Science
AAAS

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Science **337**, 310 (2012);
DOI: 10.1126/science.1215901

The Exploration of Hot Nuclear Matter

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When nuclear matter is heated beyond 2 trillion degrees, it becomes a strongly coupled plasma of quarks and gluons. Experiments using highly energetic collisions between heavy nuclei have revealed that this new state of matter is a nearly ideal, highly opaque liquid. A description based on string theory and black holes in five dimensions has made the quark-gluon plasma an archetypical strongly coupled quantum system. Open questions about the structure and theory of the quark-gluon plasma are under active investigation. Many of the insights are also relevant to ultracold fermionic atoms and strongly correlated condensed matter.

Nuclear matter in today's universe hides inside atomic nuclei and neutron stars. The nucleons (neutrons and protons) are the building blocks of such matter and consist, in turn, of quarks. Quarks are bound together by the strong interaction, which is mediated by the exchange of gluons. Unlike the uncharged photons, which mediate electromagnetic interactions but do not interact with one another, gluons have color, which is the strong interaction's analog of charge. Colored gluons interact among themselves, as well as with the quarks, making the theory of the strong interaction, known as quantum chromodynamics (QCD), rich in structure and at the same time extremely difficult to solve.

Remarkably, the strong interaction weakens at short distances—a property known as "asymptotic freedom" (*1*, *2*). Conversely, it is exceedingly strong at distances similar to the size of a nucleon (10^{-15} m), confining quarks inside nucleons and other quark-containing particles, known as hadrons. Asymptotic freedom suggests that nucleons can be "boiled" into a plasma of their constituent quarks and gluons when the strong interaction among them is weakened by increasing the density or temperature of the matter. Today, quarks are confined in nuclei and neutron stars, which are cold objects, but the early universe was extremely hot (*3*). Its temperature exceeded 150 MeV (about 2×10^{12} K) until about 10 μs after the Big Bang, and QCD predicts that such conditions are sufficient for the quark-gluon plasma (QGP), to exist (Fig. 1).

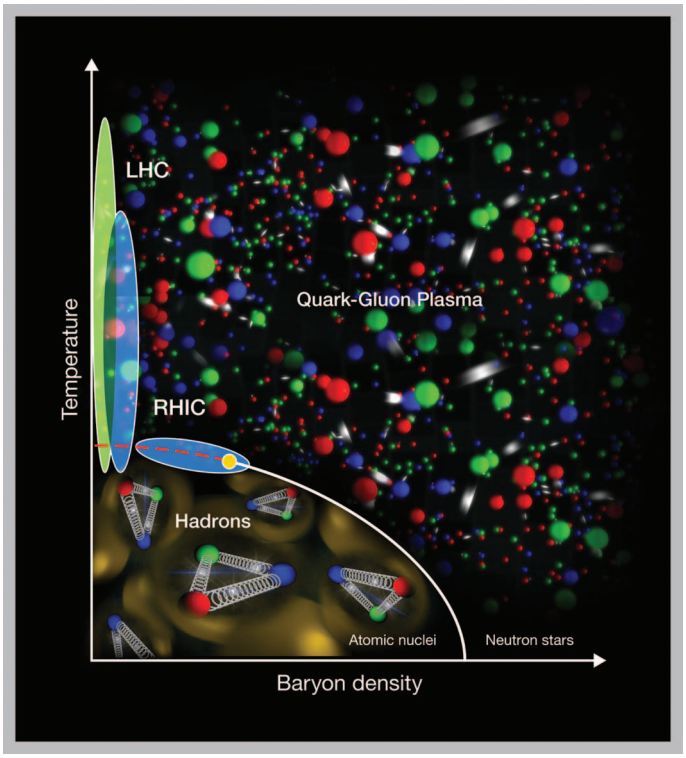

Fig. 1. Phase diagram of QCD matter in the temperature–baryon density plane. Baryons are hadrons containing three valence quarks; the most common are protons and neutrons, shown at the lower left. Colored spheres indicate individual quarks, which are not bound together in the quark-gluon plasma. RHIC (blue ovals) and LHC (green oval) explore matter with almost equal numbers of quarks and antiquarks. At lower beam energies, RHIC produces matter with a surplus of quarks, corresponding to high net baryon density. There may be a critical point (yellow circle) in the phase diagram, at the end of a line indicating a first-order phase transition. [Credit: Brookhaven National Laboratory]

