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Fireballs of Free Quarks

CERN appears to have spotted the long-sought quark-gluon plasma--last seen during the big bang

By Graham P. Collins

Not every scientific discovery is heralded by a clear cry of "Eureka!" A case in point is the study of an exotic state of matter known as a quark-gluon plasma (QGP), in which hundreds of ordinary protons and neutrons melt together and form a fiery soup of free-roaming quarks and gluons. The universe consisted of such a quark stew 10 microseconds after the big bang, about 15 billion years ago.

Seven experiments have been gathering data for the past six years at CERN, the European laboratory for particle physics near Geneva. Although the accumulated evidence is not as direct and clear-cut as had been hoped for when the program began, scientists conducting the experiments felt sufficiently confident to make their February 10 announcement. "We now have compelling evidence that a new state of matter has been created," said CERN theorist Ulrich Heinz. And that state, he continued, "features many of the characteristics" predicted for a quark-gluon plasma.

Most modern high-energy particle physics experiments smash together the smallest convenient particles--electrons or protons--because the simpler the protagonists, the cleaner the data. The CERN experiments, in contrast, use relative behemoths: lead nuclei composed of 208 protons and neutrons. These nuclei are hurled at almost the speed of light at a thin foil, also made of lead. On occasion, one of the projectiles strikes a target nucleus, producing a spray of thousands of particles that travel on to the experimental detectors. From these particles, physicists try to determine whether the collision momentarily created a seething fireball of debris, hot and dense enough to set quarks loose.

Quarks, glued together by particles aptly named gluons, are the basic constituents of matter, making up the familiar protons and neutrons as well as more exotic creatures seen only in cosmic rays and particle accelerators. Ordinarily, quarks are locked away inside their parent particles by a phenomenon called confinement. Individual quarks carry a kind of charge that is somewhat analogous to electric charge but comes in three varieties called colors.

Confinement requires that quarks group together in sets of three whose colors blend to make "white" or in pairs of quark and antiquark whose colors similarly cancel out. Separating the component quarks of a particle takes a large amount of energy, and instead of exposing their bare color charges to the world, the energy generates new quarks and antiquarks, which pair up with any potential lone quarks to keep their colors balanced. This pairing process kicks in when a quark gets farther than about a femtometer (10–15 meter) from its companions--the approximate size of particles such as protons and neutrons.

In the CERN experiments, when the two lead nuclei collide, the interactions between their component protons and neutrons generate a swarm of new particles out of the available collision energy. At lower energies, most of these particles will be new hadrons, particles made up of confined quarks and antiquarks. At sufficiently high energy densities, however, the newly generated particles are so tightly packed together that confinement stops being relevant; each quark has numerous companions within a femtometer. Instead of being a hot swarm of numerous hadrons colliding together and reacting, the fireball becomes one large cloud of quarks and gluons. The tremendous energy and pressure of the quark-gluon plasma causes it to explode outward. The temperature and density fall and soon become too low to sustain the plasma state. The quarks then rapidly pair off again, forming colorless hadrons. The fireball, now composed of hadrons, continues expanding and cooling, and ultimately the hadrons fly on to the detectors

Physicists have been eager to create the QGP in part because it provides clues about the origin of the universe. The process of the quark fireball cooling to form hadrons (and later to form atoms) mimics what happened during the big bang. Our understanding of the universe's expansion has been tested by experiment back to the third minute, when ordinary atomic nuclei formed; with the quark-gluon plasma, "we have extended our knowledge back to 10 microseconds after the big bang," says Reinhard Stock of the University of Frankfurt, who led one of the CERN experiments. The explosive pressure at that time was comparable, he remarks, to the weight of "150 solar-masses acting on an area the size of a fingernail." (Apocalyptists take note: the presumed creation of the QGP did not create a mini–black hole or other Earth-destroying phenomenon, as some press reports suggested it might last year.)

