In nucleus-nucleus collision the J/ψ over Drell-Yan ratio shows a dramatic decrease with energy density. This is shown in Figure 9. In the quark-gluon plasma scenario this is

associated with the colour screening effect which forbids the binding of the charmonium state. The ψ' is now also clearly seen and one finds that the ψ' over J/ψ ratio also decreases with increasing energy density [11]. The extra suppression of the larger ψ' is also a natural result of screening. This is shown in Figure 10.

Fig. 9 : J/ψ suppression as a function of the energy density.

Fig. 10 : The relative suppression of the ψ' to the J/ψ as a function of transverse energy.

However, the J/ψ suppression factor could be claimed to be the result of multiple scattering in the initial state, thus leading to a wider transverse momentum distribution, together with a strong absorption in nuclear matter. This has led to extensive studies on J/ψ and ψ' production in proton-nucleus reaction where the formation of a quark-gluon plasma could not be invoked. Yet there is a J/ψ suppression there too and good agreement could then be found with the absorption scenario. Absorption should certainly also be at work in the nucleus-nucleus case. Is it the all story ?

Most probably not. In the proton-nucleus case the J/ψ and ψ' ratio remain the same as the size of the target nucleus increases and, together with it, the overall absorption [12]. This is shown in Figure 11. This is then at odd with the stronger ψ' absorption which one would need to explain the nucleus-nucleus data. Different mechanisms should therefore be at play. Indeed one may say that in the nucleus-nucleus case the produced pair travel together with hot matter, which is part of the many remains of the sizable projectile, whereas in the proton-nucleus case it is shot forward almost all by itself to eventually bind or not in a charmonium state only when well outside of the target nucleus.

We still lack data on central rapidity J/ψ production in proton-nucleus, while this is where we have data in the nucleus-nucleus case.

In the absorption scenario, the absorption has to be strong to match the observed effect. This calls for very dense matter. The suppression effect is therefore in both cases, whether we consider screening or absorption, evidence for a new dense form of matter. In the absorption scenario the gluons creating a charm pair have to go through multiple scattering on the constituents which they meet before they fuse. They thus cross matter as if it were transparent to

colour. One is again not far from what to expect of a quark gluon plasma. However, one cannot differentiate it clearly from dense hadronic matter [13].

Fig. 11 : J/ψ and ψ' suppression as a function of target size in the proton-nucleus collisions.

Fig. 12 : J/ψ suppression as a function of energy density in the deconfinement and absorption scenarios.

We are at an interesting stage. We can claim evidence for dense hadronic matter with an energy density of the order of 2 GeV/fm³ or more. What we lack, however, is evidence for a phase transition between what could be a simple quark-gluon plasma and what could be a dense hadronic gas. The change of the suppression factor with energy density does not show any dramatic threshold effect as naively associated with a phase transition [14]. However, should one expect something neat and clear ? Probably not. Estimates are shown in Figure 12. The absorption scenario and the screening scenario are again hard to disentangle on that ground alone [5].

One can expect clearer effects showing up in lead-lead collisions. J/ψ suppression is a signal to study in greater details as the different parameters are varied. Going up in energy there is the great question of upsilon suppression. In that case, the system is so tiny that screening effects should be very small. Absorption is smaller too and we may be facing a conspiracy !

We now turn to **strangeness enhancement**. This is now very well documented [15]. Nothing as such is seen in proton-nucleus collisions but in nucleus-nucleus collisions one sees a dramatic increase of the ratio between the number of strange and non strange secondaries with increasing multiplicity, or energy, rapidity density. This is illustrated in the case of Λ -production by Figure 13 [16]. One sees a clear effect corresponding to a factor of two. Considering now antihyperons, the ratio between anti-cascade and anti-lambda is found to be much larger than in proton-proton collisions as if lots of anti-strange quarks were at hand [17]. This is shown in Figure 14. There is again a good factor of two over what is seen in proton-proton collisions. Nucleus-nucleus collisions have something special !

Fig. 13 : The Λ yield as a function of the number of secondaries. Results from NA35 and NA36.

Fig. 14 : Antihyperon and hyperon ratios in heavy ion collision (right) compared to the same ratio measured in other reactions (WA85).

As previously said strangeness enhancement was one of the announced signals for the formation of a quark-gluon plasma. Strangeness formation then benefits both from higher relevant cross sections in the plasma and from the high temperature which brings strange quarks on an almost equal footing as non strange ones. However, granting the fact that a large dense system is formed, do we need a plasma to increase the relative strangeness content? Is a hadron gas sufficient? If the density and temperature is high enough this could be all that is needed to produce the large relative amount of strange particles which is observed. We have seen (Figure 5) that the AGS Gold-Gold data seem to indicate that this is enough.

Fig. 15a : Antihyperon and hyperon ratios in a thermodynamical equilibrium. The two parameters are the temperature and the baryon chemical potential.

Fig. 15b : The ratios in figure 15 but assuming that strangeness has not reached its equilibrium value (J. Rafelski et al.).