Understanding the evolution of our universe thus requires knowledge of the structure and dynamics of the QGP. Although numerical ab initio simulations of the thermodynamic properties of hot QCD matter in equilibrium have made much progress over the past 30 years (*4*), the dynamical properties of the QGP remain out of reach. Experimental study of hot QCD matter can fill this gap by colliding heavy nuclei at high energies and generating the enormous temperatures required to produce QGP in the laboratory, if only for a brief moment.

Discoveries of the Past Decade

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory has explored the QGP since 2000. RHIC collides two beams of heavy ions, each with an energy up to 100 GeV per nucleon. Proton-proton (p+p) and deuteron-gold (d+Au) collisions provide control measurements without QGP formation. At top energy, the initial temperature reached in collisions between two gold nuclei is inferred to lie between 300 and 600 MeV (*5*), well above the QCD phase-transition temperature of ~150 MeV (*6*). RHIC is a flexible, dedicated facility colliding a wide range of nuclei at various energies. This allows exploration of the phase diagram of QCD matter to experimentally pinpoint the conditions for the phase transition into QGP.

Today, two large experiments built and maintained by international collaborations of scientists, PHENIX and STAR (Fig. 2), continue to operate whereas two smaller experiments, BRAHMS and PHOBOS, have completed data taking. Each experiment was optimized for a different set of experimental observables, but common capabilities allow crucial cross checks. Together, PHENIX and STAR use two kinds of plasma probes (*7*–*11*). Internal probes are particles emitted from the plasma itself. "External" probes are not external in the usual sense; they are energetic particles generated in the first stage of the collision, which traverse the plasma and interact with it on their way to the detectors.

Most of the observed particles are hadrons. Their spectra are well described by a thermal distribution blue-shifted by radial expansion of the plasma. Particle correlations reflect an anisotropic collective flow, known as "elliptic flow." They exhibit a $\cos(2\phi)$ modulation in their azimuthal angular distribution with respect to the direction of the impact-parameter vector between the two colliding ions (*12*). The amplitude of elliptic flow grows with increasing impact parameter because the overlap region of the incoming nuclei becomes more asymmetric (Fig. 3, left). The dynamics within the plasma as it expands translate the spatial asymmetry of the initial state into a final-state anisotropy in momentum space. Higher Fourier components of the angular distribution are also observed in the correlation data; these arise primarily from fluctua-

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tions in the initial positions of the nucleons within the nucleus (Fig. 3, right).

The behavior of gases or liquids is often simulated using hydrodynamics. Indeed, hydrodynamics successfully reproduces the magnitude and impact parameter dependence of elliptic flow (*13*, *14*). Surprisingly, the most faithful match to the data requires a nearly vanishing ratio of the shear viscosity (the resistance to flow or the inability of matter to transport momentum) to the entropy density, implying that the QGP is an almost ideal or "perfect" liquid. Including density fluctuations in the initial conditions of the hydrodynamical simulations also reproduces the higher harmonics with the same low shear viscosity (*15*–*17*).

Quantum mechanics imposes a lower limit of the shear viscosity η for a given particle density by virtue of the uncertainty relation. For relativistic fluids like the QGP, which do not conserve particle number, the appropriate measure of density is the entropy density s. Constraining hydrodynamics calculations with the full suite of flow data (*18*) shows that $\eta/s = (1-2)\hbar/4\pi k_B$, close to the quantum limit $\hbar/4\pi k_B$ (*19*–*21*). Low shear viscosity per particle indicates correlations or coordination within the QGP. Gases have very weakly correlated constituents, whereas the molecules in crystals move in a highly coordinated manner. Liquids fall in between the two, exhibiting the lowest shear viscosities and flowing freely, as does the QGP.

