A Question of Quarks

To learn more about the early universe, scientists are attempting to create a state of matter that hasn't existed since the first moments following the big bang.

INSIDE the accelerator, gold ions zoom toward each other at almost the speed of light. They crash together with enough force to melt the ions into a quark–gluon plasma. This hot, primordial quark soup is thought to have existed in the first millionth of a second after the big bang that created our universe. The entire universe, small though it was then, is thought to have been a quark–gluon plasma. As the universe began to expand and cool, the quarks and gluons bound together and have remained virtually inseparable ever since.

Whereas the alchemists of old tried to turn all sorts of materials into gold, modern-day physicists, including several from Livermore, are attempting reverse alchemy—turning gold into a different state of nuclear matter. By smashing gold ions together in the Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory in Upton, New York, they are working to free quarks and gluons and re-create a quark–gluon plasma on Earth.

The quark is the most elementary building block of matter. (See the box on p. 7.) By exchanging gluons—massless particles that make quarks stick together—groups of quarks constitute particles such as protons and neutrons. The binding force carried by both gluons and quarks is known as the strong force, and for good reason. Although theory says that at extremely high energy densities, protons and neutrons should dissolve into a quark–gluon plasma, no particle accelerator had been powerful enough to create the necessary conditions with high certainty.

The possibility of creating hot, dense nuclear matter by colliding large nuclei was first proposed in 1973 by several

Livermore physicists, including George Chapline and Edward Teller (*Physical Review D* **8**, 4302–4308). They predicted that experiments using Lawrence Berkeley National Laboratory's Bevelac, then the most powerful particle accelerator for heavy nuclei, would probably result in the "production of matter in a new regime of temperature and density."

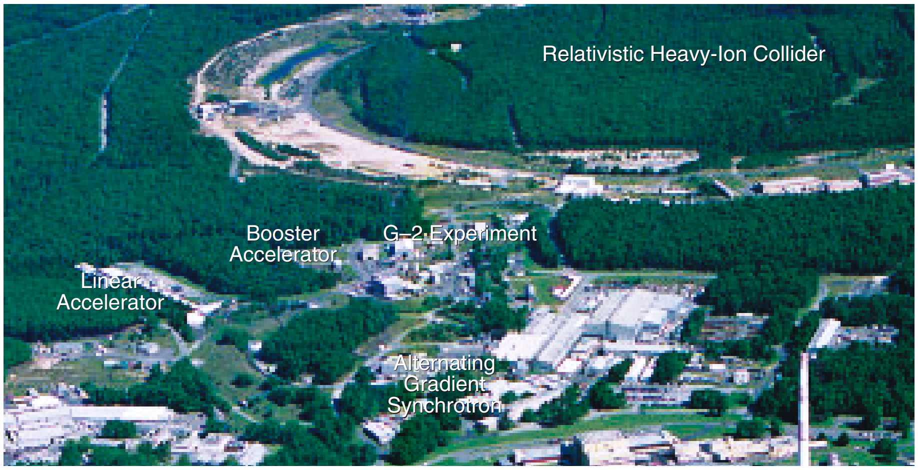
They recognized that "since the experiments explore regions very far from our experience, it is reasonable to expect surprises." In fact, they surmised that the main result of the experiment would be the "unexpected phenomena." That is what great science is often all about.

