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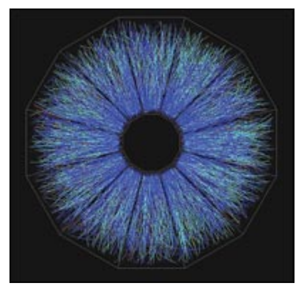
The First Few Microseconds

In recent experiments, physicists have replicated conditions of the infant universe--with startling results

By Michael Riordan and William A. Zajc | Apr 23, 2006 | 0



BROOKHAVEN NATIONAL LABORATORY / RHIC COLLABORATION

For the past five years, hundreds of scientists have been using a powerful new atom smasher at Brookhaven National Laboratory on Long Island to mimic conditions that existed at the birth of the universe. Called the Relativistic Heavy Ion Collider (RHIC, pronounced "rick"), it clashes two opposing beams of gold nuclei traveling at nearly the speed of light. The resulting collisions between pairs of these atomic nuclei generate exceedingly hot, dense bursts of matter and energy to simulate what happened during the first few microseconds of the big bang. These brief "mini bangs" give physicists a ringside seat on some of the earliest moments of creation.

During those early moments, matter was an ultrahot, superdense brew of particles called quarks and gluons rushing hither and thither and crashing willy-nilly into one another. A sprinkling of electrons, photons and other light elementary particles seasoned the soup. This mixture had a temperature in the trillions of degrees, more than 100,000 times hotter than the sun's core.

But the temperature plummeted as the cosmos expanded, just like an ordinary gas cools today when it expands rapidly. The quarks and gluons slowed down so much that some of them could begin sticking together briefly. After nearly 10 microseconds had elapsed, the quarks and gluons became shackled together by strong forces between them, locked up permanently within protons, neutrons and other strongly interacting particles that physicists collectively call "hadrons." Such an abrupt change in the properties of a material is called a phase transition (like liquid water freezing into ice). The cosmic phase transition from the original mix of quarks and gluons into mundane protons and neutrons is of intense interest to scientists, both those who seek clues about how the universe evolved toward its current highly structured state and those who wish to understand better the fundamental forces involved.

The protons and neutrons that form the nuclei of every atom today are relic droplets of that primordial sea, tiny subatomic prison cells in which quarks thrash back and forth, chained forever. Even in violent collisions, when the quarks seem on the verge of breaking out, new "walls" form to keep them confined. Although many physicists have tried, no one has ever witnessed a solitary quark drifting all alone through a particle detector.

RHIC offers researchers a golden opportunity to observe quarks and gluons unchained from protons and neutrons in a collective, quasi-free state reminiscent of these earliest microseconds of existence. Theorists originally dubbed this concoction the quark-gluon plasma, because they expected it to act like an ultrahot gas of charged particles (a plasma) similar to the innards of a lightning bolt. By smashing heavy nuclei together in mini bangs that briefly liberate quarks and gluons, RHIC serves as a kind of time telescope providing glimpses of the early universe, when the ultrahot, superdense quark-gluon plasma reigned supreme. And the greatest surprise at RHIC so far is that this exotic substance seems to be acting much more like a liquid--albeit one with very special properties--than a gas.

Free the Quarks

In 1977, when theorist Steven Weinberg published his classic book *The First Three Minutes* about the physics of the early universe, he avoided any definitive conclusions about the first hundredth of a second. "We simply do not yet know enough about the physics of elementary particles to be able to calculate the properties of such a m¿lange with any confidence," he lamented. "Thus our ignorance of microscopic physics stands as a veil, obscuring our view of the very beginning."

But theoretical and experimental breakthroughs of that decade soon began to lift the veil. Not only were protons, neutrons and all other hadrons found to contain quarks; in addition, a theory of the strong force between quarks--known as quantum chromodynamics, or QCD--emerged in the mid-1970s. This theory postulated that a shadowy cabal of eight neutral particles called gluons flits among the quarks, carrying the unrelenting force that confines them within hadrons.

What is especially intriguing about QCD is that--contrary to what happens with such familiar forces as gravity and electromagnetism--the coupling strength grows *weaker* as quarks approach one another. Physicists have called this curious counterintuitive behavior asymptotic freedom. It means that when two quarks are substantially closer than a proton diameter (about 10-13 centimeter), they feel a reduced force, which physicists can calculate with great precision by means of standard techniques. Only when a quark begins to stray from its partner does the force become truly strong, yanking the particle back like a dog on a leash.

In quantum physics, short distances between particles are associated with high-energy collisions. Thus, asymptotic freedom becomes important at high temperatures when particles are closely packed and constantly undergo high-energy collisions with one another.

