

New state of matter created at CERN

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At a recently held special seminar, webcast live on the internet all over the world, scientists from CERN, the European Laboratory for Particle Physics in Geneva, announced¹ that their experiments colliding lead ions on lead target at high energy have produced a compelling evidence for the existence of a new state of matter 20 times denser than normal nuclear matter, i.e. with a density of about 5×10^{15} grams per cubic centimeter, at temperatures over 100,000 times as hot as the centre of the sun, i.e. at about 2 trillion degrees Kelvin. The existence of such a state, called Quark-Gluon Plasma (QGP), is a key prediction of the current theory of strong interactions, quantum chromodynamics (QCD), and it can have interesting consequences for the evolution of our universe in the Big Bang theory, possibly affecting in particular the synthesis of light nuclear elements in our universe.

According to our present understanding, the basic building blocks of matter around us are leptons, which includes electrons, muons and their associated neutrinos, and quarks. Familiar particles such as protons and neutrons are made up of three quarks while mesons like the ρ -meson are made up of a quark and an antiquark. Nuclei are made up of protons, neutrons and pions while atoms have electrons going around the nuclei located at their centres. Electromagnetic forces bind nuclei and electrons together while strong interaction forces bind the quarks into protons as well as neutrons and pions (collectively called hadrons) which in turn are bound together in a nucleus. Everyday matter is made of atoms and molecules, but by heating it up to a few tens of thousand degrees Kelvin, one obtains a (electromagnetic) plasma of positively charged nuclei and electrons by overcoming the corresponding binding forces. Similarly, one can imagine strongly interacting nuclear matter of protons and neutrons at very high temperatures (and/or densities), which turns out to have different characteristics, and is the Quark-Gluon Plasma, discovered at CERN recently.

Quarks have a fractional ($2/3$ or $-1/3$) electric charge. In addition, they have a

new charge-like attribute, called colour, which the leptons do not have. The three possible colours of quarks may be labelled as red, green and blue and the total colour is specified by the amounts of each of these basic colours. Just as charge can be positive or negative, every colour has its anti-colour. The strong interactions, not exhibited by leptons, are due to the exchange of colour charge through vector bosons, called gluons. QCD describes² the theory of interactions of quarks and gluons. Quarks also have additional properties (quantum numbers), called flavours. The six known flavours of quarks are up, down, strange, charm, bottom and top, in an increasing order of the mass of the quark. Proton is made of two up and one down type quark. Changing these usual quarks of a proton one by one by strange quarks leads to heavier strange proton-like particles, Λ , Ξ , and Ω , respectively with increasing negative strangeness.

Nobody has succeeded in isolating a quark or gluon, leading to a postulate of quark (or colour) confinement: quarks are so tightly bound within hadrons that it is impossible for them to break free and exist independently. Since the energy cost of pulling apart a quark grows rapidly with distance, creation of a quark-antiquark pair costs less energy than separating them by a large distance. This leads to two colourless clusters of quarks at such distances, i.e. ordinary hadrons like proton or pion, instead of free quarks. Even if one could imagine somehow switching off the quark-antiquark pair creation, no free quarks can still be pulled apart as doing so requires infinite energy. In principle, this property of permanent quark confinement has to emerge from a theoretical analysis of QCD. In practice, however, it has turned out to be so hard that one has so far succeeded in getting this verified only numerically. This is because the conventional theoretical tool of perturbation theory can justifiably be used for only small coupling. In case of QCD, its use is possible only for distances much shorter than the radius of the proton, or at energy scales much larger than the proton mass, where the quark-

gluon coupling is sufficiently small. Consequently, reliable theoretical predictions of QCD have been obtained, and tested successfully against experimental data, only for short distance physics. Indeed, weak coupling perturbation theory has been used for all similar tests of the electromagnetic and weak interactions which together form the widely known standard model of particle interactions. However, it is only for QCD that the coupling becomes strong in the physics accessible to current experiments. One uses quantum field theory to describe all interactions of the standard model. A totally new calculational tool is required for the strong coupling region in the quantum field theory. Wilson proposed³ in 1974 to define the theory on a discrete lattice of space-time towards this end. In the limit of the lattice spacing going to zero, the usual quantum field theory is recovered. The main advantage of the lattice quantum chromodynamics is that quark confinement in QCD can be demonstrated analytically. All that one then has to show is that it survives in the limit of vanishing lattice spacing, which was shown by Creutz⁴ in 1980 using numerical Monte Carlo techniques. A lot of progress has now been made in lattice QCD and as a result one has now confidence that QCD does provide correct answers for the physics of long distances such as confinement or hadron mass spectrum. The same lattice technique indicates⁵ that at sufficiently high temperatures of about two trillion degrees Kelvin the composite protons and neutrons should melt down to quarks and gluons in a plasma. This new state of matter will be characterized by the fact that quarks could freely roam over longer distances (about several femtometers) than they can in the usual nuclear matter and should have a hundred times smaller interaction-generated effective mass than that inside nuclear matter (hadrons). The theory also tells us that this state should be reached at energy densities of $1-3 \text{ GeV}/\text{fm}^3$ (or equivalently at 20 times the nuclear density). As explained above, a free quark has not been seen, and can never be seen, in any experiment. Since QCD ex-

plains this mystical confinement and predicts a deconfinement at very high temperatures, it would be a unique test of QCD to see the deconfined QGP in laboratory experiments, and thereby achieve an indirect experimental test of the property of quark confinement itself.