The Experiment Today

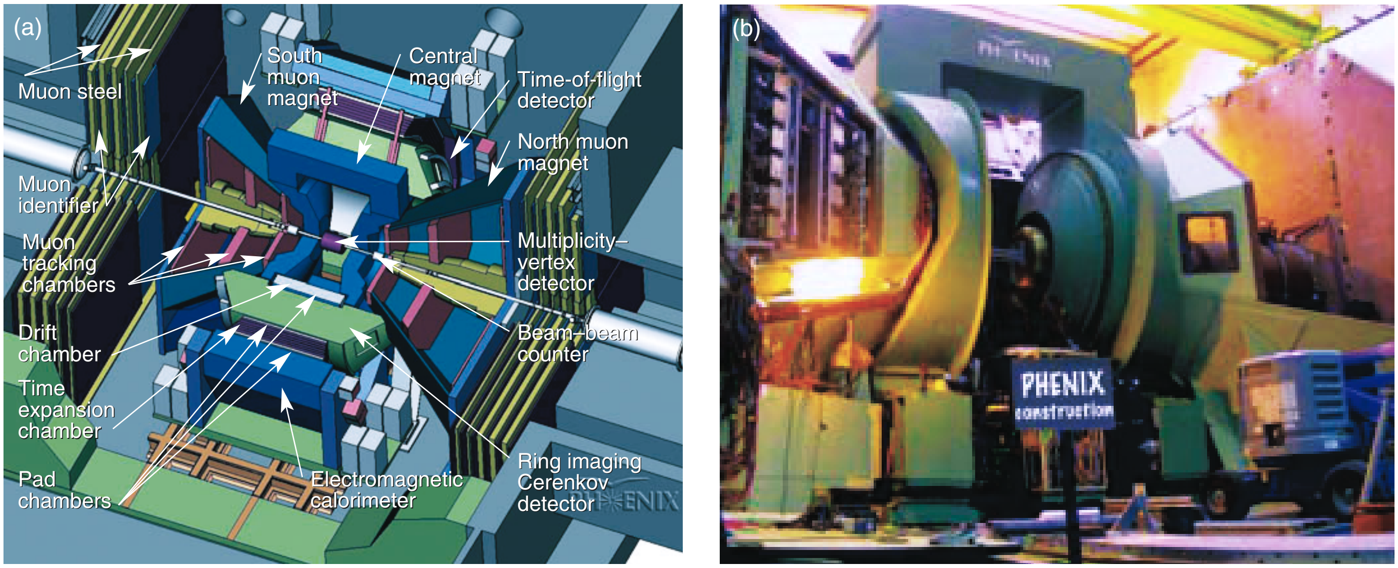
More than 25 years later, in 1999, physicists from institutions all over the world believed they might have finally established the laboratory conditions required to create not only the hot and dense region described in 1973 but also a new phase of matter. (See the box on pp. 8–9.)

Beams of gold ions or nuclei—atoms that have been stripped of their electrons—are propelled around RHIC's loops in opposite directions at 99.9 percent of light speed. When any two nuclei collide, the collision acts as a pressure cooker, liberating more than a trillion electronvolts of energy in a volume the size of an atomic nucleus. Some of the energy each nucleus had before the collision is transformed into intense heat and new particles such that new matter is created at a temperature ten thousand times that of the Sun. The collisions are highly explosive, and if a quark–gluon plasma is created, it decays into particles (bound quarks) almost as quickly as the plasma is formed.

To determine whether a quark–gluon plasma existed during an experiment, scientists look for signatures in the distribution and composition of the particles that reach the Pioneering



Aerial photograph of the 3.8-kilometer-circumference Relativistic Heavy-Ion Collider and associated particle accelerators at Brookhaven National Laboratory.



(a) A schematic of the Pioneering High-Energy Nuclear Interaction Experiment (PHENIX) detector. (b) Inside the PHENIX detector.

High-Energy Nuclear Interaction Experiment (PHENIX) detector, which Livermore helped to design and build during the 1990s.

"If the experiment continues according to plan, we will have made a quark–gluon plasma," says Livermore physicist Ron Soltz, a principal investigator for Livermore's work at RHIC. "What we're essentially trying to do is find the boiling point of nuclear matter."

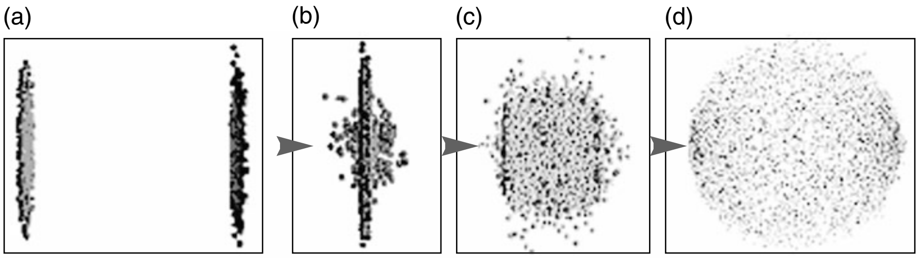
Measuring Success

Soltz's team, including physicists Stephen Johnson and Ed Hartouni and postdoctoral fellows Mike Heffner and Jane Burward-Hoy, are measuring the volume, lifetime, and violence of the collision zone (or source). A large volume and long lifetime are one of the purported signatures of a quark–gluon plasma. To take the measurements, the team examines the production of pions, a two-quark particle that is the most prevalent product of these collisions. The team is exploiting a simple property of quantum mechanics, which is that the more highly correlated the pions are in a given direction, the larger the emission volume is along that axis. A long-lived source should appear as an apparent elongation of the fireball in the direction of the detector relative to the geometric radius of the fireball. The Livermore team found almost no elongation, in contradiction to most recent theoretical expectations.

