

Physicists are colliding gold nuclei to recreate the fireball that existed in the very early universe, and they may have found evidence for a quark–gluon plasma

The RHIC gold rush

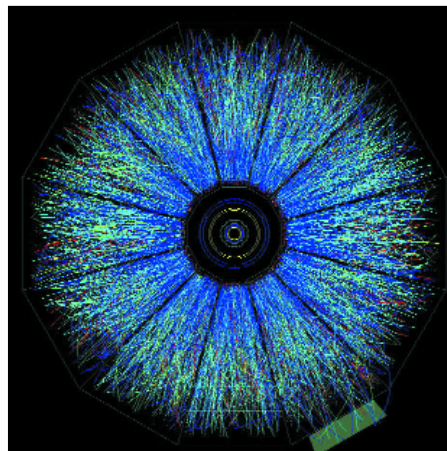
Thomas Schaefer

WHAT happens to ordinary matter as you heat it to higher and higher temperatures, or compress it to greater and greater densities? This simple question underpins a major effort to create extreme conditions in the lab, which has recently taken the shape of the Relativistic Heavy Ion Collider (RHIC). This machine has been colliding gold nuclei since 2000, and has produced tantalizing hints that a new state of matter – the quark–gluon plasma – is created in the reactions. But it has also sparked surprises that are sending researchers back to the drawing board.

Strictly speaking, the quark–gluon plasma – a hot, dense soup of free quarks, antiquarks and gluons – is not a new state of matter. As far as we can tell, this is exactly the state that the universe was in just a few microseconds after the Big Bang. As the universe cooled, the free quarks and gluons combined into particles like protons and neutrons, which bound together at even lower temperatures to form light nuclei. Some of these nuclei then condensed into stars.

While lightweight stars like our Sun end their lives quietly, heavy stars go out with a gigantic bang called a supernova. The outer regions of such stars – fusion factories for heavy nuclei such as gold – are expelled into the interstellar medium and eventually condense into new stars and planets. Some gold nuclei became part of the Earth, and they are now being injected into RHIC at the Brookhaven National Laboratory in New York state in the US to recreate the conditions that existed 14 billion years ago (figure 1).

But running the universe in reverse like this is far from straightforward. Imagine taking a gold nugget and slowly increasing its temperature. At first the behaviour of the gold is governed by electrical forces, but as the temperature rises, the thermal motion of the gold atoms becomes more violent. The crystal structure melts and the atoms eventually evaporate. At temperatures of a few thousand degrees the atoms themselves dissociate and form a plasma of positively charged gold ions and negative electrons. Temperatures of about 10^8 K are the highest that can be achieved using plasma fusion reactors. Above this temperature conventional heating mechanisms become inefficient and, more importantly, there is no way to confine the plasma.



Eye for detail – collisions between gold ions at RHIC produce thousands of subatomic particles and recreate the extreme conditions of the universe when it was just a few microseconds old.

But this is still nowhere near the temperature needed to produce a quark–gluon plasma. In order to reach higher temperatures we have to go nuclear. In collisions of individual nuclei some of the kinetic energy of the projectile and the target is converted into thermal motion (see box on page XX). Once the collision energy reaches the rest energy of individual particles – the rest mass multiplied by the square of the speed of light – these particles can be produced by the collision.

As the amount of energy deposited in the collision volume increases, the initial state becomes hotter, and once the temperature reaches 10^{10} K, the strong force between the protons and neutrons inside the gold nucleus starts to come in

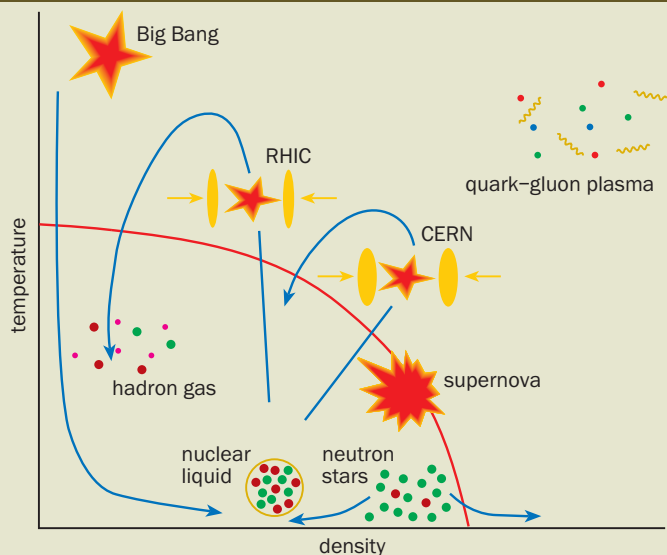
to play. The neutron and protons behave as a liquid with a boiling point of about 10^{11} K, above which they evaporate and form a hadron gas. At even higher temperatures still, the substructure of protons and neutrons – quarks and gluons – becomes relevant.