One can even try to reproduce the observed ratios for hyperons and antihyperons, considering a hot hadronic system freezing out into the final state hadrons. In such a case everything should be predictable in terms of the global parameters of the system, namely its temperature and its baryon chemical potential. One thus compared ratios within a common transverse mass

region. This was tried by Rafelski and his collaborators [18]. As shown by Figure 15a this turns out not to be possible in view of the rather precise data which are now available. However, they can obtain a good agreement provided that they assume that strangeness has not yet reached its full saturation value. If saturation is at the 70% level only, one can reproduce all the ratios with a temperature of the order of 200 MeV and a baryon chemical potential of the order of 250 MeV. This is shown in Figure 15b.

Should one then conclude that all that one sees with strangeness enhancement is the result of a hot hadronic gas in thermal equilibrium. This would already be an important result. It would show that density and size are such that a thermodynamic equilibrium can be achieved, something which was far from obvious at first. However there are several caveats to keep in mind. Firstly, there are only three independent ratios with the results available. There is little wonder that one can reproduce them with three parameters. One may, however, argue that the fit gives reasonable values, something which was not obvious to start with. This is already something important. Secondly, one has to assume that the system can be considered as a whole, with a global zero chemical potential for strangeness. Hadronization could be bulky and affect separately different parts of the system. Thirdly, hadrons are assumed to freeze out at the same time, the equilibrium values being assumed to reproduce the observed ratios. This may not be the case. Freeze out could occur at different time, and at different temperatures for different species of particles. One may also remark that the temperature value which is found (200 MeV) is high. One could a priori associate it to a plasma more than to a hadronic gas. Indeed it is the high temperature which drives the strangeness content up at equilibrium and this has to be tempered down by an assumed lack of strangeness saturation. Therefore there may be more than thermalization in the strangeness signal. The study of strangeness enhancement will certainly continue to be an important element looking for evidence for a quark gluon plasma. The Omega signal is now coming up (WA 85). There is much to expect from the increase in size going to a Lead beam. The AGS result is a strong encouragement.

Anti-hyperon ratios represent a particularly interesting signal. There are two obvious questions. The first one has to do with a possible threshold beyond which the nature of the primordial system would change. One may indeed argue that only a quark gluon plasma can provide the rapid increase of entropy needed to generate many strange quarks. This calls for Lead-Lead collisions at different energies and not only at the highest (SPS) one. The second one has to do with the competitive rôle of the strange and non strange quark densities. In that case comparing SPS and RHIC(LHC) data would be very interesting. The relative yields of hyperons and antihyperons depend on the strange and non strange quark concentration (fugacity). As emphasized by Rafelski [20], the amount of entropy (related to the strangeness production) generated per baryon seems at present to favour a quark gluon plasma over a hadronic gas. Such a ratio should be very different in a quark rich and quark poor region, as the one in central RHIC(LHC) collisions.

One should also mention hopes to find evidence of strange matter, with an anomalously high A/Z ratio, if such things could freeze out of the plasma. Problems speak for themselves but that would be a great and clear signal!

We now turn to the other important effect, namely the **size of the fireball at freeze out**. It is certainly a tricky matter to extend the Hanbury-Brown-Twiss method to hadron production. Nevertheless, with dedicated experiments, detailed results are coming up. Correlations among identical particles can be used to extract a radius at freeze out and this separately for different particles. This is shown by Figure 16 [19]. The radius for pions appears to be larger than that of the impinging ion and greater than the one obtained for kaons. Several results are put together in Figure 17 [20]. They show an increase in the fireball size from AGS to SPS energies and, as previously mentioned, a larger radius for pions than for kaons.

Fig. 16 : HBT correlation for $\pi^+\pi^-$ and K^+K^- (NA44).

Fig. 17 : Freeze out ratio for different particles in nucleus nucleus and proton nucleus collisions.

This difference in freeze out radius has long been advocated by Nagamiya. It is assumed that freeze out occurs when the mean free path, which is inversely proportional to the cross section times the density, becomes equal to the size of the system. One thus readily concludes that kaons should escape earlier than pions. According to this view, the escape radius is expected to increase according to the square root of the transverse energy rapidity density. There are therefore clear expected effects to look for with increasing ion size and with increasing energy.

The meaning of the signal is not yet fully assessed except for the fact that it points to an increasing volume within which a thermalized system could exist. This is one of the looked for conditions. In any case, the signal is there, it is now under control and it will remain an important tool. Increase in momentum resolution and in statistics will allow for a 3-D picture of the fireball and not only to some transverse radius. The remaining coherence at the production stage will be measured under different conditions.

5. CONCLUSION

The first round of experiments carried out with medium size ions have shown that the looked for energy densities are actually reached and that some thermalization seem to be operative. This is very encouraging. One can look forward to the extension of these studies to larger ion size and to higher energies. Things should be much better.

Exciting signals have been seen. The prominent ones are offered by quarkonium formation with suppression seen, strangeness production with enhancement seen, lepton pair production, with enhancement seen and finally freeze out radii, with rather large values and differentiation between hadron species.

There is no doubt that a new state of matter, with a density of at least an order of magnitude higher than hadronic matter, is created in heavy ion collisions. We do not yet know what it is and whether or not there is a phase transition between two very different forms of dense matter, as it is expected from Quantum Chromodynamics. Nevertheless, since we are after a phase transition there is nothing like volume and time and also, in order to increase time, collision energy. Since we have good proven tools now at hand, we can expect much from an increase in volume and an increase in collision energy. We can therefore approach with enthusiasm the new rounds of experiments.

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