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What Have We Learned From the Relativistic Heavy Ion Collider?

Collisions between high-energy beams of gold nuclei are providing glimpses of hot, dense states of matter reminiscent of the Big Bang.

Thomas Ludlam and Larry McLerran

For three years now, the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory has been providing experimenters with colliding beams of heavy nuclei at ultrarelativistic energies as high as 100 GeV per nucleon. The purpose of this extraordinary new accelerator is to seek out and explore new high-energy forms of matter and thus continue the centuries-old quest to understand the nature and origins of matter at its most basic level.

Early results from the RHIC experiments reveal new nuclear phenomena at temperatures and densities well into the range where quarks and gluons--rather than nucleons and mesons--are expected to define the relevant degrees of freedom. The first measurements of head-on collisions at RHIC energies, with nuclei as heavy as gold, have already taken us a major step toward the long-sought quark-gluon plasma.

Since the discovery of quarks in the 1960s, the core questions in nuclear and particle physics have evolved dramatically. The nucleus had long been viewed as a densely packed assembly of neutrons and protons bound together by a strong force carried by pions and other mesons. We now understand that these "elementary" particles are themselves made up of more fundamental pointlike constituents: quarks (and antiquarks) bound together through interactions mediated by gluons. Quantum chromodynamics (QCD), the current theory of the strong interactions, is a field theory of quarks and gluons. It forbids the appearance of free quarks or gluons, but their existence is taken to play a fundamental role in the nature of matter. Protons, neutrons, pions, and the elaborate array of other hadrons discovered in the last half-century are thought to be understood in terms of their constituent quarks and gluons.

At extremely high energy densities, QCD predicts a new form of matter, consisting of an extended volume of interacting quarks, antiquarks, and gluons. This is the quark-gluon plasma (QGP). It is predicted to come into existence at temperatures and densities more extreme than any we know of in the present natural universe. Such extreme conditions, however, are thought to have existed a few microseconds after the Big Bang. At RHIC, we seek to create the QGP in the highest-energy collisions of heavy nuclei ever achieved under laboratory conditions. The scrutiny of this new state of matter promises to answer some of the key questions of nuclear and particle physics.

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The interest in collisions of high-energy nuclei as a possible route to a new state of nuclear matter began with the emergence of QCD in the late 1970s. The particle physics community began adapting existing high-energy accelerators to provide heavy-ion nuclear beams. By the mid-1980s, as the design of RHIC was being finalized, the first ultrarelativistic nuclear beams became available. Silicon and gold ions were accelerated to 10 GeV/nucleon at Brookhaven's Alternating Gradient [proton] Synchrotron (AGS). In Switzerland, the CERN Super Proton Synchrotron (SPS) began providing 160-GeV/nucleon beams of sulfur and lead nuclei. But those high-energy beams, colliding with stationary nuclear targets, gave rather modest center-of-mass collision energies 5 and 17 GeV, respectively, per nucleon pair.


In collision experiments, the relevant energy for probing matter is the center-of-mass (cm) energy. For fixed targets, as distinguished from colliding beams, the cm energy grows only as the square root of the beam energy. Although the AGS and SPS cm energies were far below that of RHIC (where the cm collision energy between nucleons in gold-gold collisions is 200 GeV), those early fixed-target experiments provided the first opportunity for extensive studies of heavy-nucleus interactions at collision energies high enough to produce particles in abundance.

In those pioneering experiments, large collaborations of nuclear and particle physicists adapted the technology of high-energy particle detection to the extreme environment of heavy-ion collisions, where the number of particles produced in a single collision exceeds by orders of magnitude what happens in proton-proton (p-p) collisions. The AGS and SPS fixed-target experiments measured the abundances and spectra of many species of particles produced in the heavy-ion collisions.