More than any other single factor, the asymptotic freedom of QCD is what allows physicists to lift Weinberg's veil and evaluate what happened during those first few microseconds. As long as the temperature exceeded about 10 trillion degrees Celsius, the quarks and gluons acted essentially independently. Even at lower temperatures, down to two trillion degrees, the quarks would have roamed individually--although by then they would have begun to feel the confining QCD force tugging at their heels.

To simulate such extreme conditions here on earth, physicists must re-create the enormous temperatures, pressures and densities of those first few microseconds. Temperature is essentially the average kinetic energy of a particle in a swarm of similar particles, whereas pressure increases with the swarm's energy density. Hence, by squeezing the highest possible energies into the smallest possible volume we have the best chance of simulating conditions that occurred in the big bang.

Fortunately, nature provides ready-made, extremely dense nuggets of matter in the form of atomic nuclei. If you could somehow gather together a thimbleful of this nuclear matter, it would weigh 300 million tons. Three decades of experience colliding heavy nuclei such as lead and gold at high energies have shown that the densities occurring during these collisions far surpass that of normal nuclear matter. And the temperatures produced may have exceeded five trillion degrees.

Colliding heavy nuclei that each contain a total of about 200 protons and neutrons produces a much larger inferno than occurs in collisions of individual protons (as commonly used in other high-energy physics experiments). Instead of a tiny explosion with dozens of particles flying out, such heavy-ion collisions create a seething fireball consisting of thousands of particles. Enough particles are involved for the collective properties of the fireball--its temperature, density, pressure and viscosity (its thickness or resistance to flowing)--to become useful, significant parameters. The distinction is important--like the difference between the behavior of a few isolated water molecules and that of an entire droplet.

The RHIC Experiments

Funded by the U.S. Department of Energy and operated by Brookhaven, RHIC is the latest facility for generating and studying heavy-ion collisions. Earlier nuclear accelerators fired beams of heavy nuclei at stationary metal targets. RHIC, in contrast, is a particle collider that crashes together two beams of heavy nuclei. The resulting head-on collisions generate far greater energies for the same velocity of particle because all the available energy goes into creating mayhem. This is much like what happens when two speeding cars smash head-on. Their energy of motion is converted into the random, thermal energy of parts and debris flying in almost every direction.

At the highly relativistic energies generated at RHIC, nuclei travel at more than 99.99 percent of the speed of light, reaching energies as high as 100 giga-electron volts (GeV) for every proton or neutron inside. (One GeV is about equivalent to the mass of a stationary proton.) Two strings of 870 superconducting magnets cooled by tons of liquid helium steer the beams around two interlaced 3.8-kilometer rings. The beams clash at four points where these rings cross. Four sophisticated particle detectors known as BRAHMS, PHENIX, PHOBOS and STAR record the subatomic debris spewing out from the violent smashups at these collision points.

When two gold nuclei collide head-on at RHIC's highest attainable energy, they dump a total of more than 20,000 GeV into a microscopic fireball just a trillionth of a centimeter across. The nuclei and their constituent protons and neutrons literally melt, and many more quarks, antiquarks (antimatter opposites of the quarks) and gluons are created from all the energy available. More than 5,000 elementary particles are briefly liberated in typical encounters. The pressure generated at the moment of collision is truly immense, a whopping 1030 times atmospheric pressure, and the temperature inside the fireball soars into the trillions of degrees.

But about 50 trillionths of a trillionth (5 10-23) of a second later, all the quarks, antiquarks and gluons recombine into hadrons that explode outward into the surrounding detectors. Aided by powerful computers, these experiments attempt to record as much information as possible about the thousands of particles reaching them. Two of these experiments, BRAHMS and PHOBOS, are relatively small and concentrate on observing specific characteristics of the debris. The other two, PHENIX and STAR, are built around huge, general-purpose devices that fill their three-story experimental halls with thousands of tons of magnets, detectors, absorbers and shielding.

The four RHIC experiments have been designed, constructed and operated by separate international teams ranging from 60 to more than 500 scientists. Each group has employed a different strategy to address the daunting challenge presented by the enormous complexity of RHIC events. The BRAHMS collaboration elected to focus on remnants of the original protons and neutrons that speed along close to the direction of the colliding gold nuclei. In contrast, PHOBOS observes particles over the widest possible angular range and studies correlations among them. STAR was built around the world's largest "digital camera," a huge cylinder of gas that provides three-dimensional pictures of all the charged particles emitted in a large aperture surrounding the beam axis. And PHENIX searches for specific particles produced very early in the collisions that can emerge unscathed from the boiling cauldron of quarks and gluons. It thus provides a kind of x-ray portrait of the inner depths of the fireball.

A Perfect Surprise
The physical picture emerging from the four experiments is consistent and surprising. The quarks and gluons indeed break out of confinement and behave collectively, if only fleetingly. But this hot m¿lange acts like a liquid, not the ideal gas theorists had anticipated.

