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Quark–gluon plasma signals

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Abstract
We study the evolution of matter produced after the collision of two heavy nuclei at high energy. The matter produced may pass from the hadron phase into a new state of matter called quark–gluon plasma (QGP). The aim of this paper is to discuss how a new state of matter can be observed. Whilst matter is in the QGP phase, particles that arise from the interactions between the constituents of the plasma provide information concerning the state of the plasma.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The teaching of current developments in high-energy physics is an important part of the education process in elementary particle courses. The aim of this paper is to discuss how a new state of matter can be observed and which events might be quark–gluon plasma (QGP) signals. The study of QGP signals will complement the standard knowledge of students and confront them with high-energy physics at a fundamental level.

According to quantum chromodynamics (QCDs), a theory of strong interaction, at higher temperatures and pressures the basic building blocks of the nucleus are expected to break down into a new form of matter; the QGP [1–3]. The QGP is a state of matter believed to have existed for a few millionths of a second after the big bang that created our universe. Recreating this primordial state of matter under laboratory conditions and studying its properties should help scientists explain the origins of protons, neutrons and other elementary particles, and to learn how they can be combined to create the diverse forms of matter we see today. The only known way to produce a new state of matter is to smash two heavy nuclei into each other at very high energies. Physicists have been trying to determine QGP by looking at the particles that shower out from the collision. Scientists analysing the heavy-ion collisions have thought that strangeness enhancement [4], J/ψ suppression [5], enhanced production of lepton pairs [6] and abundance of high-energy photons [7] are the main signals of QGP. The prospect of detecting QGP signals has aroused much interest: at present this topic is the focus of numerous ongoing international collaborations.

Already CERN’s (the European Particle Physics Laboratory near Geneva) and BNL’s (Brookhaven National Laboratory in USA) accelerators may have spotted hints of the QGP.
The collected data from the experiments gives compelling evidence that a new state of matter has been created [8–12].

2. The building blocks of matter

What are the fundamental constituent parts of matter? Until 1932, the elementary particles were the electron, the proton and the neutron. In the 1960s the development of high-energy accelerators and more sophisticated detection systems led to the discovery of many new and exotic particles.

The first subatomic particle to be discovered was the electron, identified by Joseph John Thomson in 1897. Ten years later, the nucleus of ordinary hydrogen was discovered and was named the proton. The third basic particle in an atom, the neutron, was discovered in 1932. To the surprise of physicists, however, accelerator experiments revealed that the world of particles was very rich; many more particle types similar to protons and neutrons (called baryons) and a whole new family of particles called mesons were discovered.

In 1964, Murray Gell-Mann and George Zweig independently discovered yet another structural layer within protons and neutrons. They hit upon the idea that neutrons and protons and all the other new particles could be explained by a few states of yet smaller objects; Gell-Mann called them quarks. Gell-Mann and Zweig could explain all the observed baryons and mesons with just three types of quarks called up (u), down (d) and strange (s), and their antiquarks. Baryons are composed of three quarks. Mesons are composed of quark–antiquark pairs. The revolutionary part of their idea was that they assigned the quarks electrical charges of \( \frac{2}{3} \) and \( -\frac{1}{3} \) units of the proton charge; such charges had never been observed. At first quarks were regarded as being a mathematical construct. In the same year, 1964, the discovery of the ‘\( \Omega \)’ particle convinced people that quarks were more than a mathematical construct. The fourth quark was discovered in 1974 simultaneously at the Stanford Linear Accelerator Centre in a particle called ‘\( \Psi \)’ and at Brookhaven National Laboratory in a particle called ‘\( J \)’. This is a charm (c)–anticharm combination. In 1977 the list of quarks once again increased with the discovery of a new heavier meson called the \( \Upsilon \) (Upsilon) meson. This meson was quickly identified as the carrier of a fifth quark, bottom (b). There were expectations that another quark probably three times heavier than the bottom quark would be found but it took out another 18 years before scientists discovered the bottom’s partner—the top quark, which was 25 times heavier than the bottom quark. The top quark was finally discovered in 1995 at Fermilab.