In particular, they measured the production of the J/ψ meson--the bound state of the charmed quark and its antiquark whose historic discovery in 1974 proved the existence of the first of the really heavy quarks. The results clearly indicated that the nucleus-nucleus collisions at high energy are very different from a simple superposition of nucleon-nucleon interactions. It was becoming apparent that nuclear collisions are indeed capable of producing the conditions needed for the existence of hot, compressed nuclear matter.¹

In February 2000, after 15 years of ground-breaking experiments with the fixed-target ion beams, CERN scientists assessed the combined results from the seven large experiments in their heavy-ion program² (see Physics Today, May 2000, page 20*). They concluded that a "multitude" of different observations gave results that, taken together, could not be explained by ordinary hadronic interactions. On the other hand, the data did show several of the expected indicators for the QGP. The CERN community expressed confidence that definitive observation of the elusive QGP would be found with the higher collision energies about to become available. "The challenge now passes to the Relativistic Heavy Ion Collider at Brookhaven," said CERN Director General Luciano Maiani, "and later to CERN's Large Hadron Collider."

The RHIC era begins



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RHIC, the largest US facility for basic research in nuclear physics, provides heavy-ion beams for an international community of more than 1000 scientists participating in the four collaborations that have built the collider's major particle detectors: STAR, PHENIX, PHOBOS, and BRAHMS. Each detector occupies one of the beam-crossing regions where RHIC's countercirculating ion beams intersect and collide.³ (See Physics Today, October 1999, page 20^{*}.)

For gold-gold collisions at the highest RHIC energies, 56 equally spaced bunches of 10^9 fully stripped gold ions are injected into each of the two 4-km rings of superconducting magnets. The two countercirculating beams are then accelerated to 100 GeV/nucleon. (The nucleon's rest mass is close to 1 GeV.) Synchronized pairs of bunches in the colliding beams sweep through each other at each of the detector locations to produce about a thousand nuclear collisions per second for the duration of the beam storage cycle--typically several hours. In a few months of running, each experiment can harvest a useful sample of events so rare that they occur only a few times per billion collisions.

The most violent collisions occur when two nuclei clash head-on, that is, when the impact parameter is much smaller than the nuclear diameter. Such encounters are called central collisions. By contrast, grazing collisions with large impact parameters are labeled peripheral. A central collision at RHIC typically creates thousands of pions and other elementary particles. The term *mini-bang* has been coined to describe these interactions, in which nuclear collisions are thought to proceed in a sequence that calls to mind the formation of matter in the immediate aftermath of the cosmic Big Bang.

The presumed sequence of events begins with an initial, intense heating of the volume occupied by the two nuclei at the moment of collision, as a large fraction of their kinetic energy is converted into a high-temperature system of quarks, antiquarks, and gluons. This system, presumably a plasma of quarks and gluons, immediately begins to expand and cool, passing down through the critical temperature at which the QGP condenses into a system of mesons, baryons, and antibaryons--perhaps in thermal equilibrium. As the expansion continues, the system reaches its "freeze-out" density, at which the hadrons no longer interact with each other. The particles emerging from the freeze-out volume are the ones that stream into the detectors. (See the [box on page 50](#).)

Experiments at RHIC are in many ways analogous to certain kinds of astronomical observations. The object of interest is an extended source that emits copious radiation whose spectrum reflects thermal properties of the source, and the intensity of the radiation relates to the source's energy. For nuclear collisions at RHIC, the intensity can be measured in terms of the number of particles (mostly pions) emitted into a given interval of solid angle.

As the detector displays in [figure 1](#) show, the number of particles emitted in a single collision is extremely large.

Figure 2 shows how the phase-space density of charged particles emerging at angles near 90° (relative to the beam direction) increases steadily with

increasing collision energy.⁴ Indeed, in central collisions at RHIC, the angular density of particles produced per "participating" nucleon is larger than has previously been seen in any subatomic interactions. The estimated number of nucleons actually participating in any one nuclear collision at RHIC is, in general, less than the sum of the two nuclear mass numbers. The model-dependent estimate varies with the impact parameter, which is inferred, for example, from the observed multiplicity of particles produced.