CERN researchers cite several lines of evidence that strongly indicate they created the quark-gluon plasma. first are the relative numbers of various hadrons, which indicate the temperature and energy density that must have prevailed when they formed. The result is consistent with the levels theoretically required to produce a plasma. The energy density is about seven times that of ordinary nuclear matter, and the fireball is expanding at 55 percent of the speed of light when the hadrons "freeze out" of it.

The next observed effect is enhancement of strangeness, which refers to a type of quark. Altogether there are six different species, or "flavors," of quark, going by the whimsical names of up, down, strange, charm, bottom and top. The lion's share of ordinary matter is composed of the lightweight up and down quarks: two ups and one down quark make a proton; one up and two downs, a neutron. Strange particles, produced in particle physics experiments, contain at least one strange quark or antiquark.

Strange quarks are heavier than ups and downs, making them more difficult to produce. In the early 1980s theorists predicted that they should be unusually abundant in the QGP, where energy levels are so high that strange quark-antiquark pairs are produced essentially as easily as pairs of ups and downs are. The CERN experiments saw several features of enhanced strangeness. When conditions were ripe for a plasma, overall strangeness was two times higher, and a particle called omega, containing three strange quarks, occurred 15 times more often. Such extra enhancement of "multistrange" particles is characteristic of a plasma.

Whereas strangeness is enhanced in a QGP, certain charm particles, containing the next heavier variety of quark, are suppressed, as predicted in 1986. Attention focuses on the J/psi meson, which consists of a charm quark and a charm antiquark. Charm quarks are so massive that these charm-anticharm pairs can be produced only during the initial extremely high energy proton-neutron collisions and not during the subsequent fireball. How many of the pairs remain together to be detected as J/psi mesons depends on whether they had to endure a QGP: a hot, seething plasma separates a charm quark from its partner charm antiquark, so they end up detected as a different species of hadron. The observed pattern of J/psi suppression in the CERN experiments "rules out the available conventional [explanations] based on confined matter," asserts Louis Kluberg of the Laboratory of High Energy Nuclear Physics in Palaiseau, France.

All this evidence comes down on the side of a quark-gluon plasma. Why, then, in the words of Heinz, is this evidence "not enough to prove beyond reasonable doubt" that a quark-gluon plasma has been created?

The problem is that the evidence is indirect, involving detection of particles produced when the plasma changes back to ordinary hadrons. If there were a complete and consistent dynamical theory that described the collisions, such indirectness might be less of a concern. But such a theory does not exist: theorists must resort to various approximation schemes and computer models, incorporating guesses about which processes are most significant to try to re-create the observed data. Indeed, some theorists will now be playing devil's advocate, doing their darnedest to concoct a model involving only hadron collisions that can explain all the CERN data

A way to shortcut such efforts is to obtain untainted evidence *directly* from the plasma--by studying particles that do not interact strongly with quarks and gluons and so can escape from the QGP while it is still a plasma. They would carry direct signals of the extant conditions. For example, the formation of a QGP should greatly increase the number of photons emitted. Alas, CERN's photon data are inconclusive, almost swamped by the large background of photons that are explicable without a QGP. "There are intriguing indications of direct photons, but they are marginal," Heinz says.

Such direct evidence will have to wait for the Relativistic Heavy Ion Collider, or RHIC (pronounced "rick"), at Brookhaven National Laboratory in Upton, N.Y., which will start examining head-on collisions of two beams of gold ions in the summer [see "A Little Big Bang," by Madhusree Mukerjee, *SCIENTIFIC AMERICAN,* March 1999]. The usable collision energies will be 10 times those of CERN's program, which ought to produce a QGP with a higher temperature and longer lifetime, allowing much clearer direct observations. RHIC's plasma should be well above the transition point between a QGP and ordinary hadronic matter, allowing numerous more advanced studies of the plasma's properties, not merely an uncertain demonstration that it exists at all.

In 2005, CERN's Large Hadron Collider will come on-line and slam ions at 30 times the energy level of RHIC. "We have now scratched the surface," Heinz says. The higher energies of RHIC and the Large Hadron Collider are needed to "complete the picture."