The opacity of the QGP is measured with external probes. During initial interpenetration of the two nuclei, quark and gluon constituents (partons) can scatter with a large momentum transfer, deflecting the struck quarks or gluons by a large angle. These transit the plasma, losing energy to it. As partons cannot exist in isolation, they ultimately radiate multiple gluons, and the resulting parton cluster forms a spray of hadrons known as a "jet." In the absence of QGP, this process is calculable and can be measured in p+p collisions. RHIC experiments with Au+Au showed that energetic hadrons in the jet are suppressed relative to the production rate in p+p collisions (*22*, *23*). Back-to-back jets of moderate energy disappear entirely (*24*). Photons do not experience the strong interaction (Fig. 4A) and are observed to exit the plasma unscathed (*25*). The success of hydrodynamics with vanishingly small η/s, together with the observed high opacity, show that QGP cannot be the weakly coupled gas naïvely expected from asymptotic freedom. Kinetic theory associates a small shear viscosity with a short mean free path, implying high opacity. A short mean free path also requires strong coupling, because the scattering cross section is proportional to the coupling strength.

First results from Pb+Pb collisions at nearly 14 times higher energy at the Large Hadron Collider (LHC) confirm the physics picture derived from RHIC data (*26*). The initial temperature at LHC is ~30% higher. Hydrodynamical model fits indicate nearly the same η/s ratio as at RHIC (*27*); the hotter QGP produced at LHC is also strongly coupled. Jet quenching measurements at LHC extend the kinematic range by a factor of 5. They are consistent with a linear, or slightly slower, gowth of the opacity with matter density. The LHC's higher energy produces higher-energy jets, which simplifies reconstruction of complete jet observables. Clusters of energy corresponding to back-to-back jets are clearly visible in Fig. 4B (*28*). The data reveal that even very energetic jets lose a sizable fraction of their energy to the medium, where it appears to thermalize rapidly. Analysis of jet shapes and particle content help constrain the mechanism of the parton-QGP interaction. The yields of D and B mesons, which contain heavy quarks, are also much larger at LHC. Furthermore, the Z boson becomes available as a new electroweak probe of the QGP. First, statistically limited, results for these "external" probes can be reproduced reasonably well by extrapolation from RHIC.

Theoretical Tools

Key theoretical tools to describe QGP properties and predict experimental observables are lattice gauge theory and transport theory. Lattice gauge theory is an ab initio formalism that simulates the partition function of QCD on a space-time lattice. Advances in algorithms and computer hardware now permit simulations with physical quark masses on lattices that are simultaneously large and fine enough to be safely extrapolated