A key question for the RHIC experiments is whether the energy density created in the collisions is sufficient to initiate the QGP and its sequel of cooling stages. The rest energy density of a lone proton is roughly 1 GeV/fm³. (1 fm = 10⁻¹⁵ m is called a fermi or a femtometer, according to taste.) If an energy density that high were to prevail over a much larger nuclear region than the proton's volume of about 1 fm³, we have every reason to expect that the component quarks and gluons would ignore the boundaries of their parent nucleons and interact directly with all the others throughout the volume. More sophisticated QCD estimates of the critical energy density for the emergence of the QGP give similar results.

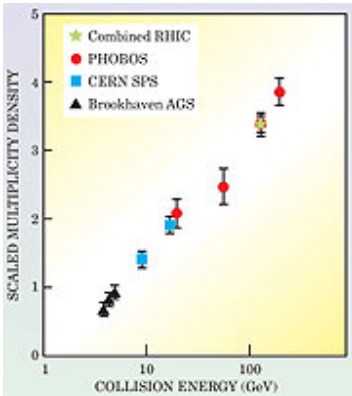


Figure 2

determine the volume and energy of the collision region occupied at t_0 . Reasonable expectations for the formation time (less than 1 fm/c or 3×10^{-24} s) yield estimates that the initial energy density exceeds 10 GeV/fm³. That density corresponds to temperatures on the order of hundreds of MeV.

In principle, one can use QCD to calculate the critical temperature T_c for the phase transition between the QGP and a system of hadrons. In practice, however, extracting precise predictions from QCD is notoriously difficult. Recent

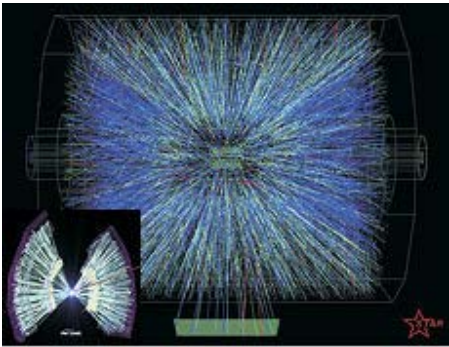


Figure 1

Among the first experimental results from RHIC was the clear indication that this threshold energy density has been far exceeded. In a given collision, the time interval between first contact and the formation of the QGP is called t_0 , the formation time. Detailed examination of the distributions of the produced particles in high-multiplicity events like those shown in figure 1 allows one to extrapolate backward to

calculations⁵ using lattice-gauge approximations give values in the range of about 170 to 180 MeV for T_c , corresponding to about 10^{12} K.

Such temperatures are sustained for only a few times 10^{-23} s. The temperature at the freeze-out point can be inferred by measuring the relative abundances of the different meson and baryon species produced as the system condenses into the final-state hadrons. Assuming that the hadronization process begins with a large number of quarks and antiquarks in thermal equilibrium, one can treat the system as an ideal gas of fermions and bosons, and thereby relate the probabilities for coalescence into the various hadron types to the temperature at which the expanding fireball reaches the freeze-out density.

The RHIC experiments have measured the relative abundances of many different particle types, including relatively rare species that harbor more than one strange quark. The measured abundances are all consistent with a temperature of about 176 MeV at the moment when the departing hadrons are formed.⁶ This indicates that the particles seen by the detector are produced at a freeze-out temperature that's very close to the prediction for T_c , and that the initial temperature of the expanding fireball is considerably higher than the critical temperature.

Exploring a new landscape

The RHIC data are already providing a basic picture of the remarkable new medium that is created for an instant when ultrarelativistic heavy nuclei collide. Experiments must determine to what extent the system is in thermal equilibrium. Achieving equilibrium requires that the system's constituents experience many scatterings during the expansion time and that the system is large compared to the constituents' mean free path.

What are the relevant time and size scales? The expanding volume is the hot source from which the detected particles are radiated. One can determine the source's size by an ingenious interferometric technique developed in the 1950s by Robert Hanbury-Brown and Richard Twiss (HBT) to measure stellar diameters. A pair of photons radiated from two different points on the stellar surface and seen in a separated pair of detectors will exhibit a correlation due to a second-order quantum interference effect whose magnitude can be related to the star's size.