Meanwhile resonance particles which are the excited state of hadrons were also discovered in bubble chambers. Today we know that there are more than 400 hadron types. The existence of quarks was demonstrated in 1969 when protons and neutrons were illuminated with beams from a 2 mile long accelerator at SLAC in California, USA. The result of the experiment was interpreted as meaning that quarks form the fundamental building blocks of protons and neutrons (figure 1). The electrically neutral ‘glue’ binding the quarks together is called gluons.
In addition to quarks there is another group of fundamental particles called leptons. A lepton is defined as a light particle that participates in electromagnetic and weak interaction but not in strong interaction. Leptons that are known to exist are the electron ($e^-$), the muon ($\mu^-$), the tau ($\tau^-$), their respective neutrinos and the antiparticles of each of these, giving a total of 12.

Now we know the building blocks of matter this leads to the question: what holds it together? All forces are due to the underlying interactions of the particles. Interactions come in four types: gravitational, electromagnetic, weak and strong. In particle processes the forces are described as being due to the exchange of particles; for each type of force there is an associated carrier particle. All known particles are classified into two main groups according to their spins (intrinsic angular momentum), fermions and bosons. Fermions are a kind of particle that have odd half spin, measured in units of $\hbar$. A boson is a particle that has integer spin measured in units of $\hbar$. As a consequence of their spins, fermions obey Fermi–Dirac statistics and bosons obey Bose–Einstein statistics. Quarks and leptons are fermions and obey a rule called the Pauli exclusion principle. All leptons have a spin of $\hbar/2$. According to the current view all matter consists of three kinds of particles: leptons, quarks and mediators.

3. Why do we need coloured quarks?

One early indication that quarks come in three colours is the existence of the $\Delta^{++}$ baryon, which is a bound state of three $u$ quarks with their spins aligned ($\Delta^{++} = u\uparrow u\uparrow u\uparrow$) and $\Omega^-$ baryon, which is a bound state of $s$ quarks with their spins aligned ($\Omega^- = s\uparrow s\uparrow s\uparrow$). In this situation three fermions are in the same state, violating the Pauli exclusion principle. The solution was to introduce a new state of freedom called colour. These colours are usually called red, green and blue. They have nothing to do with real colour, but provide three distinct quantum states. The observed hadrons are white because they either have all three colours, or a colour and an anticolour. So the three quarks either in the $\Delta^{++}$ or in the $\Omega^-$ have different colours and the Pauli exclusion principle is no longer violated.

A more dramatic proof of the existence of the three colours comes from electron–positron annihilation. In $e^- + e^+$ annihilation, pairs of charged particles are produced by the electromagnetic interaction. In this process, the intermediate state is a virtual photon and the virtual photon can turn into all charged lepton–antilepton pairs ($e^+e^-, \mu^+\mu^-, \tau^+\tau^-$) and hadrons. Hadrons are created by channel $e^-e^+ \rightarrow q\bar{q} \rightarrow$ hadrons. The hadron cross section divided by the muon pair cross section is called $R$. At the lowest order of perturbation theory, this ratio is

$$R = \frac{\sigma(e^-e^+ \rightarrow \text{hadrons})}{\sigma(e^-e^+ \rightarrow \mu^+\mu^-)} = 3 \sum_{i=1}^{n} Q_i^2$$

where $n$ is the produced quark flavour number depending on the $e^-e^+$ energies. $Q_i$ is the electric charge of quarks. The values of $R$ show that there are six quarks, each with three colours (figure 2).