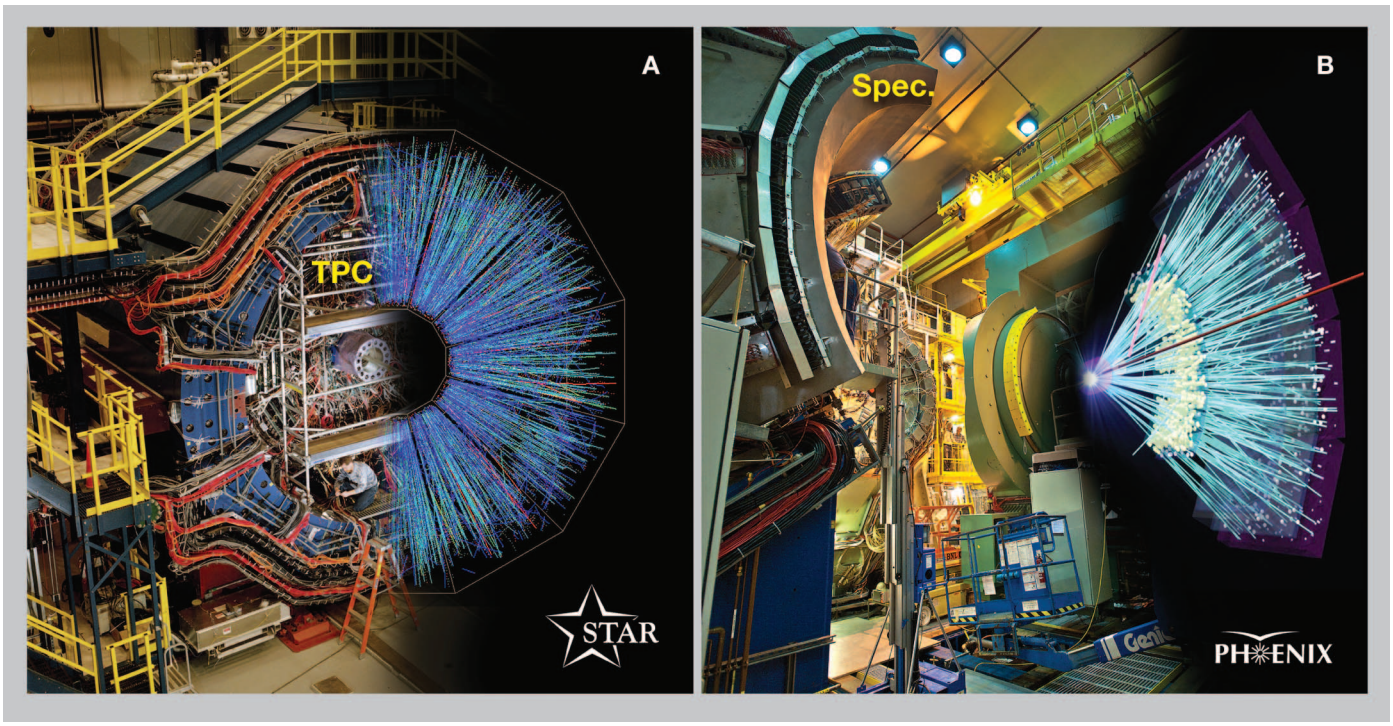

Fig. 2. (**A**) The STAR detector has a time-projection chamber (TPC), which is essentially a three-dimensional digital camera to record trajectories of particles produced in each collision. Surrounding detectors identify hadrons and tag high-momentum electrons. STAR has large acceptance and is thus well suited to study multiparticle correlations and collisions at lower energies. (**B**) The PHENIX detector has two spectrometers to measure photons, electrons, and hadrons at angles near 90°; one is visible at left (Spec.). There are also two muon spectrometers in the beam direction; these detect decays of hadrons containing charm and bottom quarks. A sample event display is shown on the right side of each detector. [Credit: Brookhaven National Laboratory]

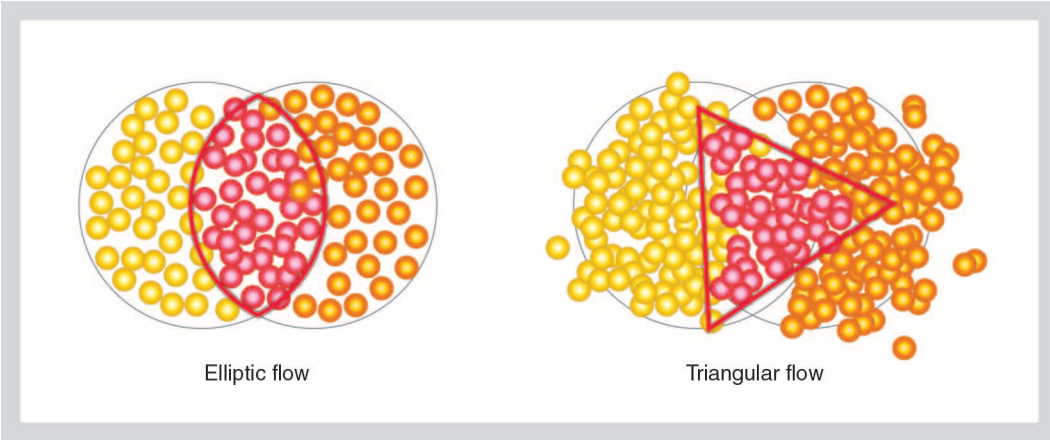

Fig. 3. Elliptic (left) and triangular (right) flow patterns arise from the locations of individual nucleons at the instant when two nuclei interpenetrate. The nucleons of one nucleus are shown in yellow and the other in orange. Red indicates those nucleons in the overlap region, which actually collide. (Left) Adapted with permission from figure 1 in (*56*) [Copyrighted by the American Physical Society]. (Right) Adapted with permission from figure 3 in (*57*). [Copyrighted by the American Physical Society]

to the thermodynamic and continuum limits (*29*). The equation of state of hot QCD matter and correlation functions, such as the screening distance of the color force, are now within reach. However, reliable calculations in lattice QCD are still limited to static properties, severely restricting our ability to address transport properties of the QGP.