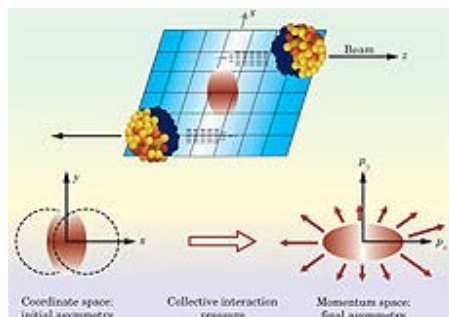
For heavy-ion collisions, the HBT technique has been extended to the measurement of similar correlations in the fluxes of pairs of identical pions or other particles created in the collision. By selecting different momentum components relative to the colliding-beam axis, one can in fact achieve a three-dimensional snapshot of the radiating volume at the moment of freeze-out. In head-on gold-gold collisions, HBT results have not only produced important insights into the dynamic evolution of the expanding system;⁷ they also confirm the expectation that the hot volume is large--significantly larger than a single gold nucleus--with a lifetime of order $10\text{ fm}/c$.

But is this hot volume in thermal equilibrium? The temperature determination, which assumes equilibrium at freeze-out, does correctly describe abundance ratios for many particle species.

That's already strong indirect evidence for a thermally equilibrated system. More direct evidence that the matter in this high-energy extended nuclear state interacts collectively comes from a surprising early RHIC result: an unexpectedly large effect attributed to a phenomenon called flow. First seen in lower-energy nuclear collisions, this kind of flow is a nuclear analogue of the many-particle collective effects seen in macroscopic properties of condensed matter.

As illustrated in [figure 3](#), when two nuclei collide slightly off-center, the initial high-density volume has the shape of their overlap region during the collision. That region is elongated along an axis perpendicular to the reaction plane--that is, the plane defined

by the beam direction and the line between the centers of the two nuclei as they collide. If the quarks and gluons occupying the initial asymmetric volume are indeed interacting collectively, pressure gradients during the subsequent expansion will result in an anisotropic distribution of the final particles with respect to the reaction plane.



[Figure 3](#)

Such anisotropy is, in fact, observed in the RHIC data.⁸ The observation of flow tells us that the RHIC collisions produce matter that interacts strongly with itself. The magnitude of the observed anisotropic flow effect is sensitive to the degree of thermalization at the collision's earliest moments. The data indicate that the strength of the effect is very nearly maximal and remarkably close to what one expects for an expanding system in thermal and hydrodynamic equilibrium.

There might be some disagreement about the specific mechanism that produces such strong anisotropic flow. But there is general agreement that the effect is largely due to very strong interactions between the system's constituents, and that the flow must occur relatively early in the collision--when the relevant constituents are quarks and gluons.

A new piece of the puzzle

One of the most striking early observations at RHIC is a phenomenon called jet quenching, which appears to provide a powerful new probe of the hot, dense matter created in the collisions. The energy is high enough to produce the direct high-energy scattering of individual quarks and gluons (the so-called partons) in the colliding nuclei. In QCD parlance, this effect, which is well known for collisions in high-energy p-p and proton-antiproton (p-p+) colliders, is called hard scattering. At RHIC, a single pair of partons from the incoming nuclei strike each other directly with such force that they scatter at large angles, with high momentum transfer.

Such hard-scattering events, which are relatively rare in p-p or nuclear scattering, even at the highest energies, give rise to narrowly collimated sprays of hadrons called jets. The direction of the jet emerging from a hard-scattering collision is presumed

to be the direction of the initially scattered parton. At RHIC, the observed mean transverse momentum p_T (the component perpendicular to the beam axis) of the produced hadrons is just a few hundred MeV. But the rare hard-scattering events give rise to a small but important tail in the p_T distribution that can extend out to tens of GeV.