After these developments in the 1970s, the quantum theory describing the interaction of coloured quarks was developed and called QCD. QCD is based on the postulate that the Lagrangian of strong interaction is invariant under local $SU(3)$ colour symmetry. $SU(3)$ symmetry is a local i.e. gauge symmetry. Just as electrically charged particles interact by exchanging photons, colour charged particles exchange gluons in strong interactions. There is, however, a significant qualitative difference between strong and electromagnetic interactions in that gluons carry colour charges while photons have no electric charge. Hence quarks interact via the strong force by exchanging particles called gluons.

However, it is understood that quarks interact very weakly with each other in deep inelastic scattering. This problem was solved theoretically in 1973 by H David Politzer and independently by David Gross and Frank Wilczek. They discovered that the colour theory of strong interaction has a special property, now called ‘asymptotic freedom’. Since gluons have...
According to QCD only colourless particles can be observed. If we try to split a baryon into its constituents and the energy is enough to produce a quark–antiquark pair \( E = mc^2 \), that energy is then converted into new quark–antiquark pairs. These quark–antiquarks produce new hadrons combining quark–antiquarks in other hadrons. Thus the energy intended to break the hadrons into their constituent parts does not separate the hadrons in this way but instead produces new hadrons. Therefore quarks cannot be observed freely (that is to say they cannot be trapped).

4. Quark–gluon plasma

Progress in high-energy physics requires the study of systems with infinite numbers of quarks and gluons. The theory that investigates the thermodynamic properties of quarks and gluons is called thermal quantum chromodynamics (TQCD). According to TQCD, at high enough temperatures and densities, matter is dissolved into its constituent parts: a soup of quarks and gluons. As the temperature and pressure rises, the presence of quarks and gluons in close proximity to each other causes a decrease in confinement potential because of screening. Finally on undergoing a deconfinement phase quarks and gluons create QGP which is accepted as a new state of matter. In the deconfinement phase the quarks and gluons are liberated from their usual bonds, and bond with one another freely. The behaviour of quarks and gluons in the deconfinement phase is similar to the behaviour of ions and electrons in electromagnetic plasma. According to TQCD, in a QGP, protons and neutrons lose their identity, and the nuclei turns into a soup of strongly interacting quarks and gluons with properties that are very different from normal nuclear matter. The transition temperature is predicted to be 150–250 MeV \((1.8 \times 10^{12}–3 \times 10^{12} \text{ K})\) [1].

Figure 2. Measurement of \( R \), the cross section for the production of hadrons divided by the muon-pair cross section in \( e^-e^+ \) annihilations [14].
Above this critical temperature, the effective coupling constant is small $\alpha_s(T) \ll 1$ and one should be able to treat the system perturbatively in terms of weakly interacting quarks and gluons. This interaction has a long-distance Coulomb nature, and the properties of the system are, in many respects, very similar to the properties of the usual non-relativistic plasma involving charged particles with weak Coulomb interactions. The only difference is that quarks and gluons carry a colour charge, but no electric charge. In the case of QGP the strong interaction becomes weak so perturbation theory can be used. In QGP long-ranged colour force is screened due to the collective excitations as in electromagnetic plasma. A better understanding of QGP might help explain the properties of strong interactions.

Can we see QGP in nature? According to TQCD, the matter in the early universe was almost certainly QGP until the temperature fell below a few trillion degrees, a millionth of a second after the big bang. Apart from that QGP may possibly exist in the deep interior of neutron stars where the density of matter exceeds $10^{15} \text{ g cm}^{-3}$ (ten times that for normal nuclear matter). It is also hoped that it will be possible to create QGP in ultrarelativistic ion collisions by smashing heavy ions with several hundred giga electronvolt energies per nucleon under laboratory conditions. By means of extraordinarily high-energy nuclear collisions (100 GeV/nucleon), physicists have been trying to produce QGP. The collisions would create temperatures over 100,000 times as hot as the centre of the Sun, and energy densities 20 times that of ordinary nuclear matter, densities which have never before been reached under laboratory experiments.

Studying the QGP phase diagram would be a new way of investigating the different properties of QCD such as confinement and chiral symmetry. According to scientists, investigating QGP is vital in understanding nucleosynthesis, neutron stars, black holes and a new view of the structure of the universe (figure 3).

