takes the electrons to cool, the electrons would be heated to even higher temperatures by the second pulse, and the CO_2 yield would be higher. However, if the delay were longer than the electron cooling time, then CO_2 production would not be boosted.

Two-pulse correlation, which made its debut in 1991,[4] simply exploits this dependence on delay. Pairs of pulses with decreasing, zero, and then increasing delays are fired at the substrate, and the production of CO_2 and CO are measured and plotted as a function of the delay. For CO_2 the production rate is sharply peaked at zero delay with a width of 3 ps. By contrast the width of the CO production rate is 20 ps. Evidently, quick-responding electrons, not slow-responding phonons, mediate the production of CO_2.

Can't hot electrons also make the adsorbed CO molecules leave the surface? Bonn's team covered a Ru surface with just CO and repeated the two-pulse experiment. CO desorption, they found, was just as slow as when the O adatoms were present. Moreover, according to theoretical calculations, the CO's first unoccupied electron state is a $2\pi^*$ orbital, which is known, from inverse photoemission spectroscopy, to lie 5 eV above the substrate's Fermi level and beyond the reach of even the tail of the hot electron distribution.

"The work is beautiful," says John Weaver of the University of Minnesota. "They've clearly shown that electrons can cause reactions that heat cannot."

The real world

The catalytic converter in your car uses platinum, a metal similar to ruthenium, to convert poisonous CO into less malign CO_2. But the catalytic reactions involve oxygen species that are weakly bound to the catalyst and take place on a complex surface, at atmospheric or higher pressure, and in thermal equilibrium—all far cries from the *in vacuo* model system in Bonn's experiment. Direct application of this work is therefore far off in the future, but, believes Wolf, now that electronic mediation has been shown to operate in catalytic-like reactions, it might prove to be important in some real-life catalysts—especially since catalysts are frequently manipulated by so-called promotors to achieve favorable electronic states.

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Going for the Gold: First Collisions at RHIC Are Set for December

Some time in December, the newly constructed Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory is expected to produce collisions between gold ions, each with 100 GeV/nucleon, providing twice that energy in the collision. Energy densities at least ten times higher than in ordinary nuclear matter are expected to be reached. With RHIC, experimenters hope to observe the phase transition from ordinary nuclear matter to a quark–gluon plasma, a deconfined state of quarks and gluons. If the experiments succeed, RHIC will have produced the inverse of the phase transition from deconfined quarks and gluons to ordinary hadronic matter that occurred a few microseconds after the Big Bang, when the universe was at a temperature of 150–200 MeV.

When RHIC experimenters collide gold ions to produce energy densities ten times higher than in ordinary nuclear matter, they hope to observe the formation of a quark–gluon plasma.

Last 24 June, the day the collider met DOE safety readiness requirements, I spent the day at RHIC talking to project director Satoshi Ozaki and spokepersons for the four detectors, toured the accelerator tunnel, and each of the detectors. That afternoon Ozaki, John Marburger (Brookhaven's director), and DOE officials signed the papers that made it possible to begin commissioning the machine later that same day.

RHIC will store countercirculating beams of gold ions in two beam pipes known as the Blue Ring and the Yellow Ring. Each ring must be cooled to 4 K because the dipole and quadrupole magnets that guide the beams are made of superconducting Nb–Ti. The beams can be made to collide in six interaction regions spaced around the tunnel circumference; four of them are currently occupied by detectors. In the round of commissioning tests that ended on 16 August, a beam of gold ions was injected, captured, and stored in the Blue Ring for as long as 45 minutes. A modest amount of acceleration was achieved—about 1 GeV per nucleon. By the time the run ended, gold ions had been injected and captured in the Yellow Ring, but stored for only tenths of a second. At the start of September, the accelerator team members had warmed the two rings and were about to begin looking for bugs in the power supply system. Plans are to resume commissioning in December and begin collisions soon after that. All four detectors are expected to begin taking data by January 2000.

The road from Isabelle to RHIC

Like the mythical phoenix, RHIC has risen from the ashes of another Brookhaven collider, Isabelle, whose construction was canceled by DOE in 1983 in response to a recommendation made by the High-Energy Physics Advisory Panel. Isabelle was to have been a proton–proton collider, with 400 GeV in each beam. Instead of Isabelle, HEPAP recommended building a proton–proton collider with 10 to 20 TeV in each beam—the Superconducting Super Collider. Years later, like Isabelle, the SSC was canceled midway through construction.