Transport theory describes the conversion of the gluon fields in the incoming nuclei into thermal QCD matter, the explosive expansion of the QGP, and finally its disassembly into hadrons. A standard scenario of distinct reaction stages has emerged (*30*). In the first stage, gluons are liberated and form a dense system of nonlinearly coupled fields, known as the glasma. The second stage, the rapid expansion of the hot QGP, is effectively described by relativistic hydrodynamics with small viscous effects. After the matter cools below 150 MeV, its final expansion and freeze-out can be described by kinetic theory for hadrons. Whereas the experimental data provide solid evidence for the validity of the description of stages 2 and 3, experimental exploration of the glasma phase is just beginning.

Physicists were astounded to find that an entirely different approach, using dualities that relate QCD at strong coupling with weakly coupled gravitational theories, can yield insights into the dynamical properties of quantum inviscid liquids. The duality of string theory in anti-de Sitter (AdS) space with conformal quantum field theory (CFT) provides an exact description of some strongly coupled systems. The formalism, known as AdS/CFT correspondence (*31*, *32*), holographically maps the intractable strongly coupled quantum field theory onto a solvable classical gravity theory in five dimensions. Thermalization of the quantum field appears as formation of a black hole in the gravity dual theory. Although the formalism is exact only in the limit of an infinite number of colors and at strong coupling, it is believed that for many quantities of interest the three colors of QCD can be considered as a large number. Lattice gauge theory (*33*, *34*) provides compelling evidence for this conjecture. The gravity dual description offers an explanation of how a strongly coupled plasma of gauge fields can reach thermal equilibrium so rapidly and why hydrodynamics furnishes a reliable description even at strong coupling, when kinetic theory fails. Unfortunately, the coupling of true QCD is not as strong as would be required for rigorous application of the AdS/CFT duality. At the moment no gravity dual for true QCD is known, and it is unknown whether one exists.

Interconnections

Understanding strongly coupled or strongly correlated systems is at the intellectual forefront of multiple subfields of physics. One example is ultracold fermionic atoms, such as ^{6}Li, where application of a magnetic field excites a strong resonance. When confined in an atomic trap, these atoms form a degenerate Fermi liquid, which can be manipulated and studied in detail (*35*). At temperatures below ~0.1 μK, the atoms interacting via the resonance form a superfluid (*36*). The shear viscosity η and the entropy density s for this system can be measured separately, showing that η/s falls with decreasing temperature. At very low temperatures, it approaches about four times the universal quantum limit (*37*), only twice as large as the value deduced for the QGP.

Strongly correlated electron systems in condensed matter provide an example of strong coupling where the elementary interaction is not strong, but its role is amplified by the large number of interacting particles and their ability to dynamically correlate their quantum wave functions. Surprisingly, holographic gravity duals have also helped to provide simple descriptions of such complex systems (*38*, *39*).

Strongly coupled systems in conventional plasma physics include warm, dense matter and dusty plasmas (*40*) residing in astrophysical environments, such as the rings of Saturn, and in thermonuclear fusion. In these plasmas, the ratio r of potential to kinetic energy is large, implying strong coupling; at sufficiently large r, such plasmas can even crystallize. The shear viscosity exhibits a minimum at a certain value of r, where the dominant mechanism of momentum transport changes from ballistic quasiparticle motion to some form of collective transport.

An advantage of QCD matter over other strongly coupled systems is that the interaction is well defined. The QGP thus offers a chance to understand how a strongly coupled fluid emerges from a microscopic theory that is precisely known. The strongly coupled QGP is also the only known relativistic liquid. Its structure is not dominated by repulsive interactions, so it challenges the traditional concept of a liquid. However, the high temperature of the QGP, combined with the fundamental nature of the QCD interaction, permits ab initio techniques to address equilibrium properties of hot QCD matter without any model assumptions or approximations. The rapidly expanding capabilities to perform definitive calculations of this kind enable newly rigorous comparisons between the theory of strongly coupled systems and experiment.

