Microcosmic Bang

Mashing atomic nuclei to create a quark soup

By IVARS PETERSON

According to modern physics, the first micromoments of the Big Bang were a time of unimaginable extremes.

No more than a cosmic spark, the universe was then so extraordinarily hot that the strong nuclear force was too weak to keep quarks bound tightly together in protons and other particles of ordinary matter. Free quarks roamed a thick broth of gluons, particles that carry the strong force.

Physicists describe this extreme state of matter as a quark-gluon plasma. Now, they think that they have glimpsed such a state in the laboratory in high-energy collisions between heavy nuclei.

Earlier this year, more than 500 physicists gathered in Heidelberg, Germany, for the Quark Matter conference. After hearing results of recent experiments observing collisions between nuclei of lead, many were ready to take seriously the notion that such collisions could produce ultramicroscopic fireballs of quark-gluon plasma.

"This represents a considerable change in mind among those who were skeptical of previous results," observes Johann Rafelski of the University of Arizona in Tucson. "It's an exciting moment in a field that has been developing rapidly."

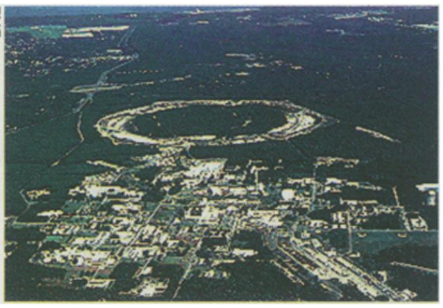
"It's very promising, very encouraging," adds theorist Robert L. Sugar of the University of California, Santa Barbara, who has been using computer simulations to study the transition between ordinary matter and the quark-gluon plasma.

These findings "highlight an unexpected physical phenomenon that could be the signature of the quark-gluon plasma," says Rafelski. They offer a way of checking whether modern physics is on the right track—that is, whether what physicists hypothesize happened in the aftermath of the Big Bang is consistent with the behavior of subatomic particles.

If the experimental results are strengthened and confirmed, says Helmut Satz of the University of Bielefeld in Germany, the Heidelberg meeting may well be remembered for the first report of a "little bang."

The nucleus of a lead atom consists of 82 protons and about 124 neutrons. Protons and neutrons, in turn, are composed of quarks. The standard model of particle physics posits that quarks come in six varieties: up, down, charm, strange, bottom, and top.

Quarks typically are found in pairs or triplets. A proton, for example, is made up of two up quarks and one down quark, and a neutron is made up of two down quarks and one up quark. Other sorts of particles, called mesons, consist of a quark and an antiquark bound together.



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Aerial view of the site of the Relativistic Heavy Ion Collider, now under construction at the Brookhaven National Laboratory, where researchers hope to create a quark-gluon plasma.

Under normal conditions, gluons keep these combinations of quarks from flying apart. At extremely high energies and densities, theory suggests, quarks and gluons begin to mingle freely, breaking out of the confinement that defines protons and other subatomic particles.

Obtaining experimental evidence of this state of matter has proved difficult. Only collisions between heavy atomic nuclei traveling at nearly the speed of light produce a central core of particles endowed with large quantities of energy.

At the European Laboratory for Particle Physics (CERN) in Geneva, researchers use the Super Proton Synchrotron to strip heavy atoms of their electrons, and they accelerate the bare nuclei at targets composed of various materials. Previous experiments involved sulfur nuclei fired at a sulfur target. The latest round had lead nuclei hitting a lead target at a record energy of 3.6 teraelectronvolts.

At the Brookhaven National Laboratory's Alternating Gradient Synchrotron in Upton, N.Y., physicists conduct similar experiments using gold projectiles and targets, but at lower energies than at CERN. Their results may establish a lower limit for the quark-gluon plasma.

In theory, the energy of a collision should melt the participating nuclei into a blob of plasma. However, because the interaction takes place in a very short time and in a very small space, obtaining detailed information about what would occur inside such a blob has proved troublesome.

Researchers have to rely on their observations of the shower of ordinary particles left over after the initial fireball breaks up. By looking at the proportions of different types of particles that emerge, physicists can try to reconstruct the conditions in the fireball.

The most striking results presented at the Heidelberg meeting came from the NA50 collaboration at CERN, led by Louis Kluberg of the École Polytechnique in Palaiseau, France. It determined the rate at which lead-lead collisions generate a particular type of particle.

A J/ψ particle, a meson that consists of a charm quark and its antiparticle counterpart, has such a large mass that it rarely forms in proton-proton collisions, the standard experiment in high-energy physics. In nuclear interactions, howev-

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er, protons collide repeatedly as the participating nuclei begin to merge, generating larger than normal numbers of J/ψ particles.

Because they are most often produced in that initial contact between colliding nuclei, J/ψ particles end up moving through the remainder of the merged nuclear matter, or blob. By comparing collisions in which these particles travel different distances through this material, researchers can, in a sense, image the blob. In other words, the J/ψ particles act like X rays penetrating an opaque object.

The NA50 team detected only about half as many J/ψ particles as they would have expected if there had not been a high-density, high-temperature environment to break apart quark-antiquark pairs. This finding suggests that at least some fraction of the material in a lead-lead nuclear collision is a quark-gluon plasma.