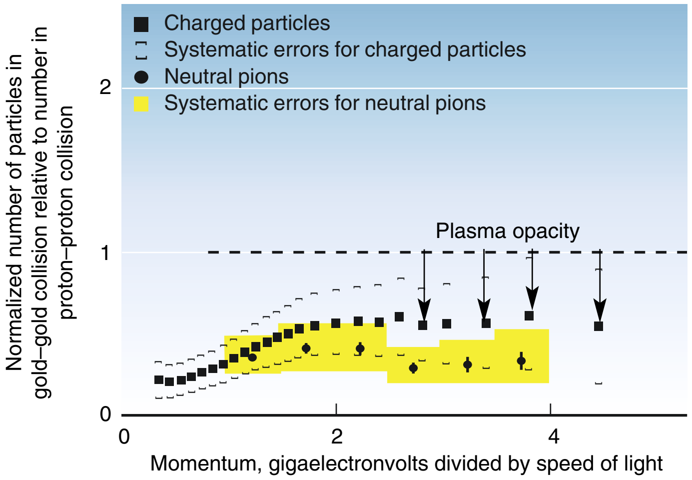
However, the story does not end there. Even before the Livermore team had finished its analysis, other collaborators were finding signs of the plasma in another signature.

"If no plasma is formed, particles with high momentum escape the collision unscathed," notes Johnson. "But if a quark–gluon plasma has been created, the interaction between high-momentum particles and the medium increases dramatically, significantly lowering the velocity of the particles."

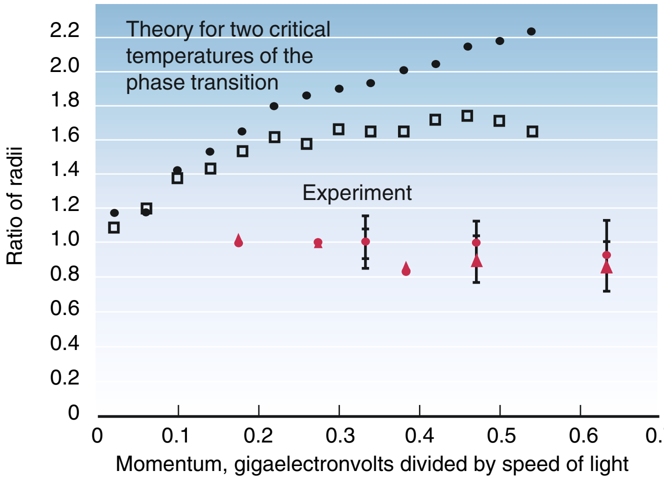
Quantum chromodynamics theory (see the box on p. 7) predicts that in the presence of a quark–gluon plasma,



(a) Inside Brookhaven's Relativistic Heavy-Ion Collider, two gold nuclei approach one another at almost the speed of light. Traveling at relativistic speeds causes them to look flat rather than spherical. (b) As the two nuclei collide and pass through each other, some of the energy they had before the collision is transformed into intense heat and new particles. (c) If conditions are right, the collision liberates the quarks and gluons in the nuclei to form a quark–gluon plasma. (d) As the area cools off, thousands more particles form. Many of these new particles will travel to a detector where their distinctive signatures give physicists clues about what occurred inside the collision zone.



A paucity of high-momentum particles during the collision of gold nuclei, which is the result of an opaque source, is consistent with theory and indicates the existence of a quark–gluon plasma.



Results from the STAR and PHENIX detectors show that the elongation of the collision zone (indicated by the ratio of two radii) was considerably less than theory predicted. In fact, there was no elongation at all, with ratios of about 1.

substantially fewer high-momentum particles will make their way to the detector. That relatively low number is, in fact, what PHENIX found by counting high-energy pions.

