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Cooking Up Hot Quark Soup

Near-light-speed collisions of gold ions provide a recipe for in-depth explorations of matter and fundamental forces.

Imagine the hottest "soup" on the planet—250,000 times hotter than the center of the sun. You won't find any letter-shaped noodles or bits of veggies and chicken. Under these conditions, all regular matter melts—even the protons and neutrons that make up atoms! Instead, you'll find the tiniest known pieces of matter—quarks and the gluons that ordinarily hold them together—zipping around and interacting as they did some 14 billion years ago, before they coalesced to form protons, neutrons, atoms, stars, planets, and galaxies.

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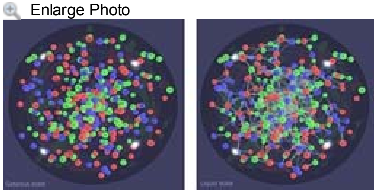

Image courtesy of Brookhaven National Laboratory

These images contrast the degree of interaction and collective motion, or "flow," among quarks in the predicted gaseous quark-gluon plasma state (Figure on left, see mpeg animation) vs. the liquid state that has been observed in gold-gold collisions at RHIC (Figure on right, see mpeg animation). The green "force lines" and collective motion (visible on the animated version only) show the much higher degree of interaction and flow among the quarks in what is now being described as a nearly "perfect" liquid.

Physicists are cooking up just such a soup at the Relativistic Heavy Ion Collider (RHIC), a 2.4-mile circular atom smasher at the U.S. Department of Energy's Brookhaven National Laboratory. Inside RHIC's twin accelerator rings, two beams of gold ions travel in opposite directions at nearly the speed of light, smashing into one another millions of times a second to recreate the hot, dense conditions of the early universe. These light-speed smash-ups pack enough energy into a tiny space to raise the temperature to 4 trillion degrees Celsius, liberating the quarks and gluons that make up the ordinary protons and neutrons and creating thousands of new particles. Sophisticated detectors positioned at the collision points take "snapshots" of the smash-ups and disentangle the ingredients that make up the collision environment.

"Gazing into this hot quark-gluon soup is like taking a journey back in time, to the very beginning of the universe, to get a glimpse of these fundamental particles and the forces through which they interact—feeding our insatiable desire to learn all we can about our history and the nature of the world around us," said Steve Vigdor, Brookhaven's Associate Director for Nuclear and Particle Physics, who leads the RHIC research program.

In addition to generating superhot temperatures, RHIC and its detectors have served up some startling discoveries.

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Photo courtesy of Brookhaven National Laboratory

Brookhaven National Laboratory's Relativistic Heavy Ion Collider (RHIC) is really two accelerators in one—made of crisscrossing rings of superconducting magnets, enclosed in a tunnel 2.4 miles in circumference. In the two rings, beams of heavy ions are accelerated to nearly the speed of light in opposite directions, held in their orbits by powerful magnetic fields.

For one thing, the quark-gluon matter produced at RHIC is a nearly "perfect" liquid, rather than a gas. In other words, the early universe was more soup-like than expected! With extremely low viscosity, or resistance to flow, RHIC's quark-gluon liquid may be the most perfect liquid ever observed. The high degree of collective motion among its constituent particles can be well explained by equations designed to describe hypothetically frictionless fluids expanding at near light speed.

Remarkably, RHIC's hot perfect liquid shares some features with ultracold atomic gases, which also exhibit near-perfect liquid-like behavior when released from an optical trap. And the mathematical techniques of string theory—including equations that make use of a hypothetical black hole in a supposed fifth dimension—are helping to elucidate the properties of both the hot and cold strongly interacting near-perfect liquids.

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"The connections among ultrahot quark-gluon matter, ultracold atomic matter, and string theory were completely unanticipated at the time RHIC was built," said Vigdor. "This serendipity is what makes basic research with cutting-edge facilities and instrumentation so much fun. We are currently exploring other possible connections, for example, among RHIC results, the dominance of matter over antimatter in our universe, and the remarkable material properties of one-atom-thick layers of carbon known as graphene."

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The latter connections are related to recent reports from RHIC scientists of the first hints of profound symmetry transformations in the hot quark soup. Measurements of an asymmetric charge separation in particles emerging from all but the most head-on collisions indicate that "bubbles" formed within the hot soup may internally disobey the so-called "mirror symmetry" that normally characterizes the interactions of quarks and gluons.

"These results suggest that RHIC may have a unique opportunity to test in the laboratory some crucial features of symmetry-altering bubbles speculated to have played important roles in the evolution of the infant universe," Vigdor said, such as the violation of symmetry that resulted in a predominance of matter over antimatter in our world.