While such temperatures could have existed in our universe a few microseconds after the Big Bang in a region few kilometers across, one hopes to reach them in a laboratory by smashing heavy ions⁶ head-on at high energies in a region few femtometers across, i.e. a factor $\sim 10^{-18}$ smaller in size. The CERN experiments use lead ion beam at 33 TeV (i.e. at 0.99998 times the speed of light) on a stationary lead target to pump huge amount of energy in a tiny region of few femtometer radius. Their measured⁷ energy density is close to the theoretical value needed for QGP formation. The hot fireball of QGP is expected to cool rapidly by expanding and turn into usual hadrons like protons and pions. Further expansion of the hadronic fireball results in a cessation of interactions amongst its constituents, as their density becomes very small. From then on they fly away as free-streaming particles and reach the experimental detectors. In their momentum distributions, these hadrons carry the information of the temperature when they became free. Since there are a variety of charged particles the experimentalists can detect, like the pions, kaons or protons, observation of a common temperature for all of them is a strong hint for the existence of the fireball. Furthermore, since the expanding fireball comes towards us, as opposed to the expanding universe in which galaxies recede from us, the observed temperature is blueshifted. A common velocity of about half the speed of light has been estimated from these blueshifts in the CERN experiments. The common temperature of freeze-out, at which the hadrons became free-streaming, or the interactions were frozen out, was found to be about a trillion degrees Kelvin.

A technique similar to the famous Hanbury Brown and Twiss technique from astronomy is used to deduce the size of the fireball at the time of freeze-out from the measured momentum correlations of a pair of particles. Using further the knowledge of how rapidly the system expands, one can extrapolate backwards and work out the original energy density from the measured energy of

produced particles. It works out to be two to four times the theoretically predicted value of the critical energy density for quark liberation, suggesting that quark-gluon plasma formation could have occurred in lead-lead collision in CERN.

Since what gets finally detected in the experiments are not quarks or gluons, which are confined, but ordinary particles after the condensation of the quark-gluon plasma, as described above, it is a great challenge to reconstruct what may have happened. The question is which of the distinguishing properties of QGP will definitely leave its imprint on the left-over hadrons after condensation, i.e. what is the signature of QGP formation. While 99.9% of the produced particles are hadrons, some produced particles, like photons, can escape even during the expansion and their detection could provide a direct glimpse of the QGP phase itself. There are heavy particles like J/ψ , which are mesonic bound states of a charm quark-antiquark pair, and are formed in very early stages of the collisions. A QGP phase would suppress their formation. Since they cannot be formed during condensation due to the lack of enough energy, a reduction in the observed number of J/ψ would be a signature of QGP. The strange proton-like particles mentioned above are easily formed from QGP since it has a substantial number of strange quark and antiquarks. In fact, then the relative probability of forming them with respect to, say, proton-proton collisions, should increase as number of strange quarks in a hadron is increased: $N_{\Omega} > N_{\Xi} > N_{\Lambda}$, where N is the ratio of particles produced in lead-lead collisions to proton-proton collisions. If no QGP were to be formed, on the other hand, then these strange particles have to be produced in pairs of particle-antiparticle. As a result, the increasing energy threshold as the number of strange quarks increases leads to an opposite pattern for these relative abundances.

In fact, a large number of such QGP signatures have been proposed and many experiments at CERN designed their apparatus to look for as many of them as possible. The experiments therefore became huge in size and were possible only as an international collaborative efforts of scientists from many countries like the Czech Republic, France, India, Italy, Germany, Sweden and Switzerland. Seven

large experiments were involved in measuring different aspects of lead-lead and also lead-gold collisions. Analysis of the data of most of them suggested a thermal freeze-out temperature of about 100 MeV or a trillion degrees Kelvin. From the ratios of abundances of various types of hadrons with different flavours, one was able to go further backwards in time, or higher in temperature, like the nucleosynthesis in the early universe. At a temperature of about 170 MeV, the strangeness changing reactions were found⁷ to drop out of equilibrium, leading to a chemical freeze-out of flavours of quarks. This is very close to what lattice QCD predicts as a transition temperature for QGP. Counting the number of strange hadrons, a factor of two enhancement in lead-lead collisions was found compared to proton-proton or electron-positron collisions. These extra strange quarks, probably due to QGP formation, are also reflected⁸ in an increased production of the very rare particles that contain two or three strange quarks. Thus number of Ω 's shot up by about 15 times, while those of Ξ by about 7-8 times, confirming the expected specific enhancement pattern due to QGP. Finally, the number of J/ψ was indeed seen to decrease⁹ in lead-lead collisions by factors of 5-10 compared to expectations without assuming QGP. A variety of indications thus point towards the formation of quark-gluon plasma in the lead-lead collisions.

In summary, physicists at CERN have recreated matter in a state never seen before, at energy densities twenty times higher than that inside the atomic nucleus. The same conditions have only existed in the first few microseconds after the Big Bang. Our understanding about how the universe was created needs experimentally tested ideas from theoretical physics. Up to now we had been successful at about three minutes after the Big Bang when the light nuclei were created in the amounts we observe today. Now the physics needed at a few microseconds seems to be experimentally tested and the corresponding theory verified. Whether it allows us to extend the observed domain of the early universe to that time scale will perhaps be explored once we know the properties of the deconfined state in much more detail.

Indeed, even the case based on circumstantial evidences mentioned above will have to be made more direct or concrete by ruling

out alternative explanations of these results and/or observing photons at the relevant temperature. Going further will luckily be possible in perhaps theoretically even better but experimentally more demanding conditions at the Relativistic Heavy Ion Collider (RHIC) in Brookhaven National Laboratory, New York, where experiments at 10 times more colliding energy will begin this year itself. An increase by a further factor of 25 will be possible in the planned Large Hadron Collider at CERN in 2005. Indian physicists will take part in both the theoretical and experimental efforts for both of these and are looking forward eagerly to the exciting days of the

condensed matter of quark physics.

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