Hammering gold into primordial energy-matter soup

By David F. Salisbury
September 3, 2003

Vicki Greene has had a lot of good news lately.
The soft-spoken associate professor of physics at Vanderbilt is a member of an elite cadre of physicists who are trying to create and characterize an exotic state of matter called the quark-gluon plasma. The entire universe may have existed in this state 14 billion years ago, a few millionths of a second after the Big Bang, and it may be recreated briefly in the hearts of exploding stars.

Greene and her fellow scientists are not ready to proclaim that the $600 million atom smasher, called the Relativistic Heavy Ion Collider (RHIC), has succeeded in reproducing this primordial plasma in the fiery micro-explosions that it creates by slamming the massive nuclei of gold atoms together at nearly the speed of light. But the results of their last two series of experiments make it highly likely that this is the case.

"In these kinds of experiments, there are always other explanations so we are being very, very cautious about the claims that we make," Greene stresses.

Vanderbilt Professor of Physics Charles Maguire, who is also a member of the RHIC team, adds that "there are about three chances in four that the plasma is there, but scientists don't like to claim something until they are 95 percent certain."

RHIC is located at Brookhaven National Laboratory in Long Island. It operates by accelerating two beams of heavy ions, such as gold nuclei, to nearly the speed of light in opposite directions around a ring 2.4 miles in circumference. At four different places around the collider's path the two beams are brought together so that the ions will crash into one another. At each of these "interaction points" different teams of scientists have designed and built elaborate detectors that track the showers of subatomic particles that are produced in these collisions.

Greene and Maguire both work on PHENIX, the largest of the four instruments. It weighs 3,000 tons, is 40 feet wide and four stories tall. By analyzing the information produced by PHENIX, the Vanderbilt physicists and their colleagues are attempting to reconstruct events that take place at a scale that is almost unimaginably small and in times that are fantastically brief.

At the interaction points where the two beams collide, a small percentage of the gold nuclei flying past each other collide head on, creating microscopic fireballs that last less than a trillionth of a nanosecond and produce showers of subatomic particles that the scientists can track and identify.

If you could expand a gold atom until it fills the distance between the earth and the moon, most of the space would be filled by its electron shell, the outer part of the atom that determines its chemical properties. Its nucleus sits at the center and forms a sphere with the diameter equivalent to the length of a golf course with the holes lined up end-to-end. The nucleus would be filled with 197 balls, each the width of a football field. These are the protons and neutrons. But protons and neutrons are not elementary particles. When you look at them closely, you find that they are made out of even smaller, point-like objects called quarks and gluons. Even at this expanded scale, quarks and gluons would be less than the size of golf balls.
The gold-gold collisions at RHIC bring nearly 400 protons and neutrons into collision at 99.995 percent the speed of light. When two nuclei hit head-on, temperatures spike to more than 300 million times that to the solar surface. At these temperatures, scientists predict that individual protons and neutrons inside the merged gold nuclei should melt, leaving free-roaming quarks and gluons. At lower temperatures, quarks and gluons are never seen alone but always stick together in pairs and trios to form a wide array of subatomic particles.

In a nanoscopic way, this recreates conditions that scientists think existed when the universe was created. For a brief period, the universe consisted of a blazing plasma made of a mixture of quarks and gluons. As the universe expanded and cooled, quarks and gluons were organized into various combinations to create protons, neutrons and a host of other less stable particles. In this fashion, the familiar atomic structure of matter came into being.

If the quark-gluon plasma ever existed and has been recreated in RHIC, then it should have properties that are quite different from normal matter. So the scientists have been looking for signatures of these properties in the tracks of the thousands of sub-atomic particles that are created in head-on collisions, and they have found some.

The PHENIX detector is designed to look primarily at the daughter particles with trajectories perpendicular to the beam line. In off-center collisions, most of the particles are thrown forward or backward from the interaction point. In head-on collisions, however, the two nuclei stop each other cold and daughter particles stream off in all directions. Head-in collisions not only are the most violent, but they also produce the highest proportion of transverse particles. So the PHENIX team has programmed their computers to select the 5 percent of collisions that produce the highest proportion of transverse particles.