The energy densities achieved in head-on collisions between two gold nuclei are stupendous, about 100 times those of the nuclei themselves--largely because of relativity. As viewed from the laboratory, both nuclei are relativistically flattened into ultrathin disks of protons and neutrons just before they meet. So all their energy is crammed into a very tiny volume at the moment of impact. Physicists estimate that the resulting energy density is at least 15 times what is needed to set the quarks and gluons free. These particles immediately begin darting in every direction, bashing into one another repeatedly and thereby reshuffling their energies into a more thermal distribution.

Evidence for the rapid formation of such a hot, dense medium comes from a phenomenon called jet quenching. When two protons collide at high energy, some of their quarks and gluons can meet nearly head-on and rebound, resulting in narrow, back-to-back sprays of hadrons (called jets) blasting out in opposite directions. But the PHENIX and STAR detectors witness only one half of such a pair in collisions between gold nuclei. The lone jets indicate that individual quarks and gluons are indeed colliding at high energy. But where is the other jet? The rebounding quark or gluon must have plowed into the hot, dense medium just formed; its high energy would then have been dissipated by many close encounters with low-energy quarks and gluons. It is like firing a bullet into a body of water; almost all the bullet's energy is absorbed by slow-moving water molecules, and it cannot punch through to the other side.

Indications of liquidlike behavior of the quark-gluon medium came early in the RHIC experiments, in the form of a phenomenon called elliptic flow. In collisions that occur slightly off-center--which is often the case--the hadrons that emerge reach the detector in an elliptical distribution. More energetic hadrons squirt out within the plane of the interaction than at right angles to it. The elliptical pattern indicates that substantial pressure gradients must be at work in the quark-gluon medium and that the quarks and gluons from which these hadrons formed were behaving collectively, before reverting back into hadrons. They were acting like a liquid--that is, not a gas. From a gas, the hadrons would emerge uniformly in all directions.

This liquid behavior of the quark-gluon medium must mean that these particles interact with one another rather strongly during their heady moments of liberation right after formation. The decrease in the strength of their interactions (caused by the asymptotic freedom of QCD) is apparently overwhelmed by a dramatic increase in the *number* of newly liberated particles. It is as though our poor prisoners have broken out of their cells, only to find themselves haplessly caught up in a jail-yard crush, jostling with all the other escapees. The resulting tightly coupled dance is exactly what happens in a liquid. This situation conflicts with the naive theoretical picture originally painted of this medium as an almost ideal, weakly interacting gas. And the detailed features of the elliptical asymmetry suggest that this surprising liquid flows with almost no viscosity. It is probably the most perfect liquid ever observed.

The Emerging Theoretical Picture

Calculating the strong interactions occurring in a liquid of quarks and gluons that are squeezed to almost unimaginable densities and exploding outward at nearly the speed of light is an immense challenge. One approach is to perform brute-force solutions of QCD using huge arrays of microprocessors specially designed for this problem. In this so-called lattice-QCD approach, space is approximated by a discrete lattice of points (imagine a Tinkertoy structure). The QCD equations are solved by successive approximations on the lattice.

Using this technique, theorists have calculated such properties as pressure and energy density as a function of temperature; each of these dramatically increases when hadrons are transformed into a quark-gluon medium. But this method is best suited for static problems in which the medium is in thermodynamic equilibrium, unlike the rapidly changing conditions in RHIC's mini bangs. Even the most sophisticated lattice-QCD calculations have been unable to determine such dynamic features as jet quenching and viscosity. Although the viscosity of a system of strongly interacting particles is expected to be small, it cannot be exactly zero because of quantum mechanics. But answering the question "How low can it go?" has proved notoriously difficult.

Remarkably, help has arrived from an unexpected quarter: string theories of quantum gravity. An extraordinary conjecture by theorist Juan Maldacena of the Institute for Advanced Study in Princeton, N.J., has forged a surprising connection between a theory of strings in a warped five-dimensional space and a QCD-like theory of particles that exist on the four-dimensional boundary of that space [see "The Illusion of Gravity," by Juan Maldacena; *Scientific American*, November 2005]. The two theories are mathematically equivalent even though they appear to describe radically different realms of physics. When the QCD-like forces get strong, the corresponding string theory becomes weak and hence easier to evaluate. Quantities such as viscosity that are hard to calculate in QCD have counterparts in string theory (in this case, the absorption of gravity waves by a black hole) that are much more tractable. A very small but nonzero lower limit on what is called the specific viscosity emerges from this approach--only about a tenth of that of superfluid helium. Quite possibly, string theory may help us understand how quarks and gluons behaved during the earliest microseconds of the big bang.