How can scientists prove that QGP is created in heavy-ion collisions? Can we observe QGP directly in high-energy experiments? The heavier the ions are, the greater the energy is released in the crash and the larger the amount of energy is squeezed into a small space.

Experiments using heavy ions (i.e. those with many more nucleons), increases the lifetime of the fireball. This should make it easier to observe QGP signals. In reality, though, the only thing observed in these experiments is a shower of particles. In theory it should be possible to analyse these signals and gain information about QGP. In practice this is very difficult. The
main reason for this is well known: the strong collective interaction in the system erases most of the traces of the dense stage as it expands and cools.

As the tiny inferno cools, the quarks condense into hadrons (a process known as ‘hadronization’). These hadrons continue to interact with each other for as long as the particle density is high enough. The problem is that physicists can only see the particles that escape from the fireball and reach their detectors. From these signals they have to reconstruct what has happened before, to work out whether the quarks and gluons were produced in a dense enough state to form plasma. Even if QGP is created, this state rapidly explodes, simultaneously expanding and cooling. Physicists have been trying to determine QGP by looking at the particles that shower out from the collision. Physicists’ expectation regarding the observation of QGP signals has caused considerable excitement in the science world and investigations in this field are being conducted by numerous international collaborations.

5. Quark–gluon plasma signals

The production, detection and study of QGP constitute one of the most important research topics in present day high-energy physics. There are plausible reasons for believing that this deconfined state of strongly interacting matter may be produced in collisions involving heavy nuclei. 

In 1986, experimental studies of high-energy nuclear collisions began at the BNL AGS (alternating gradient synchrotron) and the CERN SPS (super proton synchrotron). The AGS started with $^3$He (at 15 GeV/nucleon) and later went on to $^{208}$Au beams (at 12 GeV/nucleon) incident on heavy targets. These experiments were followed in 1994 by the CERN lead beam programme (at 160 GeV/nucleon). A series of experiments using CERN’s lead beam have presented compelling evidence for the existence of a new state of matter.

Similar efforts are taking place using a new Brookhaven machine known as the relativistic heavy ion collider (RHIC). The RHIC is the first collider designed specifically to create and detect this primordial soup. A decade in the making, costing $600 million, RHIC has a superconducting racetrack in a tunnel 3.8 km long and more than 1100 scientists have participated from 19 countries [16]. Smashing together the cores of heavy atoms such as gold at 99.95% of the speed of light, researchers at RHIC are aiming to produce a new state of matter. Scientists think that QGP existed briefly after the big bang, when the universe was much hotter and denser than it is today.

Much of the data obtained from CERN SPS experiments are exciting and hopeful. Scientists studying the results of heavy-ion collisions have thought that the following events might be QGP signals.

5.1. Strangeness enhancement

Strangeness enhancement was proposed in 1982 by Rafelski and Müller as a signature of the transition to QGP [4]. The mass of the strange quark goes down in the case of the restoration of chiral symmetry. Therefore it is expected that there should be an increase in the number of strange particles in the QGP phase caused by chiral symmetry restoration. In normal hadronic matter it is energetically favourable to produce up and down quarks rather than strange quarks in ion–ion collisions because the masses of the up and down quarks are considerably less than the strange quarks. The colliding ions consist not of $s$ quarks, but of $u$ and $d$ quarks. High energy causes pair production $s\bar{s}$. Strangeness in QGP originates from the annihilation process $gg \rightarrow s\bar{s}$ or $q\bar{q} \rightarrow s\bar{s}$.