In July 1983, just as Isabelle was being canceled, the Nuclear Science Advisory Committee was meeting to decide what the next major nuclear physics project should be, and concluded that a heavy-ion collider should have the highest priority. By 1986, DOE had approved R&D funds for RHIC. Construction began in 1991. Total construction cost was $487 million, of which $115 million went for the four detectors.

Since 1987, heavy-ion experiments at Brookhaven's Alternating Gradient Synchrotron (AGS) and CERN's Super Proton Synchrotron (SPS) have improved our understanding of what may be learned—first at RHIC, and then at ALICE, a heavy-ion detector being built at CERN's Large Hadron Collider (also under construction). ALICE, scheduled to operate in 2005 or perhaps later, will study collisions with 2.7 TeV/nucleon.

RHIC will be the first accelerator to collide beams of heavy nuclei at high energies over a large volume. The Blue and Yellow Rings occupy the old Isabelle tunnel, which is 3.8 km in circumference. Heavy ions originate in a tandem Van de Graaff accelerator, proceed to a booster synchrotron, and then enter the AGS. From there, ions are extracted in bunches and transferred to each of the two collider rings. After each ring is filled (in about a minute), the ions are to be accelerated to the design energy of 100 GeV/nucleon. At this energy, the design luminosity of RHIC is $2 \times 10^{26}/\mathrm{cm}^2/\mathrm{s}$, and according to Brookhaven's deputy director, Peter Paul, that value is expected in a couple of years. The ion beams will coast around the rings for about ten hours before the mutual Coulomb repulsion within each bunch degrades the luminosity to unacceptable levels.

TWO RINGS OF CRYOSTATS house the superconducting magnets that carry RHIC's heavy-ion beams, in opposite directions, on their collision course. The view is one of the arc sections of the RHIC tunnel. (Photo courtesy of Thomas Ludlam, Brookhaven National Laboratory.)

A major part of the RHIC construction effort consisted of producing the superconducting magnets. Designers picked 3.45 tesla for the field produced by the bending dipole magnets, to take advantage of the existing Isabelle tunnel dimensions. Instead of the separate, stainless steel collars used in Fermilab's Tevatron to contain the magnetic forces that tend to make the coils fly apart, the RHIC magnets used yoke laminations to serve as collars.

Brookhaven's goal was to have magnets built to Brookhaven specifications, and Northrop-Grumman Corp in Bethpage, New York, built the required 380 dipole and 420 quadrupole magnets. "Uniformity from magnet to magnet is outstanding," says Ozaki. "In phase 1, we made 30 magnets, and we measured every one of them at superconducting temperature. After that we just tested 10% cryogenically. All our magnets, both dipole and quadrupole, reached 30% above the operating current."

What will RHIC look for?

RHIC will study high-energy, high-density many-body physics. It will produce 10 000 particles in a single collision. Once the energy density becomes ten times higher than nuclear matter, says Brookhaven theorist Dmitri Kharzeev, "the vacuum will change its character and a phase transition to the deconfined phase will occur. Quantum chromodynamics describes strong interactions of quarks and gluons. In our world, they're not observable because of confinement. But as the energy density increases, the average distance between quarks and gluons becomes smaller. At such short distances, the forces between quarks get weaker because of asymptotic freedom, and the transition occurs."

Lattice gauge theory is a way of simulating QCD in the nonperturbative regime, using a discrete lattice of space–time coordinates. These calculations attempt to predict the pressure, energy density, and temperature at which the transition to a quark–gluon plasma will occur. Predictions for the temperature have been 150–200 MeV, within the range of RHIC. Says Kharzeev, "Lattice QCD simulations so far have not been capable of using true mass values for the light quarks. . . . It's not known whether the transition will be first order, second order, or a smooth crossover."