Open Questions and Challenges

The surprising experimental results present an entirely new set of questions about the QGP. Roughly following the time development of heavy ion collisions, one must now ask: What is the nature of QCD matter at low temperature but high density, and how does it affect plasma formation? How can the plasma thermalize so rapidly? Does it exhibit novel symmetry properties along the way? The QCD plasma is strongly coupled, but at what scales? Does it contain quasiparticles, or does the strong coupling completely wipe out long-lived collective excitations? What impact does the coupling have on color screening? Is there a characteristic screening length, and if so, what is it? What is the mechanism for parton-plasma interactions, and how does the plasma respond to energy deposited in it?

Gravity dual calculations show that thermalization propagates at the speed of light and all anisotropies disappear quickly in the strong coupling limit (*41*, *42*). Plasma instabilities may play a role. The microscopic structure of the strongly coupled QGP is still poorly understood; in the gravity dual picture, no quasiparticles exist except phonons. Lattice simulations confirm that the quantum numbers associated with quarks—baryon number, electric charge, and flavor—are carried by elementary, quarklike constituents at temperatures above the critical temperature for QGP formation, T_c. However, they are unable to

address the dynamic response of the plasma and provide no information about the presence or absence of propagating quasiparticles. Energy loss of heavy quarks is sensitive to the spectrum of excitations of the QGP and may provide a handle on quasiparticles and their properties. Photons and leptons should preserve imprints of the early stages of the collision.

Shear viscosity and speed of sound are two important indicators of the microscopic structure of any material. The viscosity probes how the constituents of the material are coupled, whereas the speed of sound is sensitive to both the mass of the constituents and the strength of their interaction. Because strongly coupled theories do not allow particle-like excitations, the very nature of the plasma constituents is a question. A promising way to measure both quantities in the QGP is by systematic studies of the response of the matter to initial density fluctuations.

contain bottom quarks. The small size of these mesons enables their existence in QGP because screening occurs only at larger distance scales. Quarkonia have different excited states with varying binding energies; loosely bound, larger states are easier for the QGP to screen. Indeed, suppression of charm quarkonia (charmonia) in QGP, compared to p+p collisions, has already been observed (*47–51*). It should be possible to infer the color screening scale with spectroscopy of different quarkonium states as a function of beam energy, meson momentum, and the emission angle with respect to the beam. Untangling initial state effects on heavy quark production and final state effects, which can re-form bound states, requires control measurements in (p or d)+nucleus collisions, along with theoretical study of color screening in an expanding plasma.

Highly energetic partons created in the initial phase of the collision lose energy as they pass

discriminate between radiative and collisional energy loss. Because little difference has been found in the suppression of light and heavy (mostly charm) quarks (*52*), separating the charm quark from the even heavier bottom quark is a key experimental goal.

The Look Ahead at RHIC and LHC

Recent RHIC upgrades have increased both the luminosity and the range of particle species available. Higher luminosity makes rare probes, such as jets and hadrons containing c and b quarks, more accessible. PHENIX and STAR are being upgraded with state-of-the-art silicon microvertex detectors to enable precise measurements of heavy quarks by tagging their decays. These will allow separation of the charm quark from the bottom quark, which is three times heavier and should sail right through the QGP. A new ion source at RHIC provides additional beam species, such as