So right now, the data are inconclusive. "Obviously, we need more information," says Soltz. "We're considering two options at this point. One is to study rarer particle signatures, which would require a lot of data that we don't have. The other option is to go to a simpler experiment whose results will be easier to interpret."

A Simpler Experiment

When two gold nuclei collide, many interactions occur between all of the nucleons (protons and neutrons). Although these numerous interactions are responsible for creating the conditions necessary to form a quark–gluon plasma, researchers have difficulty differentiating between signals resulting from the plasma and those that may be caused by other interactions of the nucleons.

Atomic Parts and Particles

All things, living and inanimate, are made of atoms. Almost all of an atom's mass is in its nucleus, where protons and neutrons reside. Protons and neutrons consist of various combinations of quarks. At the moment, scientists believe that quarks are the smallest particles in our universe and that they form the basis for all matter. However, just as scientists until the late 19th century believed that the atom was the smallest particle, they may someday discover particles smaller than quarks.

In the meantime, theory holds that quarks, with the help of gluons to hold the quarks together, make up everything in the nuclei of atoms. Up, down, charm, strange, top, and bottom—these are the six "flavors" of quarks. Up and down quarks are the least massive and are more prevalent than other types. Protons always have two up quarks and one down quark, whereas neutrons have two down quarks and an up quark. Other more exotic and more massive particles are composed of other quark combinations. A lambda particle, for example, has an up, a down, and a strange quark, while a kaon has a strange and an up quark. Gluons carry the strong force that glues quarks together to form protons, neutrons, and other particles and keeps them together in an atom's nucleus.

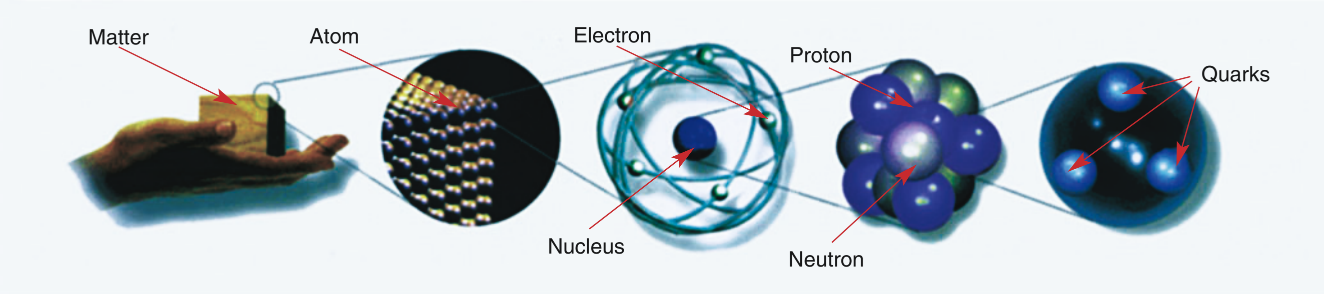
In contrast, the electron is not made of quarks and is not subject to the strong force. Instead, the electromagnetic force keeps an electron in its orbit spinning around an atom's nucleus.

After discovering that the atom was not the most elementary particle, scientists realized that subatomic particles behave differently from larger, bulk quantities of matter. The field of quantum mechanics was developed to explain this apparently eccentric behavior.

Then they discovered quarks and gluons, whose existence was first inferred from the spectra of elementary particles and from electron-scattering experiments in particle accelerators. Quarks and gluons possess a type of charge that has been whimsically termed color. Color is the source of the powerful forces that first cluster the quarks and gluons to make protons and neutrons and, in turn, grip these nucleons to one another to form atomic nuclei. A new theory, quantum chromodynamics, was developed late in the 1960s and early 1970s to describe these phenomena.

Quantum chromodynamics, which explains the strong force, bears many similarities to quantum electrodynamics, which explains electrical charges and light. Atoms can be ionized and the fundamental electrical charges of quantum electrodynamics can appear in isolation, but in quantum chromodynamics, the fundamental quark and gluon constituents of protons and neutrons can only be liberated in conditions identical to those of the big bang. This property of quark–gluon confinement gives stability to all matter as we know it.