The scientists then looked at the total number of electrically charged particles that were produced in these collisions. Generally, as the amount of energy in the beams increased, the number of daughter particles produced also increased. When the energy reached a certain level, however, they noticed that the number of particles being produced was declining, rather than increasing. Something had begun suppressing particle production.

When they looked at this phenomenon more closely, the researchers found an interesting pattern. When individual quarks collide, they generally shoot off in opposite directions and shed their excessive energy by producing showers of sub-atomic particles, which the scientists call back-to-back jets. In the most energetic collisions, however, the scientists discovered many instances where only single jets were being produced.

This is an effect that had been predicted for the quark-gluon plasma. Many quark collisions occur near the surface of the combined nuclei. So the quark heading away from the nuclei would encounter normal conditions and so produce a normal particle jet. The quark traveling in the opposite direction, however, would be forced to plough through the molasses-like quark-gluon plasma, slowing the particle down and absorbing it before it produced an offsetting jet.

The RHIC collaborators announced these results in a series of papers last January in the journal *Physical Review Letters*.

As Greene is quick to point out, however, that there are other possible explanations for this suppression. One such alternative holds that the suppression is caused by some change in the initial state of the gold nuclei. One change that might be responsible is a relativistic effect called Lorenz contraction. As an object travels closer and closer to the speed of light, it becomes foreshortened in the direction of travel and this foreshortening might account for the observed jet suppression.

So the RHIC researchers ran a series of experiments from January to May designed specifically to test this alternative explanation. They replaced the gold nuclei in one of the beams with the nuclei of deuterium, which contains one proton and one neutron. Deuterium-gold collisions do not release enough energy to create a quark-gluon plasma. The small deuterium nuclei passes through the large gold nucleus like a bullet without heating or compressing it very much. But these collisions do contain enough power to knock loose pairs of energetic quarks and the gold
nucleus retains all the characteristics, including Lorenz contraction, that it had in the gold-gold collisions.

When they analyzed the results of these runs, however, they found that the deuterium-gold collisions invariably produced back-to-back jets. They did not find significant examples of jet suppression. The failure to find jet-suppression provided significant additional support for the quark-gluon plasma hypothesis.

This result was announced on June 18th at a special symposium at Brookhaven National Laboratory, leading Peter Rosen, associate director for high energy and nuclear physics at the Energy Department to comment, “A new fundamental phenomenon has been discovered here.”

Over the next year, the RHIC researchers will be searching for a number of other “signatures” of quark-gluon plasma.

One of those efforts is being conducted by a team headed by Maguire. One prediction is that the mass of quarks will go to zero when they are in the quark gluon plasma. “When things get very hot, they also get very simple… and very dull,” Maguire explains.

Of course, the scientists cannot weigh the quarks directly. But they think that such a weight reduction will show up in the behavior of one of the daughter particles produced by such quarks. The short-lived particle is called a phi meson. Normally, 49 out of every hundred decay into a pair of short-lived particles called kaons and only three out of every 1,000 turn into electron/positron pairs. When quarks loose their mass and decay in phi mesons, a higher proportion of the phi particles should transmute into pairs of electrons and positrons. According to Maguire, they expect to get the information they need make this analysis in the next year.

In addition to the fact that their experiment is running smoothly and producing exciting new data, the Vanderbilt physicists have another reason to celebrate. They have managed to hire a key RHIC staff scientist who will be joining the Vanderbilt physics department in August. Her name is Julia Velkovska and she has produced some of the strongest data that supports the existence of the quark-gluon plasma.

According to David Ernst, chair of the physics and astronomy department, “One of her senior colleagues describes Julia as a physicist who can do anything and actually does everything.”
CELLS IN MOTION

RELATED STORIES
Vanderbilt physicists in the thick of creating highly condensed energy-matter soup

ADDITIONAL INFO
Relativistic Heavy Ion Collider web site
http://www.rhic.bnl.gov/

Prof. Charles Maguire’s web page
http://www.physics.vanderbilt.edu/cv/maguire.htm

Prof. S. Victoria Greene’s web page
http://www.physics.vanderbilt.edu/cv/greene.htm

RHIC/PHENIX animations web page
http://www.phenix.bnl.gov/WWW/software/luxor/ani/