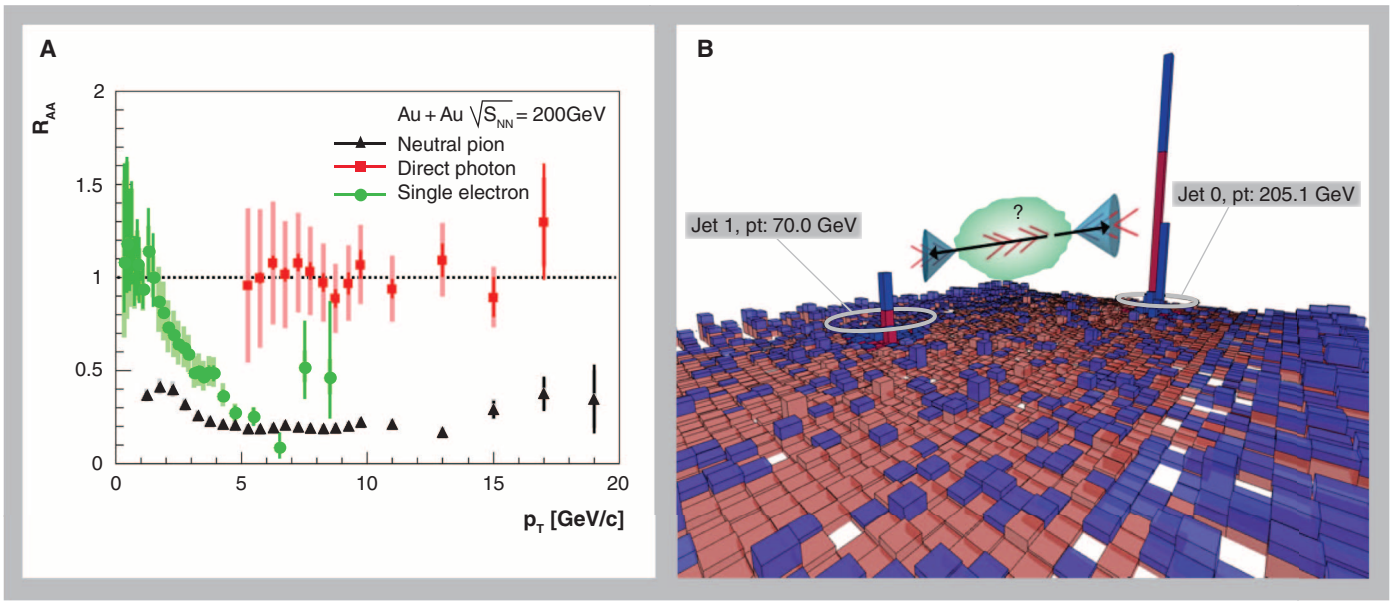

Fig. 4. (**A**) Ratio of particle yield in Au+Au to p+p collisions by PHENIX at RHIC, as a function of particle momentum transverse to the beam direction. Data from (*25*) and adapted with permission from (*52*, *58*) [Copyrighted by the American Physical Society]. The emission of pions and electrons from the decay of heavy quarks is strongly suppressed in Au+Au, whereas photon emission is not suppressed. The suppression of hadrons is a measure of the color opacity of the QGP. (**B**) The cartoon illustrates energy measured in the jet cone on each side of a dijet, along with energy deposit into the QGP, shown as a green shape. The black arrows indicate the path of the energetic partons that create the two jets. The rest of the figure depicts a Pb+Pb event display at LHC from the Compact Muon Solenoid (CMS) (*28*) [Credit: CMS Collaboration; reprinted with permission from https://twiki.cern.ch/twiki/bin/view/CMSPublic/HIEventDisplays]. The angular distribution of energy emitted has been unfolded onto a plane; the height of the peaks is proportional to the amount of energy observed. The Pb beams enter perpendicular to the page. This event was triggered by the jet on the right, and a large energy loss by the jet on the left is seen.

In the QGP, color is screened, akin to the electromagnetic Debye screening observed in conventional plasmas. Lattice QCD shows that above T_c, screening of color is incomplete (*43–45*); partial screening is characteristic of strongly coupled plasmas (*46*). Screening in the QGP can be probed experimentally by measuring the survival rate of heavy quark bound states. Charm or bottom quarks are produced in pairs, which sometimes remain bound and are detected as heavy mesons called quarkonia. The mesons called J/ψ and ψ' are composed of charm quarks, the Upsilon mesons (Υ)

through by exciting modes of the medium (collisional energy loss) or by radiating off gluons (radiative energy loss). The second mechanism, akin to bremsstrahlung of photons by electrons passing through matter, becomes less effective as the mass of the parton increases. In a weakly coupled medium, thermalization of deposited energy occurs through a cascade of collisions among quarks and gluons in the plasma; in a strongly coupled medium, the energy is dissipated directly into thermal excitations and sound waves. Measurements of quarks with different mass should

the highly deformed uranium nucleus. U+U collisions, along with asymmetric beam combinations, offer novel ways to control the nuclear geometry, and thus the path length, for probes transiting the QGP. Excitation functions for rare probes can now be used to study predicted features of the QCD matter phase diagram. These measurements, along with RHIC's polarized proton-proton collisions, will systematically test theoretical models, provide benchmarks to isolate the effects of hot QCD matter on observables, and map the parton structure of nuclei in the relevant kinematic range.