Photo courtesy of Brookhaven National Laboratory

The PHENIX detector at Brookhaven National Laboratory's Relativistic Heavy Ion Collider (RHIC) records many different particles emerging from RHIC collisions, including photons, electrons, muons, and quark-containing particles called hadrons. The detector is shown here in a disassembled condition during maintenance.

This is no small matter: Our very existence hinges on what triggered more matter (our whole universe) to be left in the wake of the Big Bang! According to Vigdor, "We still have to rule out more mundane possible explanations for the RHIC observations, but we can do this by exploiting the extensive flexibility of the RHIC facility, providing collisions of a wide variety of nuclei over a wide range of energies."

Speaking of antimatter, RHIC has produced the most massive antimatter nucleus ever discovered—and the first containing an anti-strange quark. The presence of strange antimatter makes this antinucleus the first to be entered *below* the plane of the classic Periodic Table of Elements, marking a new frontier in physics. RHIC physicists expect to find evidence for even heavier antimatter nuclei—though perhaps not of the strange variety—as they analyze more collision data.

RHIC scientists are also engaged in a quest to understand another mystery: the origin of proton spin, a quantum property that describes a particle's intrinsic angular momentum. The mystery arose when scientists realized quarks themselves account for a mere fraction of total proton spin. By colliding beams of polarized protons, RHIC allows researchers to probe the effects of gluons, and possibly of quark and gluon orbital motion. But findings from RHIC so far reveal that gluons don't appear to carry much of the spin, either.

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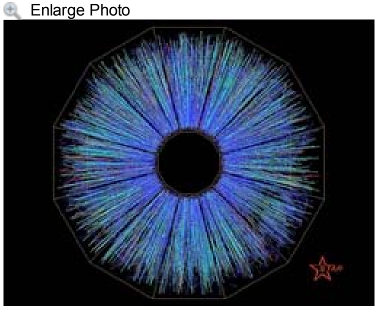

Image courtesy of Brookhaven National Laboratory

End view of a collision of two 30-billion electron-volt gold beams in the STAR detector at the Relativistic Heavy Ion Collider at Brookhaven National Laboratory. The beams travel in opposite directions at nearly the speed of light before colliding.

"Like many scientific mysteries, this one turns out to be more complex the more we learn about it," Vigdor said.

So now, the physicists are exploring finer details. For example, how quarks of different types, or "flavors," contribute to spin. A new method that relies on the measurement of particles called W bosons, produced when quarks and antiquarks collide, gives the scientists direct access to quarks known as "sea quarks," which wink in and out of existence as gluons split and reform within the protons.

"What we've learned so far at RHIC has enriched our understanding of matter," Vigdor said. "But some of the most intriguing findings have also raised compelling new questions."

To address these, key improvements are planned to increase RHIC's collision rates and improve the detectors. In the longer-term, the addition of a high-energy electron beam could allow physicists to probe another new form of matter locked deep inside ordinary nuclei.

These upgrades would capitalize on large investments already made in RHIC by the DOE Office of Science and a wide range of international collaborating scientific agencies and institutions. They would also exploit the use of new high-end computing facilities installed recently and planned for the future at Brookhaven—computers specifically designed for state-of-the-art calculations of the theory that describes quark-gluon interactions.

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Photo courtesy of Brookhaven National Laboratory

RHIC user Christine Aidala checks connections inside the PHENIX detector.

Said Vigdor, "These additional capabilities would further expand our ability to explore the newest and most intriguing questions about the substructure of the world around us—and help instill an appetite for discovery in the next generation of scientists."

—Karen McNulty Walsh, Brookhaven National Laboratory, kmcnulty@bnl.gov

Funding

RHIC Operations and Research: DOE Office of Science, Office of Nuclear Physics

Publications

A. Adare et al. "Cross Section and Parity-Violating Spin Asymmetries of $W^{\pm}$ Boson Production in Polarized p+p Collisions at $\sqrt{s}$=500 GeV," *Phys. Rev. Lett.* **106** 062001 (2011).

M.M. Aggarwal et al. "Measurement of the Parity-Violating Longitudinal Single-Spin Asymmetry for $W^{\pm}$ Boson Production in Polarized Proton-Proton Collisions at $\sqrt{s}$=500 GeV," *Phys. Rev. Lett.* **106** 062002 (2011).

"First Three Years of Operation of RHIC," *Nuclear Physics* **757**, 184 (2005).

"First Three Years of Operation of RHIC," *Nuclear Physics* **757**, 102 (2005).

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PI's: More than 1,000 physicists from around the world collaborate on research at RHIC, contributing to the design and operation of the accelerator and four detectors, STAR and PHENIX (still operational) and PHOBOS and BRAHMS (with operations completed in 2005 and 2006, respectively).
For more information, see http://www.bnl.gov/rhic.