When strong becomes weak

The behaviour of matter in this regime is described by quantum chromodynamics (QCD), which is the theory of quarks, gluons and their interactions. The strong force is mediated by the exchange of gluons between particles that have a property called “colour charge”. The six quarks – up, down, charm, strange, top and bottom – come in three colours, while their corresponding antiparticles come in three anti-colours. The underlying equations of QCD are formulated in terms of quarks and gluons, and are deceptively simple. But neither quarks nor gluons have ever been observed directly. Instead we observe colour-neutral bound states of quarks and gluons called hadrons, which come in two types. Baryons, such as protons and neutrons, contain three quarks, while mesons contain quark–antiquark pairs.

The key to understanding why quarks are confined in these colourless bound states is that the gluon itself carries colour charge, which leads to a rather counterintuitive property known as asymptotic freedom. This simply means that the strength of the interaction between quarks and gluons becomes weaker as they move closer together. At these short length scales the quarks and gluons therefore provide the

1 Hadronic matter



Matter that is made from quarks can exist in a number of different states depending on its temperature and density. The phase transitions between these states are marked by the red line, and density is defined in terms of how much energy is required to add one more baryon to the system. Matter in the universe was created in the Big Bang at a very high temperature and low baryon density (top left). As matter cooled (blue arrow) below a critical temperature, quarks and gluons combined into colour-neutral hadrons, which eventually formed nuclei. Collisions of gold nuclei at RHIC and CERN essentially run this process in reverse. They produce hot and almost baryon-free matter, which expands, cools and passes through the quark-gluon plasma phase transition. The quarks and gluons then recombine into colour-neutral hadrons that are eventually registered in the RHIC detectors.

appropriate language with which to interpret the experimental results. Over long distances, on the other hand, the interaction between coloured objects is very strong and a description in terms of quarks and gluons is cumbersome. In this case it is much more natural to interpret experimental results in terms of colour-neutral hadrons.

When the temperature of our gold nugget reaches about 10^{12} K, its structure changes dramatically. The protons and neutrons in the gold nuclei dissolve and a quark-gluon plasma is formed. To understand this remarkable phase transition, imagine that we can momentarily turn off the strong coupling between quarks and gluons. With nothing to hold the quarks and gluons together, their typical momentum will follow a Boltzmann distribution that depends on their temperature.

To check whether real matter at such temperatures does look like this free gas of quarks and gluons we have to understand what happens when we turn the colour force back on. Since the momenta of the quarks and gluons is large, the only interactions that can significantly alter their motion involve large momentum transfers. But according to asymptotic freedom, such interactions are governed by weak coupling and are therefore rare. This implies that strongly interacting matter behaves almost like a free gas of quarks and gluons. This state is referred to as a plasma, rather than a gas, because it shares many of the properties of ordinary electromagnetic plasmas. Indeed, in the plasma phase, QCD starts to behave much more intuitively – colour and anti-colour charges in the hot gas tend to “shield” the interaction, and the force between quarks and antiquarks is weak.

Weak-coupling arguments cannot provide a reliable estimate of the transition temperature at which a hadronic gas

becomes a quark-gluon plasma. However, after many years of intense effort, numerical simulations of the QCD equations have pinned down the critical temperature, T_c , to be about 1.4×10^{12} K – about 100 000 times hotter than the centre of the Sun. Simulations also show that the transition is by no means smooth – the energy density changes by more than an order of magnitude near the critical temperature. Just above T_c the energy density of the quark-gluon plasma is about 1.5 GeV fm^{-3} – 10 times larger than the energy density inside a nucleus.