The observation of hard-scattering processes in p-p collisions was one of the early, compelling arguments for the existence of a parton substructure in hadrons. By observing the particle types, numbers, and momenta in a jet, one can reconstruct the kinematic and quantum properties of the initially scattered parton. Such measurements can then be compared with predictions of perturbative QCD, a relatively tractable corner of the full theory.

Hard parton-parton scattering is now being seen for the first time in nuclear collisions. These observations provide a direct signal of high-energy quarks or gluons emerging from the initial collision stage. Significantly, the RHIC data show a deficit of high- p_T particles from jets in the most central collisions--those that produce the most particles. They are the most violent collisions, for which evidence of the formation of a new state of hot matter is strongest.⁹

In p-p hard-scattering collisions, the struck quark flies off into the vacuum as it metamorphoses into a jet of hadrons. This process can be quite different in collisions between two heavy nuclei. At RHIC, the scattered parton is embedded in a large volume of newly formed hot, dense matter. Perhaps the observed deficit of high-energy jets in the collisions of heavy nuclei is the result of a slowing down, or quenching, of the most energetic quarks as they propagate through a dense QGP.

The rate of that energy loss should be spectacular. Whereas a high-energy charged particle moving through ordinary matter loses energy at a rate of a few MeV per centimeter, the hard-scattered quarks would suffer an energy loss of several GeV per femtometer in a QGP. Measurements of jet quenching can provide a quantitative means of determining the properties of the hot primordial matter. In effect, such measurements probe the medium with beams of energetic partons.¹⁰

If the jet quenching already seen at large p_T is due to rescattering of particles produced in hard parton scattering, it is very likely that the quark-gluon matter produced in the nuclear collision is thermalized. Cross sections for elementary processes in QCD fall rapidly with increasing momentum. So if high-energy particles plowing through the hot medium lose so much energy, surely the low-momentum particles in the medium must be interacting very strongly with each other.

First, however, it is important to verify the energy-loss interpretation of the observed jet quenching in gold-gold collisions. Recent theoretical work has conjectured that, in very high-energy nuclear interactions, the initial-state density of partons (mostly gluons) becomes so high that the effective number of interacting particles in the collision saturates, thus limiting the number of hard-scattering events. Thus, another possible interpretation of the paucity of jets might simply be that the wavefunction of a nucleus during a high-energy collision differs significantly from a simple superposition of nucleon

wavefunctions.¹¹ Evidence for such an effect comes from recent electron-accelerator experiments in which high-energy electrons are used to probe nucleons.

The RHIC results for the total number of particles produced and their distribution in phase space are, thus far, in good agreement with the scenario of the initial, formative stages of the QGP. This concord has given rise to theoretical predictions of a universal form of matter called the color glass condensate (CGC). ("Color," as in quantum *chromodynamics*, refers here to the hadronic analogue of charge rather than to anything optical.) As described by QCD, this condensate is present in all strongly interacting particles, but it shows itself only in very high-energy collisions. The putative CGC is a very dense superposition of gluons, similar to a Bose condensate. It has properties similar to glasses--that is, very slow evolution compared to the natural time scales of constituent interactions.

The CGC is a relatively new idea. It is thought to provide the initial conditions for the QGP produced in high-energy collisions of heavy nuclei. Whether or not its effects are manifested in the jet-quenching results observed at RHIC is, fortunately, a question that can be addressed directly by experiment. One can test the CGC conjecture by bombarding heavy nuclei with free nucleons and seeing if the results differ from a straightforward superposition of nucleon-nucleon collisions.

