Abstract

The outcome of several years of research on heavy ion interactions at CERN was recently reviewed with the announcement the discovery of a new state of matter where quarks are deconfined. This discovery, which made a big impact in the world press, is presented here.

Résumé

Le résultat de plusieurs années de recherche sur les collisions d’ions lourds au CERN a été recemment présenté avec l’annonce de la découverte d’un nouvel état de la matière où les quarks ne sont plus confinés. La presse mondiale a donné un large écho à cette découverte, qui est présentée ici.

1-A simple view of confinement.

One can separate the atoms in a molecule and put back the molecule together from its atoms. Atoms can be ionized, stripped of their electrons, and the protons and neutrons within their nucleus can be separated from one another. Yet, when considering the quarks within the protons and neutrons, they are permanently bound within the particules which they build. Quarks are confined within hadrons. They carry "colour" and the vacuum is opaque to "colour". Free quarks cannot exist as such. They have to group themselves together into "colour neutral" objects, with 3 quarks for a baryon and a quark and an antiquark for a meson. Hadrons can be seen as little bubbles in the vacuum, about a fermi (10-15 m.) in size, within which quarks and the "colour" carrying gluons, which they constantly exchange, are confined.

Let us take an image and attempt to separate a quark from a proton, leaving the other two "inside". It is like pulling on a string. It costs 1 GeV par fermi to try to penetrate the vacuum with the "colour" of the quark "in hands".
Nothing prevents this energy to materialize into a quark-antiquark pair, since forming a \( \pi \) meson costs only 0.14 GeV. The antiquark sticks with the quark leaving us a meson ‘in the hands’, while the quark snaps back to join the other two, making back a proton.

When one attempt to do that in a more direct and violent way, shooting aside quarks during high energy collisions, one does not see quarks as such but instead jets of hadrons (mainly \( \pi \) mesons) taking up the energy and the momentum which had been given to the quark during the collision for its doomed attempt to escape.

It has been however long realized that if one could squeeze protons and neutrons together or bring them to very high temperature, which is the same thing in terms of energy density, they would lose their entity and quarks would freely roam around in the volume where the required energy density would have been reached. The conditions are rather well known. One needs an energy density of about 1 GeV/fm\(^3\), which is 7 times the density of nuclear matter, or a temperature in excess of 150 MeV, which is about 100,000 times the temperature at the centre of the sun. In the early eighties it was realized that such conditions could be reached, at least through a fleeting instant, during heavy ion collisions at high energy. A good constituency of researchers, coming in half from particle physics and in half from nuclear physics could organize itself. The exploratory heavy ion programme, which started at the CERN SPS in the mid eighties, received a big boost in the mid nineties when a lead beam became available.

The outcome of the different experiments which took place since is rather spectacular. It was recently deemed appropriate to go through a joint analysis as this research with heavy ions will soon change gear with the completion of the dedicated heavy ion collider (RHIC) at Brookhaven. The evidence which one now has for this new state of matter is still indirect. One can only observe remains resulting from its formation but collected only long after it no longer existed. It is like watching the smile of the Cheshire cat in Alice in wonderland, a smile which remains even after the cat has disappeared. It is necessary to reconstruct a sequence of events from the observation of final particles which, for most of them, come out only after a long series of interactions. Nevertheless a good and faithful picture can now be presented and one can claim that a new state of matter, with deconfined quarks, briefly exists over the volume of the colliding ions.

2- In search of a quark gluon plasma.

What are we looking for?

According to Quantum Chromodynamics, which is much discussed at this conference, hadrons cannot exist under the density and temperature conditions which have been mentioned. They melt into a plasma of quarks and gluons. A plasma, because hadrons are dissociated into their coloured constituents in much the same way as atoms are dissociated into their charged elements in a standard plasma. It is a plasma “of quarks and gluons” and not only of quarks because, at such temperatures, the radiation (gluon) energy density is very important. Thermodynamical calculations, which are at the
limit of present computer power, can provide some valuable pieces of
information. The phase transition temperature between the hadron gas (at
lower temperature) and the quark gluon plasma (at higher temperature) is
found to be of the order of 170 MeV. The transition seems to be of second
order. It is a rather smooth one with no clear latent heat jump in energy
density between the two phases.