One of the most remarkable observations in high-energy nuclear collisions is the relative abundance of secondary hadrons. It is possible that enhancement of strangeness is a signal for QGP. However, it is hard to argue that strangeness alone suffices to show the formation of the QGP phase. The CERN experiment WA97, which studies strange particle production at central rapidity in Pb–Pb, p–Pb, p–Be collisions at 158 A GeV/c, has already reported a
pronounced enhancement of hyperon production and these results have been supported by
the STAR experiment in RHIC which is capable of a wide variety of measurements of the
production of $\Lambda$ and $\bar{\Lambda}$ particles in nuclear collisions. The particles studied are $\Lambda$, $\Xi$ and $\Omega$
hyperons and $K^0$ and $K^+$ mesons. Physicists mostly focus on $K^+(u\bar{s})$ and $\Phi(s\bar{s})$, having a
large mean free path. As a result of such experiments, it has been observed that the ratios of
$K^+/\pi^+$, $\bar{\Lambda}/\Lambda$ and $\bar{\Xi}/\Xi$ increase [8, 11].
These extra-strange quarks are mostly reflected by the increased production of the very rare
particles that contain two or three strange quarks (for example, the Omega baryon $\Omega = sss$ and
antibaryon $\bar{\Omega} = \bar{s}\bar{s}\bar{s}$, whose numbers are increased up to 15 times), rather than in the generally
more common particles that only contain one. This again hints that the ‘extra strangeness’ was
formed before the hadrons themselves, and is the other central prediction for the formation of
QGP (comparing the ratios obtained from the low-energy collisions).

5.2. $J/\psi$ suppression

In 1986 Matsui and Satz predicted that the $J/\psi$ yield would be suppressed in a deconfined
medium due to the Debye screening of the attractive colour force which binds the $c$ and $\bar{c}$
quarks together [5]. $J/\psi$ particles contain $c$ and $\bar{c}$ which are so heavy that they can only be
produced at the very early stages of the collision. The processes related with $c$ and $\bar{c}$ production
in QGP are $q + q \rightarrow c + \bar{c}$, $g + g \rightarrow c + \bar{c}$.

According to Matsui and Satz, since the colour screening length is less than the bound
state radius of a $J/\psi$ particle, either $c$ and $\bar{c}$ quarks in the mixed phase combine with other
quarks creating new particles or move around freely. As a result, it is proposed that there
should be a decrease in the number of $J/\psi$ particles. On the other hand, an increase in the
number of charmed particles in the QGP phase is also expected (caused by chiral symmetry
restoration) as with strangeness enhancement.

The most weakly bound state, $\psi'$, is already dissociated in sulfur–uranium collisions
(NA38) while the more tightly bound $J/\psi$ state requires higher energy densities to ‘melt’. However, analysis of the data collected by the NA50 collaboration with Pb–Pb collisions at
158 GeV/nucleon shows that $J/\psi$ is anomalously suppressed in central collisions that and the
observed pattern can be considered as a strong indication for QGP production [9, 11].

5.3. Enhanced production of lepton pairs

Direct lepton pairs ($e^+e^-$ or $\mu^+\mu^-$) are considered, by Feinberg, to be one of the more reliable
probes of hot and dense matter’s dynamics [6]. Leptons interact only electroweakly with the
medium and consequently can leave the interaction region without any final state interaction
carrying information about the properties of the matter at the time of their production.

Dileptons are mainly produced by thermal quark–antiquark annihilation ($q\bar{q} \rightarrow e^+e^-$ or
$\mu^+\mu^-$) and in the mixed phase by the decay of $\rho$, $\omega$ and $\phi$ mesons. In addition to these events, the
decays and the bremsstrahlung processes of mesons and baryons after hadronization can create
leptons. Of particular interest is the $\rho$ meson since it provides a unique opportunity to observe
in-medium modifications of the vector meson properties (mass and/or width) which may be
linked to chiral symmetry restoration because of $\rho$ meson’s very short lifetime ($\tau = 1.3$ fm/c),
as compared to the typical fireball lifetime of 10–20 fm/c at SPS energies.