Quantum chromodynamics theory predicts that deconfinement will occur at sufficiently high temperatures, nuclear densities, or both. Quarks and gluons will break free of their bondage in atomic nucleons, re-creating the earliest moments of our universe.



Simpler to study than the collision between two nuclei is a collision between a single proton and a nucleus. While one proton may have several interactions within a nucleus, scientists do not expect that these interactions will create a plasma. But exactly how many such interactions are there? Finding the answer to this question for each proton–nucleus collision will allow scientists to make proper comparisons with the results from nucleus–nucleus collisions. If scientists can measure the number of interactions, they should be able to verify the underlying signatures of a quark–gluon plasma.

Under Johnson's leadership, the Livermore team has begun adding a detector to PHENIX that will make these measurements in proton–nucleus collisions. The new detector is a calorimeter that measures the pieces of the fragmenting nucleus after a proton has blasted through it. To provide this entirely new capability in short order at a minimal cost, the Livermore group adopted detectors and equipment from previous Brookhaven experiments. The result is what they jokingly refer to as the "Scrounge-a-Cal." The calorimeter is being instrumented in PHENIX now, and the first results will be analyzed this spring.

Answering Quark Questions

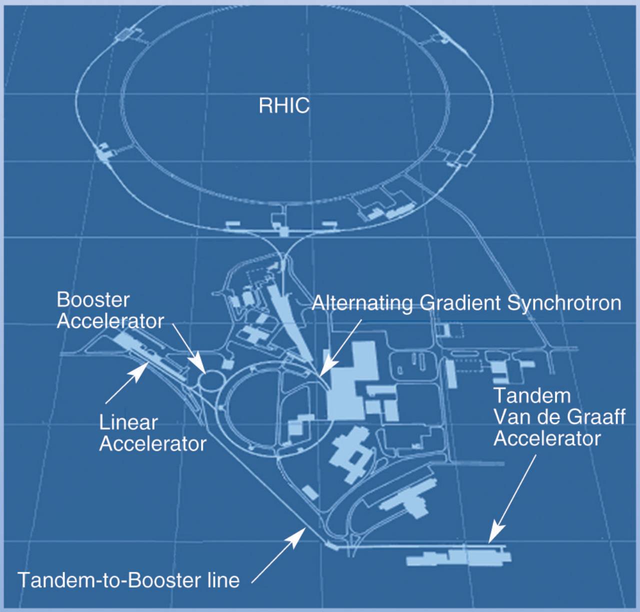
Research at Brookhaven and elsewhere is beginning to answer some new and old questions about quarks. Researchers at the National Aeronautics and Space Administration's Chandra X-Ray Observatory recently discovered what appears to be a collapsed star with

PHENIX and RHIC Rise

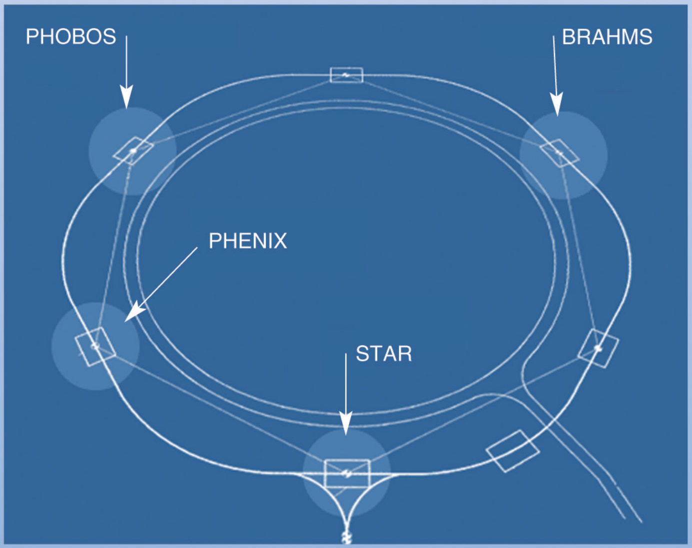
Only massive experimental equipment such as the Relativistic Heavy-Ion Collider (RHIC) and the Pioneering High-Energy Nuclear Interaction Experiment (PHENIX) detector at Brookhaven National Laboratory make it possible to study the almost infinitesimally small dot known as the quark.