One property of QCD is chiral symmetry breaking. Massless spin-$1/2$ particles such as u and d quarks possess chirality; they are either left- or right-handed. In QCD, there's a very strong attraction between left-handed quarks, q, and right-handed antiquarks, $\bar{q}$ (and between right-handed q and left-handed $\bar{q}$). This attraction leads to a condensate—large numbers of $q\bar{q}$ pairs filling the vacuum. When high enough temperatures are reached in RHIC collisions, the complications of confinement melt away, according to Frank Wilczek (see PHYSICS TODAY, April 1998, page 11). "At high temperatures, the asymptotically free quarks, antiquarks and gluons should be liberated, and stand revealed in their pristine glory."

When the quark–gluon plasma cools down, chiral symmetry breaking should occur again, which is analogous to the magnetization recurring at the Curie temperature in ferromagnetism. When the plasma cools, a left-handed u quark might pair with a right-handed $\bar{d}$ instead of its normal partner (a right-handed $\bar{u}$), comparable to a magnet pointing in a different direction. Such a possibility was explored about five years ago by Wilczek and Krishna Rajagopal (now at MIT). When this cooling from the quark–gluon plasma occurs, how do you get back to normal hadronic matter? A so-called disordered chiral condensate could occur, producing pions that could radiate coherently (a pion laser).

Last year Kharzeev, Robert Pisarski (Brookhaven) and Michel Tytgat (Free University of Brussels) proposed a new kind of parity and time-reversal violation in the strong interactions. Says Kharzeev, "In QCD, we don't understand why there is both P and CP conservation. The ground state of our theory is a vacuum, which would have P and CP even. But close to the transition, a metastable state could be produced that would be odd under both P and CP. Once you excited such states, you could observe parity odd correlations of the product particles." At least one of the four RHIC detector groups, STAR, will search for P and T violation.

Can we learn about the behavior of neutron stars? Gordon Baym (University of Illinois at Urbana-Champaign) notes that matter produced at RHIC will reach temperatures above 100 MeV, much higher than the 1 MeV temperature of a neutron star. "But," says Baym, "as you learn to explain high-temperature quark matter, you'll get a guide to the theory of low-temperature quark matter, which may exist in neutron stars."

Four detectors

Detecting the large number of particles produced in just a single collision requires sophisticated and ingenious detectors. Their complexity is comparable to the largest detectors in high-energy physics. But unlike those, the RHIC experiments need to identify a larger range of particles, and they also need to retain sensitivity to low-energy particles. STAR and PHENIX are both large, multipurpose experiments, each with about 400 collaboration members. The other two experiments, Phobos and BRAHMS, are smaller and more focused experiments.

STAR (which stands for solenoidal tracker at RHIC) will specialize in tracking the thousands of particles that will be produced in each RHIC collision. As T. D. Lee (Columbia University) has remarked, every RHIC event can therefore be viewed as an experiment. The STAR detector uses the large, solid-angle tracking and particle identification capability of a cylindrical time-projection chamber, placed in a large solenoidal magnet. In addition to the tracking detectors, the electromagnetic calorimeter (of which only 10% will be ready for initial RHIC operation) will measure the transverse energy of events, and measure photons, particles, and jets having high transverse momentum. The STAR collaboration has emphasized detection of the global features of the hadrons and jets as the signatures for quark–gluon plasma formation. A ring-imaging Čerenkov detector for a limited solid angle is being installed in STAR as a joint venture with the ALICE collaboration at CERN, which is contributing one of its large-area prototypes.

PHENIX (which stands for pioneering high energy new ion experiment) is intended to detect leptons, photons, and hadrons in selected solid angles with a high rate capability, which will provide a broad range of quark–gluon plasma indicators. PHENIX spokesperson William Zajc (Columbia University) explains that with the detector's four spectrometers, the team will be able to detect both e^+e^- and $\mu^+\mu^-$ pairs. By detecting thermal photons from $q\bar{q}$ annihilation, one can study the evolution of the radiation produced in the collision, analogous to detecting x rays from a conventional plasma. The emphasis on lepton pairs also gives PHENIX excellent sensitivity to the rate of production of J/ψ particles; currently a drop in this rate is the leading "unambiguous" candidate to signal the formation of a quark–gluon plasma. A glimpse of such suppression was found in 1987 at the CERN SPS, but it hasn't been clear that's evidence for quark–gluon plasma formation. The decay of the J/ψ into either e^+e^- or $\mu^+\mu^-$ pairs has completely different experimental constraints, which are reflected in the vastly different designs of the various spectrometers. The central region of PHENIX has an axial magnetic field and two detector arms that contain, among other items, ring imaging Čerenkov and time-of-flight counters, and electromagnetic calorimeters. Additional, simpler arms will detect muons.