For technical reasons, it is easier to do that test at RHIC by colliding deuterons (d) accelerated in one of the collider's two rings with heavy nuclei in the other ring. Earlier this year, a two-month program of deuterium-gold collisions was carried out at RHIC, with each of the countercirculating beams accelerated to 100 GeV/nucleon. First results from that run show no dramatic jet suppression at large p_T . Because deuteron-gold collisions do not produce the extended hot-dense state created in collisions between two heavy nuclei, the observed absence of jet suppression in the deuteron run tells us that initial-state effects are small, so that the suppression observed at large p_T in gold-gold collisions is most likely due to jet energy loss in the hot extended medium.¹²

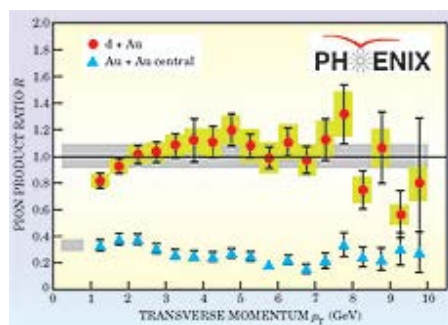


Figure 4

That contrast is nicely illustrated by the results shown in figure 4. Data from the PHENIX detector show that the production rate of high- p_T pions, scaled to account for the number of participating nucleons, is significantly

suppressed in gold-gold collisions as compared to proton-proton or deuteron-gold collisions at the same energy per nucleon. The STAR data show the angular correlation between high- p_T particles produced in the same event. The recoil peak at 180° , clearly indicating the production of back-to-back jets in proton-proton and deuteron-gold collisions, is strikingly absent in the gold-gold data.

The emerging picture

The RHIC data already give convincing evidence that high-energy collisions of heavy nuclei produce a penultimate hot, dense state of hadrons characterized by strong collective interactions. Earlier in the collision process, the energy density far exceeds the theoretical requirements for the creation of the QGP. And RHIC may be giving us a window on yet another elemental form of matter predicted by QCD: the color glass condensate.

Figure 5 shows a theoretical interpretation of the RHIC results in terms of the rise and fall of the energy density with time: At maximum energy density, the initial condensate of color glass becomes a QGP in various stages of increasing thermalization, condensing eventually to an expanding thermalized state of hadrons, which stop interacting after a time of about 10 fm/c and make their way to the detectors.

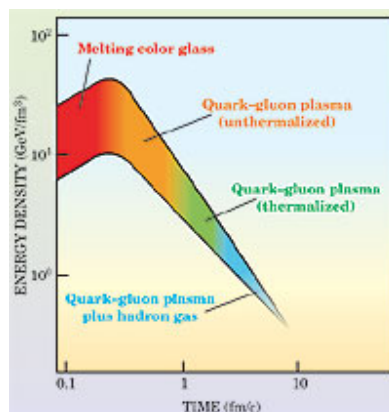


Figure 5

RHIC has begun to explore a regime in which thermalized matter is created at energy densities so high that the relevant degrees of freedom must be quarks and gluons. Many of the experimental tests for the existence of the QGP have been satisfied. But unequivocally establishing the existence of this predicted state of matter and establishing its essential properties will require more. Experiments must determine its equation of state and the character of its phase transition to ordinary hadronic matter.

The next steps involve larger data samples and sensitive measurements of relatively rare processes:

- The RHIC detectors will soon be able to record energetic photons emitted in quark-antiquark interactions in the plasma phase. Such data might provide further, direct confirmation of the existence of the QGP and of its evolution toward thermal equilibrium.
- The measurement of the production rate of the J/ψ and other charmonium mesons was a key indicator of possible new phenomena in the pioneering CERN experiments. The production rates for other heavy-quark states at RHIC energies may yield another definitive piece of the puzzle.
- More precise studies of particles from high-energy jets, with very large data samples and improved ability to distinguish among specific types of parent quarks, may allow a detailed tomography of the hot matter as it evolves. Such studies might also elucidate initial collision state and possibly display specific effects of a color glass condensate.

RHIC lets us study matter at densities that prevailed in the immediate aftermath of the Big Bang. Precisely what forms of matter are produced under such extreme conditions, and what can they reveal about the fundamental properties of the strong interaction? These questions form the basis of the scientific program at RHIC.

Thomas Ludlam is a member of the STAR collaboration at Brookhaven National Laboratory in Upton, New York. **Larry McLerran** is a theorist at Brookhaven.

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