An inverse relationship exists between the size of the object being studied and the size and expense of the equipment needed to examine it: the smaller the object, the greater the energy needed to probe it, and thus, the larger the equipment required. Particle and nuclear physicists, who want to examine the fundamental building blocks of matter up close, need hugely expensive machines often measuring a kilometer or more in diameter. Given their expense and size, few such machines can be built. Many nuclear and particle physicists must concentrate their efforts on the few particle accelerators and colliders available around the world.

Lawrence Livermore is just 1 of 55 institutions from 11 countries involved in the quark–gluon plasma experiments being performed on the PHENIX detector at Brookhaven. There are 450 scientists participating, each



A schematic of the Relativistic Heavy-Ion Collider (RHIC) complex.



The layout of the detectors around the RHIC tunnel.

a quark core. If accurate, this discovery complements the current search for the quark–gluon plasma at RHIC. It also confirms a prediction made 25 years ago by Livermore physicist Chapline about extremely dense stars with a quark–gluon plasma at their core rather than the bound quarks usually found in neutron stars.

Equally important—for basic science and a better understanding of how our universe got started—the experiments at Brookhaven's RHIC hold the key to answering one of the questions posed recently by the National Research Council Committee on Physics of the Universe. In its report, *Connecting Quarks with the Cosmos: 11 Science Questions for the New Century*, number 7 on the council's list was "Are there new states of matter at ultrahigh temperatures and densities?" Livermore researchers and their collaborators hope to answer that question soon.

—Katie Walter

Key Words: Brookhaven National Laboratory, particle physics, Pioneering High-Energy Nuclear Interaction Experiment (PHENIX) detector, quark–gluon plasma, Relativistic Heavy-Ion Collider (RHIC).

For further information contact Ron Soltz (925) 423-2647 (soltz1@llnl.gov).

Additional information on the Relativistic Heavy-Ion Collider is available at:

www.bnl.gov/RHIC

The team celebrates completion of testing of the PHENIX detector.

responsible for a different task in this challenging endeavor.

RHIC, which measures 3.8 kilometers in circumference, was commissioned in October 1999. It was the first colliding-beam facility specifically designed to accommodate the requirements of heavy-ion physics at relativistic, or speed-of-light, energies.

RHIC is actually the newest link in a chain of accelerators that make up the RHIC accelerator complex. Heavy ions destined for RHIC originate in a Tandem Van de Graaff Accelerator, proceed into the Booster Accelerator, and then into the Alternating Gradient Synchrotron, which injects heavy ions into RHIC for experiments. Before RHIC was completed, Livermore physicists contributed to major discoveries about the properties of nuclear matter using the Alternating Gradient Synchrotron.

When RHIC is operating, bunches of heavy ions can be injected into each of its two rings, which are in a tunnel. Then, with both rings filled, the ions are accelerated in minutes to the top energy where the ion beams coast for hours in stable orbits around the rings. The tunnel is configured so that the circulating ion beams can cross and collide in six places. Four of the six collision spaces now hold detectors that electronically record the results of the interactions between particles. During experiments, particles are made to collide head-on at the rate of tens of thousands of collisions per second at the position of each detector, shown in the right-hand figure on p. 8. The two largest detectors are PHENIX and STAR. Two smaller detectors are known as PHOBOS and BRAHMS. Each detector uses different technologies to determine whether a quark–gluon plasma is present in RHIC.

A team of scientists from Lawrence Livermore and Brookhaven national laboratories developed the three powerful magnets in the PHENIX detector. Livermore was responsible for the design and supervised fabrication and testing of the magnets.

PHENIX weighs 3.6 million kilograms and has a dozen detector subsystems. The three magnets produce high magnetic fields to bend charged particles along curved paths. Tracking chambers record hits along the flight path to measure the curvature and thus determine each particle's momentum. Other subsystems identify the particle type and measure the particle's energy with calorimeters. Still others record where the collisions occurred and determine whether a collision was head-on or peripheral.

Each type of particle has a distinctive mass and charge associated with it, which allows accurate identification. Each particle will bend and move differently in the magnetic field, allowing scientists to resolve the type of particle it is and its energy. By combining information from all detectors, scientists attempt to reconstruct what happened during the collision.