During the head-on collision between two lead nuclei, a very large amount of
energy is liberated within the collision volume associated with the colliding
ions. Early experiments in the mid eighties could quickly show that the
stopping power was strong enough for that. Deconfinement conditions could
thus be met. In Lead Lead collisions one can indeed estimate an energy
density reaching 3 to 4 GeV/fm³ and the required conditions should therefore
be satisfied. Collisions in the plasma build pressure and the high energy
density blob expands very fast as it cools down. It eventually hadronizes
(circa 1 GeV/fm³ and/or a temperature of 170 MeV) but the hadrons still
overlap much in what appears to be a statistical equilibrium. We have now a
high density blob of hadronic matter which continues to expand and cool
down. As the energy density falls to 50 MeV/fm³ (circa 100-120 MeV) the
hadrons stop to interact and fly asunder. They do not do that from the surface
but throughout the whole volume. This is called "freeze out". The explosion
velocity is then about half the speed of light. This is referred to as the "little
Bang".

One can build such a picture with confidence, combining the results of all the
experiments done with the lead beam, at present 7 in number. They have
different purposes. Some provide a global view. Other focus on specific hard
to see but particularly interesting features. As CERN wanted to review the
situation, I was called in back as an old "wise" man to provide a status report.
I had indeed long been following this research as one of its first promoters in
the early eighties and later as the keynote speaker in quark matter
conferences. I did this review in collaboration with Ulrich Heinz, who is now
a great expert in the field and who is also attending this meeting. We had to
write a status report which would meet the agreement of all the collaborations
at this stage. This is in that paper, which is on the web, that you can find
more information and explicit references.

In order to attract public attention, some emphasis had to be put on the
connection with the early universe issued from the Big Bang. This is
natural. We expect that the universe was a quark gluon plasma which
hadronized about 10 microsecond after the Big Bang. Studying such a
transition brings us as far as we can go today in the early history of the
universe.

3-The Big Bang analogy.

The expansion of the universe, described by Hubble's law, leads us to expect
that at the beginning the universe started from a state of extreme temperature
and extreme density. This can be made more precise through General
Relativity which we can use when extrapolating the present trend to the distant past, about 15 billions years ago. So far we only translate in more quantitative terms an idea prompted by the observed expansion. If the Big Bang has become the Standard Model of Cosmology, it is because it leads to specific predictions which can be verified and have been beautifully verified. One of them is the microwave background at $2.7 \, \text{K}$ which should have resulted from a dramatic event in the history of the universe, 300,000 years after its birth. The temperature had then dropped down to about 1 eV. Atoms could form and the universe became transparent to light. The microwave background is the cooled down fossil of this bright flash of visible light, after a long expansion stretching the radiation wave lengths all the way to microwaves. This is an allegoric translation of the use of the Stefan and Wien laws when following the declining energy density. In any case, the observation of the microwave black body radiation was a big boost for the Big Bang theory.

An other prediction of the Big Bang is the helium abundance. Helium makes up about $1/4$ of the visible mass of the universe, practically all the remainder being hydrogen. All the stars shining through over 10 billions years could produce only a small fraction of that helium. With the Big Bang, one predicts that practically all that helium was cooked between 100 and 200 seconds when light nuclei could at long last be formed since the temperature was dropping well below 1 MeV. At that time there were still enough neutrons in the universe to bind $1/7$th of the protons into helium nuclei. The observation of the helium ratio and also of that of other light elements, provide again a strong support to the Big Bang theory. This was also a dramatic event in the history of the universe. It was a fusion reactor for about 2 minutes.

We are now after still another dramatic event when the universe, which had been transparent to colour, became suddenly opaque to it as it coooled down below 170 MeV, forcing quarks to bind into hadrons.

The evidence which we now have for the transient formation of a state with deconfined quarks, is similar in some respect to the one which one can claim for the Big Bang. If one has to be still more cautious however, it is because things happen so fast. Everything is over within $10^{-22}$ second!

4-Reconstructing the sequence of events.