The Phobos detector is designed to examine a very large number of collisions (10^9 per year) because the Phobos experimenters believe interesting collisions might be rare. For each collision, Phobos will give a global picture of what happened, and detailed information about a small subset of the fragments ejected from the very central hottest collision regions (by means of two high-precision multiparticle spectrometers). Phobos is able to detect particles with very low transverse momentum. These slower particles streaming transverse to the beam direction from the collision region are expected to be especially sensitive to the larger coherent effects that would be indicative of a phase change, according to Phobos spokesperson Wit Busza (MIT). As Phobos experimenter Russell Betts (Argonne National Laboratory) explains, "As the quark–gluon plasma cools, the quarks coalesce, forming mostly mesons. The number of particles that come out, their angles, their type, and momentum spectrum can be used to determine the thermodynamic properties of the plasma."

BRAHMS (broad range hadron magnetic spectrometers) will use two movable aperture spectrometers to identify and study charged hadrons emerging over a 90° range, including very forward angles (0.8 millisteradian). Says spokesman Flemming Videbaek (Brookhaven), "We'll detect identified charged hadrons over a wide rapidity and momentum range."

Computing will also involve a major effort at RHIC. Comparing RHIC's planned capability with that of Fermilab's Advanced Computer Program four years ago, then the biggest computing effort in particle physics (see the article by Joel Butler and David Quarrie, PHYSICS TODAY, October 1996, page 50), Brookhaven's Bruce Gibbard says the data volumes and transfer rates will be about 15 times higher and the CPU capacity is about 100 times greater. Two-thirds of the computing costs at RHIC will be spent on robotic storage.

GLORIA B. LUBKIN

Single Microwave Photons Can Be Measured Nondestructively

Individual atoms passing through a microwave cavity can sense whether it contains zero photons or one—and leave the photon number unchanged.

A deeply held tenet of quantum mechanics, dating back to its infancy, is that one can't measure a system without disturbing it. That doesn't mean, however, that one can't influence the form such a disturbance takes. Over the past 25 years, researchers have been developing schemes for controlling the effects of measurements so that the properties of interest emerge unscathed. Now a group led by Serge Haroche at the Ecole Normale Supérieure (ENS) in Paris has demonstrated such techniques at the most fundamental level—detecting the presence of a single photon in a nondestructive way.[1]

Quantum nondemolition

The Heisenberg uncertainty principle fundamentally expresses the effect of a measurement on a quantum system: The better we know one observable of a system, such as its position, the less we can know about other, noncommuting observables, such as its momentum. But the dispersion that a measurement imparts to noncommuting observables can later influence the observable we care about, producing so-called back action. Thus, although we can measure a particle's position at one time, uncertainty in its momentum prevents us from saying anything about its exact position at a later time.

Quantum nondemolition (QND) provides a way around such back action. The idea of QND measurements—developed in the 1970s by Vladimir Braginsky (Moscow State University), Kip Thorne (Caltech), Carlton Caves (University of New Mexico), and others, originally in the context of gravitational-wave detectors—is to configure the measurement around an observable that is totally decoupled from the other observables. In this way, the back action in the other observables doesn't interfere with the measured quantity, whose value can be preserved throughout successive measurements.[2,3]

QND measurement ideas started being applied to the field of quantum optics in the mid-1980s (for a review, see ref. 3). Researchers have been able to determine the intensity of lasers without absorbing any of the light: In a nonlinear medium, the interaction between the laser to be measured and another laser, which serves as the "meter," can produce a phase shift in the meter beam that can be detected using interferometry. Those experiments involved microwatts to milliwatts of power, corresponding to macroscopic numbers of photons. In contrast, the ENS group has measured whether just one photon is present in their cavity.

Detecting a single photon

Unlike photomultipliers and other devices that measure light by absorbing photons, a QND measurement leaves the photon number unchanged. To ac-