Turning up the heat

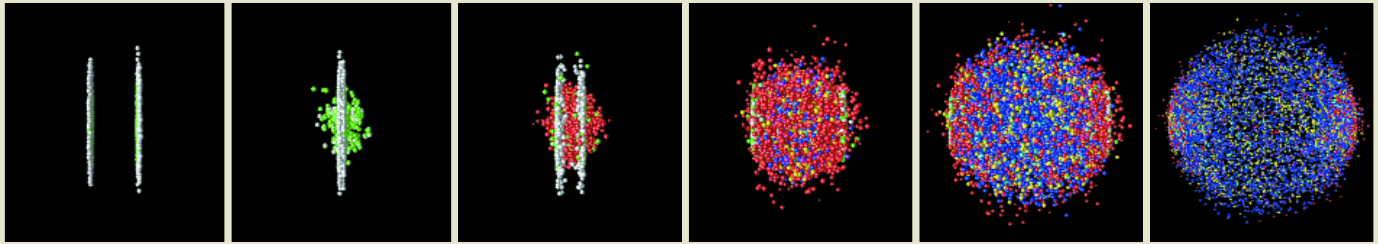
The transatlantic race to create a quark-gluon plasma in the lab began in 1986. The heavy-ion programmes at the AGS accelerator in Brookhaven and the SPS at CERN both collided beams of various nuclei, culminating in lead on lead collisions at CERN in 1994. These experiments showed that heavy-ion collisions can produce matter with a high energy density, and that the energy density grows with the beam energy and system size. This is far from obvious. One could imagine that in a heavy-ion collision a typical nucleon in one of the nuclei only collides once, and then leaves the reaction zone. If this were the case, then the experiments would not produce hot matter. But it turns out that nature is kind. Collisions between heavy ions produce a lot of secondary particles, and it is the rescattering between these particles that allows them to reach thermal equilibrium quickly while the energy density is still large.

In February 2000 experiments at CERN provided strong evidence that an unusual state of matter had been created (see Quercigh and Rafelski in further reading). By smashing a 33 TeV beam of lead ions into a fixed target of lead, researchers were able to create a fireball that had an initial energy density of about 2.5 GeV fm^{-3} – well above the critical value. Also, the production of J/ψ particles – bound states of a charm and anti-charm quark – was strongly suppressed, hence revealing the charge-shielding phenomenon of a weakly interacting QCD system. Furthermore, many strange quarks were produced. In ordinary hadronic collisions the production of strange quarks is suppressed because they have large masses and are not constituent parts of the initial hadrons. Finally, the collisions showed no indication of hadronic resonances – short-lived bound states of quarks – which indicated that hadrons had “melted” in the hot medium.

Later in 2000 the first gold-gold collisions were recorded at RHIC. The beam energy at RHIC is comparable to the SPS at CERN but RHIC is more efficient because it is a collider rather than a fixed-target experiment. Two counter-circulating beams – each with an energy of 17 TeV – are made to collide in four interaction areas, which gives a collision energy that is about an order of magnitude higher than at CERN. This means that the initial energy density is larger and that the system spends more time in the high-temperature phase. In addition, collisions at RHIC produce high-energy quark jets and photons that can serve as probes of the hot initial state. A key signature of a quark-gluon plasma would be a thermal photon spectrum with a characteristic temperature well above the critical one.

There are four detectors at RHIC: two large multipurpose detectors called STAR and PHENIX, and two smaller, more specialized, detectors called PHOBOS and BRAHMS (figure 2). Both the inaugural 2000 “run” at a centre-of-mass