Future Challenges

Astonishingly, the hottest, densest matter ever encountered far exceeds all other known fluids in its approach to perfection. How and why this happens is the great experimental challenge now facing physicists at RHIC. The wealth of data from these experiments is already forcing theorists to reconsider some cherished ideas about matter in the early universe. In the past, most calculations treated the freed quarks and gluons as an ideal gas instead of a liquid. The theory of QCD and asymptotic freedom are not in any danger--no evidence exists to dispute the fundamental equations. What is up for debate are the techniques and simplifying assumptions used by theorists to draw conclusions from the equations.

To address these questions, experimenters are studying the different kinds of quarks emerging from the mini bangs, especially the heavier varieties. When quarks were originally predicted in 1964, they were thought to occur in three versions: up, down and strange. With masses below 0.15 GeV, these three species of quarks and their antiquarks are created copiously and in roughly equal numbers in RHIC collisions. Two additional quarks, dubbed charm and bottom, turned up in the 1970s, sporting much greater masses of about 1.6 and 5 GeV, respectively. Because much more energy is required to create these heavy quarks (according to $E = mc2$), they appear earlier in the mini bangs (when energy densities are higher) and much less often. This rarity makes them valuable tracers of the flow patterns and other properties that develop early in the evolution of a mini bang.

The PHENIX and STAR experiments are well suited for such detailed studies because they can detect high-energy electrons and other particles called muons that often emerge from decays of these heavy quarks. Physicists then trace these and other decay particles back to their points of origin, providing crucial information about the heavy quarks that spawned them. With their greater masses, heavy quarks can have different flow patterns and behavior than their far more abundant cousins. Measuring these differences should help tease out precise values for the tiny residual viscosity anticipated.

Charm quarks have another characteristic useful for probing the quark-gluon medium. Usually about 1 percent of them are produced in a tight embrace with a charm antiquark, forming a neutral particle called the J/psi. The separation between the two partners is only about a third the radius of a proton, so the rate of J/psi production should be sensitive to the force between quarks at short distances. Theorists expect this force to fall off because the surrounding swarm of light quarks and gluons will tend to screen the charm quark and antiquark from each other, leading to less J/psi production. Recent PHENIX results indicate that J/psi particles do indeed dissolve in the fluid, similar to what was observed earlier at CERN, the European laboratory for particle physics near Geneva [see "Fireballs of Free Quarks," by Graham P. Collins, News and Analysis; *Scientific American*, April 2000]. Even greater J/psi suppression was expected to occur at RHIC because of the higher densities involved, but early results suggest some competing mechanism, such as reformation of J/psi particles, may occur at these densities. Further measurements will focus on this mystery by searching for other pairs of heavy quarks and observing whether and how their production is suppressed.

Another approach being pursued is to try to view the quark-gluon fluid by its own light. A hot broth of these particles should shine briefly, like the flash of a lightning bolt, because it emits high-energy photons that escape the medium unscathed. Just as astronomers measure the temperature of a distant star from its spectrum of light emission, physicists are trying to employ these energetic photons to determine the temperature of the quark-gluon fluid. But measuring this spectrum has thus far proved enormously challenging because many other photons are generated by the decay of hadrons called neutral pions. Although those photons are produced long after the quark-gluon fluid has reverted to hadrons, they all look the same when they arrive at the detectors.

Many physicists are now preparing for the next energy frontier at the Large Hadron Collider (LHC) at CERN. Starting in 2008, experiments there will observe collisions of lead nuclei at combined energies exceeding one million GeV. An international team of more than 1,000 physicists is building the mammoth ALICE detector, which will combine the capabilities of the PHENIX and STAR detectors in a single experiment. The mini bangs produced by the LHC will briefly reach several times the energy density that occurs in RHIC collisions, and the temperatures reached therein should easily surpass 10 trillion degrees. Physicists will then be able to simulate and study conditions that occurred during the very first microsecond of the big bang.

The overriding question is whether the liquidlike behavior witnessed at RHIC will persist at the higher temperatures and densities encountered at the LHC. Some theorists project that the force between quarks will become weak once their average energy exceeds 1 GeV, which will occur at the LHC, and that the quark-gluon plasma will finally start behaving properly--like a gas, as originally expected. Others are less sanguine. They maintain that the QCD force cannot fall off fast enough at these higher energies, so the quarks and gluons should remain tightly coupled in their liquid embrace. On this issue, we must await the verdict of experiment, which may well bring other surprises.

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Web sites of the RHIC collaborations, which include links to research papers: www.rhic.bnl.gov/brahms/; www.phenix.bnl.gov; www.phobos.bnl.gov; and www.star.bnl.gov

Cosmic Timeline

Colliding and Detecting Particles

A Mini Bang From Start to Finish

Evidence for a Dense Liquid