In the Aug. 26 Physical Review Letters, Jean-Paul Blaizot and Jean-Yves Ollitrault of CE-Saclay in Gif-sur-Yvette, France, account for the missing J/ψ particles by saying that these particles "melt" in the hot central region of the nuclear fireball.

Because current theoretical models of the production and decay of J/ψ particles offer conflicting predictions, however, the full implications of these results remain uncertain.

"Whatever the final theoretical picture, the experimental effect cannot be argued away," Rafelski remarks.

Physicists had previously obtained unconfirmed results that hint at the formation of a quark-gluon plasma in particle collisions (SN: 10/8/88, p. 229). This time, however, a number of different experiments have provided data consistent with the NA50 finding.

Six CERN teams studied the same lead-lead collisions that the NA50 collaboration observed. Each one focused on different particles and made different measurements.

"Everyone found something that was not easily explainable in terms of conventional physics," Rafelski notes.

For example, the WA97 group, led by Emanuele Quercigh of CERN, furnished convincing evidence that far more particles composed of strange quarks were produced than can be accounted for in the absence of a quark-gluon plasma.

The NA52 collaboration, headed by Klaus Pretzl of the University of Bern in Switzerland, looked at antimatter production in these collisions. The surprisingly large quantities of antiparticles, such as antiprotons and antideuterons, generated in these interactions also suggested an origin in a quark soup of some sort.

Each set of findings, though preliminary, contributes to the overall picture of the creation of a quark-gluon plasma at the core of lead-lead collision products. Now, researchers need to refine their results and complete their analyses of the experimental data.

A crucial extension of the investigations is the determination of whether there is a sharp transition between the quark-gluon plasma and the confined quark state. It's possible, for example, that a small reduction in the energy of the lead projectiles could stop the production of quark-gluon plasma.

Theorists are using the recent data to refine their estimates of the production rates of different quark-based particles under varying conditions during collisions. Experimenters are now preparing to observe low-energy collisions at CERN to see if a threshold for plasma creation exists.

As construction of the Large Hadron Collider proceeds (SN: 4/6/96, p. 214), CERN is gradually closing down its experimental program involving heavy nuclei in order to conserve funds. However, researchers are looking forward to completion of the more powerful Relativistic Heavy Ion Collider, now being built at Brookhaven. The increased energy available at that facility and the use of two colliding beams of nuclei instead of one beam and a fixed target should greatly enhance the chances of creating a quark-gluon plasma.

The first collisions between nuclei in opposing beams is scheduled to take place at this facility in early 1999.

"Progress has been very rapid in the last decade in this field of physics," Rafelski says. "If these projects are carried through, we should have the answer by the turn of the century." □

Letters

Lunar lapse

I was sorry to see you pull the ancient boner that the moon increases its velocity through space as it recedes from Earth ("The Moon's Tug Stretches Out the Day," SN: 7/6/96, p. 4). Though its angular momentum increases, the moon slows down.

Back to physics 1A for all of you.

Hal Lewis
Santa Barbara, Calif.

Casting a cloud over passive heat

As owners of a passive solar house, we are directly affected by jet airplane activity in our area ("Ten Thousand Cloud Makers," SN: 7/6/96, p. 12). The living room temperature can be as low as 45°F when we arise in severe subzero weather, but that's not hard to take when we know we'll be basking like lizards shortly after the sun rises. So we don't start a fire.

By the time the sun rises on some days, however, it is blocked out by the contrails of jet planes engaged in some sort of training exercise. So we are obliged to start a fire after all, adding our bit to the general pollution.

David D. Robinson
Canaseraga, N.Y.

Change of venue for record keepers?

Researchers involved in deciding that "Warming reaps earlier spring growth" (SN: 7/13/96, p. 21) obviously didn't visit New England this spring as we dug our way out of drifts of snow while asking, "Where is global warming when we need it?" and waiting for warmer air to bring spring blossoms to our gardens. Perhaps temperature records should be kept by gardeners here instead of by researchers atop Mauna Loa.

N.A. Hayward
Falmouth, Mass.

When safety strips become hazards

I was dismayed to see that the AAA Foundation for Traffic Safety is planning chevrons or other painted schemes to slow down four-wheeled traffic ("Illusions: The route to safer roads?" SN: 7/13/96, p. 31). These devices are hazards for people on motorcycles.

Any painted spot on the road can become as slick as ice when rain, oil, or antifreeze from passing vehicles falls on it. In addition, rumble strips and raised areas make tire adhesion problems worse, particularly going around a corner.

A car or truck, with four or more tires providing relatively large tire-to-road contact areas, should not have a problem. However, for motorcycles, with their two small tires, such large painted areas become death traps.

Believe me, having your front tire start to slide out in a corner is not a pleasant experience. It is also a potentially fatal one.

I hope the foundation thinks about all the vehicles that use our highways before they try this solution.

David Klein
Atlanta, Ga.

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A bit of a mixup

"Communicating with trits, not bits" (SN: 7/13/96, p. 31) claims that transmission of three letters of the alphabet normally requires 24 bits rather than "just 15 trits."

By my calculations, three letters can be transmitted in 15 bits, and nothing "remarkably clever" is involved.

Edson C. Hendricks
San Diego, Calif.

Clarification: The three letters of the alphabet were transmitted as ASCII characters, which require 8 bits each. —I. Peterson

In "Communicating with trits, not bits," the terminology raises the question: When they can encode four pieces of information, will they call it quits?

David Ellison
Chattanooga, Tenn.