Golden collision



BROOKHAVEN NATIONAL LABORATORY

Working backwards from the final conditions, physicists have devised a rough time line for a collision between two gold ions at RHIC. These collisions take place in about the same time it takes light to travel the diameter of a proton. The incoming gold nuclei are travelling so fast that relativistic contraction makes them look more like disks than spheres. The initial collisions all take place during the first 10^{-24} s, during which time many gluons and quark–antiquark pairs are created. These particles are either produced in “hard” collisions between quarks and gluons that are part of the incoming nuclei, or they are shaken loose from gluon fields in the nuclei. During the next $1\text{--}5 \times 10^{-24}$ s the quarks and gluons collide and reorganize them-

selves in thermal equilibrium. When this process is complete, the temperature is very likely to be above 2.2×10^{12} K. During the next stage matter starts to expand and cool, and when the temperature drops below the critical temperature of 1.4×10^{12} K, quarks and gluons become confined into hadrons such as pions, kaons and protons. These hadrons continue to rescatter and change their identity, but after about $30\text{--}50 \times 10^{-24}$ s the matter becomes too dilute for further rescattering to take place and the fireball falls apart into individual hadrons. These hadrons encounter no additional material until they reach the detectors that surround the collision about 10^{-9} s later.

energy of 130 GeV and the 2001 run at the full design energy of 200 GeV have provided an impressive array of exciting results. A global picture of the collisions can be seen in the particle spectra recorded by the STAR detector (see page **XX**). If the two gold nuclei collide head on, each collision produces about 5000 particles, most of which are pions – bound states of up and down quarks and antiquarks.

The distribution of the pion momenta indicates that the particles were emitted from a source that looked approximately like a rapidly expanding “fire-cylinder”. The boundaries of the cylinder are determined by fragments of the initial gold nuclei that are receding at almost the speed of light. Along the radial direction, matter is accelerated by the pressure of the hot matter created in the collision. At the moment when the fireball becomes dilute and the pions are emitted, the temperature of the fireball is about 1.3×10^{12} K and the radial expansion velocity has reached more than half the speed of light.

Two recent results from RHIC that have attracted a lot of attention are the elliptic-flow measurements at STAR and the large-transverse-momentum spectra obtained by the PHENIX collaboration. Together these results provide strong evidence that a quark–gluon plasma has been produced in heavy-ion collisions at RHIC.

The evidence: soft and hard

An important property of an equilibrated quark–gluon plasma is that it can be characterized by an equation of state. This describes the relationship between the temperature, density and pressure of the system. At a temperature just below the transition to a plasma, most of the energy in a hot hadronic system resides in heavy resonances. Since the resonances are heavy there is not much thermal motion and the pressure is low. In a quark–gluon plasma, however, most of the energy resides in the thermal motion of the quarks, which are almost massless, and the gluons (which have zero mass). This makes the pressure higher.

The difference in behaviour between a normal hadronic system and a quark–gluon plasma can be detected by meas-

uring the ratio of the pressure, P , to the energy density, ϵ . This ratio controls the expansion of the system. P determines the force that drives the fireball explosion that is created in the collision, while ϵ controls the inertia of the system. Consequently, a high value of P/ϵ produces a large explosion, whereas a lower ratio leads to a slow burning fireball.

Experiments at CERN and RHIC study the nature of the explosions by measuring the particle spectra – the number of secondary particles produced as a function of their momentum. These spectra show a distinct blueshift, which means that the typical energy of a particle is higher than that expected given the temperature of the source. This effect is the exact opposite of the redshift of the cosmic background radiation due to the expansion of the universe – the energy of a photon observed today corresponds to a temperature that is much lower than that when the photon was emitted.

The blueshift measured in the heavy-ion experiments is due to the collective expansion velocity in the final stages of the exploding fireball, and it implies an expansion velocity of more than half the speed of light. The problem in relating this observation to the equation of state is that there are two possible explanations for a high expansion velocity: either a large acceleration occurs over a short time, or a small acceleration takes place over a long time. In order to disentangle these two possibilities, experimentalists have measured the directional variation, or anisotropy, of the blueshift factor.

If the collision is slightly off-centre, the initial region where particles are produced – and the corresponding pressure gradients – are anisotropic. A large value of P/ϵ will then cause a blueshift anisotropy called elliptic flow, while if P/ϵ is small then the pressure anisotropy tends to fade before any blueshift is generated. For particles that have a transverse momentum of less than 2 GeV, the anisotropy agrees very well with the prediction for an ideal gas of quarks and gluons (see figure 3a). For particles with larger transverse momenta, the results deviate from an ideal plasma, but such particles are quite rare.

The bulk of the matter expands according to hydrodynamics with a quark–gluon plasma equation of state. Ulrich Heinz from Ohio State University in the US and co-workers

on the STAR experiment suggest that the success of the hydrodynamic description implies that a thermalized quark–gluon plasma was formed very early in the collision and survived for about 2×10^{-23} s before the first hadrons appeared (see Adler *et al.* in further reading).