Consequently, it is hard to use lepton pairs as a probe due to the contribution of different
kinds of sources. The main problem is in differentiating the contributions coming from
different processes when we analyse the lepton spectrum. Taking into account chiral symmetry
restoration, modification of the $\rho$ meson decay channels predicts the increase of lepton pairs
in the intermediate mass region: this is supported by experimental results.

In 1996, the CERES/NA45 collaboration reported an excess of dileptons in the low
invariant mass region 0.2–0.6 GeV/c² which can be explained by the presence of a QGP phase.
Other interacting dilepton data that have demonstrated an enhanced yield over that measured
in proton–nucleus reactions are the dimuon spectra in the intermediate mass region from about 1 GeV to roughly 2.5 GeV, measured by the Helios-3 and NA38/50 collaborations [10].

5.4. Photon production

Among the proposed ‘probes’ of the QGP are directly produced photons. However, there are also many other processes capable of producing photons. Kapusta et al [7] found that the dominant contributions come from the annihilation processes $q\bar{q} \to g\gamma$, $q\bar{q} \to \gamma\gamma$, from the QCD Compton process $qg \to q\gamma$, $\bar{q}g \to \bar{q}\gamma$ and from the electromagnetic bremsstrahlung of quarks $q \to q\gamma$. Photons interact only electromagnetically with the medium and so their mean free paths are much larger than the transverse size of the region of hot matter created in any nuclear collision. As a result, high-energy photons produced in the interior of the plasma usually pass through the surrounding matter without interacting, carrying information directly from wherever they are formed to the detector.

Unfortunately photons can also be emitted during the hot hadron phase because many hadrons are electrically charged. Pions and $\rho$ mesons are the main constituents of such a phase. Scientists have expected that the dominant contributions come from the $\pi\pi \to \rho\gamma$, $\pi\rho \to \pi\gamma$, $\pi\eta \to \pi\gamma$ reactions and the $\omega \to \pi^0\gamma$, $\rho^0 \to \pi^+\pi^-\gamma$ decays. Thus there is a huge amount of background noise.

If the thermally produced photon component can be extracted from the background, it will provide an excellent thermometer for ultrarelativistic nuclear collisions. Experiments searching for these photons observed an enhancement of the number of photons at high energies, but we cannot yet be absolutely certain that it originated from free quarks. Here we suppose that we put hadron gas in one box and QGP in another, and maintain them at the same temperature $T$. We make the walls transparent to the photons. Can we tell which box contains the QGP by measuring the photon spectrum? Since quarks and gluons have different momentum distributions in the QGP and hadrons phase, by analysing the photon spectrum one can get information about transition to the QGP phase. Hydrodynamic models applied to QGP have shown that the increase in photons having large transverse momenta $p_T$ is the QGP signal. A measurement of direct photon production in Pb + Pb collisions at 158 A GeV has been carried out in the CERN WA98 experiment. Significant direct photon excess is observed at $p_T > 1.5$ GeV/c in central collisions [11].

6. Conclusions

Models depending on the hadronic interaction mechanism are not enough to explain the results of heavy-ion collision experiments. Predicted signals for QGP have been supported by the data obtained experimentally. The focus of heavy-ion research now moves to the RHIC. Collisions will be studied with four of the most advanced detectors for high-energy particles yet designed, BRAHMS, PHENIX, PHOBOS and STAR. These devices have been designed and built by scientific collaborations involving nearly 100 universities and laboratories worldwide. In 2005 CERN’s large hadron collider (LHC) experimental programme will include a dedicated heavy-ion experiment, ALICE. In the near future, LHC will collide beams of heavy ions such as lead with total collision energies in excess of 1250 TeV, about 30 times higher than at the RHIC under construction at the Brookhaven Laboratory in the USA. If the initial energy of the colliding nuclei is high enough, the plasma formed will have a longer lifetime and it will be possible to detect the direct measurement of plasma radiation.

Although measurements do not show a sharp, well defined transition between ordinary matter and QGP, the experiments done up to now have already produced some intriguing results indicating that we are on the right track to producing QGP.
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