The wide range of beam energies available at RHIC also makes it possible to explore the phase diagram of QCD matter at higher baryon densities, because nucleons are partially stopped in collisions at lower energies (*53*). According to some predictions, the transition between hadron and quark matter becomes of first order beyond a critical point in the phase diagram. The results from an exploratory beam energy scan, which hopes to locate this critical point by searching for the signatures of critical fluctuations, are expected soon. Higher beam luminosities will greatly increase the sensitivity of future searches.

The upgrades already under way at RHIC will answer some of the questions posed in the preceding section. Fully exploiting the versatility and luminosity of RHIC requires further detector capabilities. Accessing the early dynamics calls for measuring photons over a larger range of angles, as well as the flow patterns of those photons. Quantifying the color screening length entails precise measurements of heavy quarkonia over a large acceptance, as a function of the mass, momentum, binding energy, path length through the plasma, and initial temperature of the system. Disentangling initial- and final-state effects on bound-state formation implies comparably sized sets of nucleon-nucleus collision data. To pin down the role of gluons in the nuclear wave function (*54*), forward angle detectors for photons, leptons, and hadrons are necessary. To determine the jet energy loss mechanism, full reconstruction of moderate energy jets, which radiate partons near the QGP scale, will be indispensable. Measurement of the energy redistribution in the medium-modified jets coupled with modeling of energy and particle flow will help tease the different mechanisms apart. RHIC is the ideal facility to do this, whereas the higher-energy jets at LHC yield the parton energy dependence of the jet-QGP interaction.

The LHC data will provide stringent tests of jet quenching theory complementary to those at RHIC—for example, via the momentum dependence of heavy quark energy loss, which is predicted to be different in strongly and weakly coupled regimes of the QGP. The higher beam energy at LHC makes the rate of rare probes much higher than at RHIC. This opens a larger kinematic range for hadrons, photons, and b quarks and accesses new probes such as the Z boson. Study of hadrons inside jets energy is determined by an opposing Z boson will provide new constraints on the parton-medium interaction.

The higher energy density reached at LHC should lead to stronger color screening and thus to larger suppression of heavy quark bound states. This effect may be overwhelmed by coalescence of heavy quarks into such states when the QGP converts back into hadrons; coalescence should be more prominent at LHC than at RHIC because more heavy quark pairs are produced in each collision. High statistics spectroscopy of the Υ states will allow comparison of color screening in QGP at different temperatures.

Challenging theoretical advances, including higher-order jet calculations and effective theories for heavy quarks that connect lattice simulations with transport processes, are needed to extract reliable values for the energy loss parameters and the color screening length in the plasma from high-precision data. Major numerical advances will be required to solve the transport equations describing rapid formation of an equilibrated QGP. Development of an exact gravity dual of QCD would enable realistic calculations of dynamical processes in the strong coupling limit. So-called "stringy" corrections for finite numbers of colors would allow bracketing the real-world regime of intermediate coupling from both sides. Such advances will not only elucidate the physics of the QGP but also address intellectual challenges of strong coupling in many areas of physics. The successes and limitations of the string theory–based approach suggest opportunities for the development of novel mathematical techniques applicable to strongly coupled systems.

Exploration of hot QCD matter has made enormous progress during the past decade. Experiments have discovered a new high-temperature phase, the strongly coupled QGP, which persists to the highest temperature probed. Surprising features of the QGP include near-perfect fluidity and extreme opaqueness to all colored probes. The rapid development of theoretical and experimental tools promises quantitative insights into the still mysterious properties of the QGP during the coming decade. These will also inform the study of other strongly coupled systems in nature and in the laboratory.

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Acknowledgments: This work was supported by grants from the U.S. Department of Energy.

10.1126/science.1215901