Elliptic flow is considered to be a “soft probe” of the plasma because the signal is carried by particles that have similar momenta to the plasma temperature, which is true for the majority of the particles. Another way to study the properties of the fireball is to use hard probes – rare particles with very large momenta. Ideally researchers would like to shoot a very fast quark or gluon through the plasma and study how rapidly it loses energy. A colour-charged particle travelling through a medium of coloured charges loses energy much more rapidly than it would if it only encountered colour-neutral hadrons.

In the actual experiments there is no separate beam of fast quarks that can be used to measure the energy loss. However, at RHIC there is a significant chance that a quark or gluon in the initial state of the reaction produces a pair of particles with high energies, such as a quark and an antiquark. Since the momentum transfer is large the effective QCD coupling is small, which means that the process is fairly well understood theoretically. If the quark and antiquark lose energy very quickly, then there is a large probability that at least one of the particles becomes thermalized in the hot medium and does not emerge as a hard particle. As a result, fewer particles with high transverse momenta will be seen than are expected in the experiment.

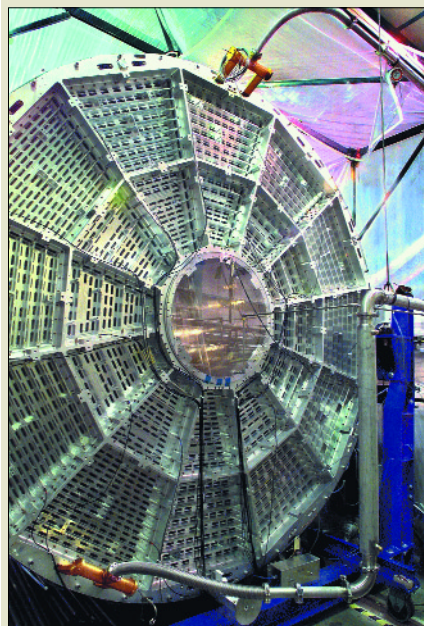
The production of neutral pi-mesons (pions) that have large transverse momenta has been measured by the PHENIX detector (figure 3b). In peripheral reactions the number of pions is about the same as would be expected if the system consisted of just protons, whereas in central collisions there is a significant suppression of pions with high transverse momenta. Miklos Gyulassy and co-workers at the PHENIX experiment estimate that the initial density of the plasma would have to be about two orders of magnitude larger than the density of cold nuclei in order to account for the suppression of pions with high transverse momenta (see Adcox *et al.* in further reading).

The future is hot

The STAR and PHENIX results are very encouraging, but many important problems remain. For example, even though hydrodynamics correctly describes the blue shift of the spectra and the observed anisotropy of the expansion of the quark–gluon plasma, current calculations fail to reproduce the overall space–time picture of the collision. Information about global aspects of the collision, such as its total duration and the final geometry of the fireball, is provided by a technique called pion interferometry.

Pions are bosons, which means that they prefer to be in the same quantum state. If a detector records a pion with a given

2 RHIC detectors



Part of the STAR detector before it was assembled at the RHIC. STAR is one of four large particle detectors that are positioned around the 4 km circumference of the RHIC accelerator.

momentum, then the likelihood of finding another pion with a similar momentum is increased. This increase is only observed if the difference between the momenta of the two pions is smaller than a certain value, which is determined by the size of the original source. A large source will cause the difference in momentum to be small, while a small source will result in a large spread in pion momentum. Pion interferometry is therefore a very useful tool with which to image the exploding fireball.

Experimental results from both STAR and PHENIX support the expected picture of a rapidly expanding, explosive source. But the results do not agree quantitatively with the hydrodynamical calculations that explain the observed elliptic flow. Until this problem is resolved we cannot conclude that elliptic flow provides unambiguous proof of the existence of a quark–gluon plasma.