One can observe the final hadrons produced in the collision. There are on the average 2,500 particles produced in each event. The fact that one could face such multiplicities was actually one of the reasons for the enthusiasm gathered in the early eighties for this new research domain. From the analysis of the energy distribution of these hadrons and also from that of the size of the fireball when the hadrons escape, as it can be determined from interference effects between identical points, one can infer the outgoing energy flow and estimate what should have been the energy density when the fireball started to expand. This is a complicated analysis but one can confidently say that central lead lead collisions with 160 GeV/nucleon incident energy yield an energy density of 3 to 4 GeV/fm3. This is the condition met at the origin of the little Bang. One can then make predictions. Under that condition one first
predicts a rather large production of strange quarks since their mass energy (about 150 MeV) is lower than the typical collision energy in this initial blob. These strange quarks and their antiquark partners are eventually captured into strange hadrons when hadronisation takes place and nothing can then much change the strange nature of these particles, even in the dense hadronic state in which they are formed and which is expanding. One predicts therefore an enhancement of strange particle production as compared to what is observed in proton-proton collisions and the more so the higher the strangeness content of the particle are. For Omega (made of 3 strange quarks) one sees an enhancement by a factor 15!

The different hadrons observed with their wide mass diversity bear witness to a thermalized distribution which was effective when they were formed. This leads to place the phase transition at about 170 MeV. Whereas one does not expect much change in strangeness content, one can see some evidence for an evolution within this very dense hadronic mixture. In particular the shape of the rho resonance which can swiftly decay into a lepton pair, which just escape the blob as the rho decays, bears evidence to its interaction. The shape of the rho resonance is strongly deformed.

An other prediction is that charmed quarks, which have to be formed in pairs and at a very early stage because of their very high mass (about 1500 MeV), cannot bind right away into charmed-anticharmed system (the charmonium states). They are readily destroyed if formed and the numerous quarks and gluons screen the heavy quarks from each other. A charmed quark can bind only at a later stage and the anticharmed partner, with which it has been formed, is no longer around. One expects a strong depletion in the charmonium production and the lead lead results show indeed a dramatic drop for central collisions. This behaviour cannot be explained without this suppression at formation.

As with the Big Bang, one sees that predictions which can be made as consequences of the very high energy density reached at collision time, are verified experimentally. This builds confidence in the picture arrived at, with its succession of events. This is with these pieces of evidence at hands that one can say that a new state of matter with deconfined quarks is reached for a fleeting instant during these collisions.

It would be great to collect direct information about this state, such as its radiation of energetic photons and its production of jets of hadrons bearing marks of their passage through the plasma. Nothing like that could be seen at the present energy but one may hope to observe and measure such signals at RHIC and therefore directly "see" the quark gluon plasma for which we have so far only indirect, though trustworthy, evidence.

If we try to translate that with an allegory (as necessary with the press) one could say that we have seen boiling water but that we do not know yet the properties of water vapour and still do not know much about the boiling process.

In connection with the ("boiling") hadronization/confinement process one can however already say that it appears to be of a rather short range nature. One does not see any of the long range fluctuations from event to event which a classical phase transition (such as boiling water) would normally imply. This
Enhancement relative to p+Be

Figure 1

SUPPRESSION DU J/ψ

DENSITÉ D'ÉNERGIE (GeV/fm³)

Figure 2
short range effect may have some similarities with the one met in high Tc superconductivity, where the transition between the superconducting state and the conducting one appears over short range zones as opposed to the global transition met in standard superconductivity, at a typically lower critical temperature.

Two figures illustrate the key predicted and observed features, namely strangeness enhancement and charmonium (J/psi) suppression.

Figure 1 shows strange particle yields for lead lead collisions normalized to those observed in proton beryllium collisions. These results are from experiment WA-97.

Figure 2 shows the J/psi yield as a function of the energy density reached in the collision. It is normalized to what expected from standard production and absorption mechanisms which could be studied earlier with oxygen and sulphur collisions. These results are from experiment NA-50.

Whereas it was a great pleasure for me to participate in several Moriond meetings almost twenty years ago, the European Physical society, with its Council meetings in March, and then my advisory role in Member State affairs at CERN, with its RECFA meetings in March, long prevented me to attend the Moriond meetings in recent times. I am therefore very thankful to have been invited to come back this year. The spirit of the Rencontres is just as great as I remembered it.