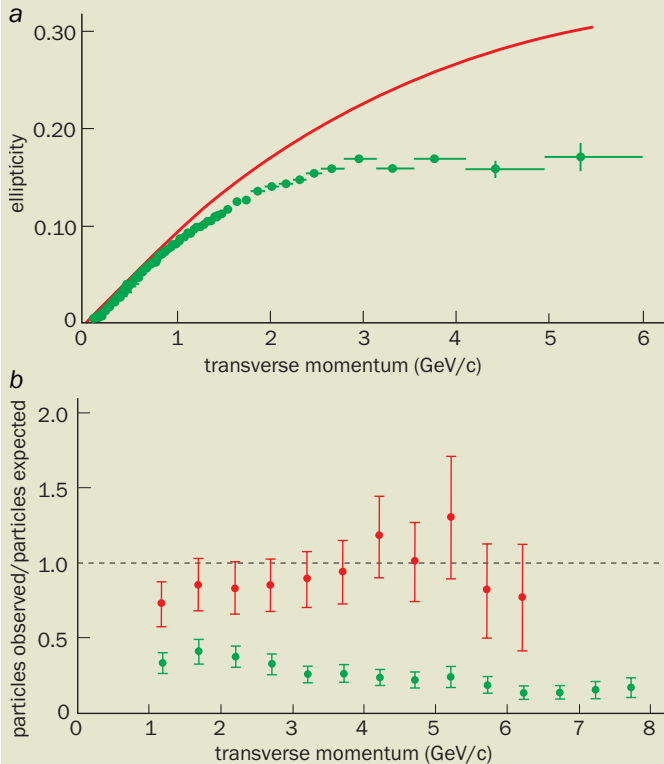
Another problem is that while experiments have detected a significant suppression of pi-mesons with high transverse momenta, no such effect is

seen for baryons. In the simplest version of the energy-loss mechanism, the suppression should be the same for mesons and baryons. Larry McLerran and Dmitri Kharzeev from Brookhaven and Eugene Levin from Tel Aviv University in Israel have suggested an alternative to the energy-loss mechanism. According to their theory the suppression of particles with high transverse momenta is the consequence of a pile-up of gluons in the initial state of the collision. In this “saturation” picture the gluon density in the initial state becomes so large that the colour field essentially behaves classically. Once this happens, nonlinear interactions between gluons limit the further growth of the field and invalidate the simple scaling of the number of particles produced with the number of nucleon–nucleon collisions.

Since December 2002 RHIC has been colliding gold nuclei against deuterons – nuclei that contain just one proton and one neutron. This provides a tough test for the saturation and energy-loss interpretations. No plasma is created in these collisions, and the energy-loss interpretation predicts that no suppression of transverse-momentum particles will be observed. The saturation picture, on the other hand, predicts that the suppression is a feature of the wavefunction of a high-energy nucleus, and that a significant effect will be observed in deuteron–gold collisions. The first results can be expected later this year and they will provide an important baseline not only for the energy-loss measurements, but also for many other observables. Future runs will focus on achieving high luminosity in nucleus–nucleus collisions to enable accurate measurements of very rare processes, such as the production of photons, or bound states consisting of heavy quarks such as the charm and bottom.

We can also look forward to heavy-ion collisions at even higher energies at the Large Hadron Collider (LHC) at CERN towards the end of this decade. This facility will provide another factor of 28 increase in the collision energy com-

3 Signs of a quark–gluon plasma



Data from gold–gold collisions at RHIC provide evidence for the production of a quark–gluon plasma. (a) The STAR collaboration found that the production of charged particles (green circles) is anisotropic. The red line shows the predicted behaviour of an ideal fluid of quarks and gluons, which agrees well with the data at low momentum, but fails to describe rarer particles with large momenta. (b) Data from the PHENIX collaboration show the number of pions that are produced in gold–gold collisions compared with that expected if no quark–gluon plasma was created. In a peripheral collision (red circles) this ratio is equal to one, but in very central collisions (green circles) a significant reduction is observed, which indicates that a new state of matter has been created.

pared with RHIC, leading to even higher-energy densities in the initial state and better access to hard probes of the collision. It will also provide a big challenge for theorists.

The LHC is an “asymptotic-freedom” machine, which means that the bulk of the initial particle production is governed by weak coupling. Theorists should therefore be able to predict the initial temperature as well as the transverse energy and multiplicity in the final state. Time will tell if they are up to the asymptotic challenge.

Further reading

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