

BROOKHAVEN STARTS BUILDING THE RELATIVISTIC HEAVY-ION COLLIDER

Brookhaven has finally been allowed to start building RHIC, the relativistic heavy-ion collider designed to occupy the 4-km-circumference tunnel left vacant eight years ago by the cancellation of the Colliding Beam Accelerator project. CBA, née Isabelle, was to have been a 200×200 -GeV proton-proton collider, but construction never got beyond the civil engineering stage.

RHIC will accelerate countercirculating beams of heavy nuclei, all the way up to gold, to energies of 100 GeV per nucleon. For lighter nuclei, with more charge per unit mass, the top RHIC energies per nucleon are correspondingly higher: For naked protons, the lightest of all nuclei, the maximum beam energy will be 250 GeV.

The quark-gluon plasma

This unique collider, which is being built by the nuclear physics community with active participation by elementary-particle physicists, should be ready for the experimenters in 1997. The guiding impulse of those who are already planning the detectors and experiments is the quest for the "quark-gluon plasma." Quantum chromodynamics, the present standard theory of the hadronic (that is to say, strong) interactions between elementary particles, predicts unambiguously that if one excites nuclear matter, or even just the vacuum, to high enough energy density over an extended region, the result will be this new state of matter in which quarks and the gluons that bind them are no longer confined inside individual nucleons or mesons: They are free to wander over distances much larger than 1 fermi—the characteristic size of a hadron. Such a state of affairs would not be altogether new. Cosmologists believe that the entire universe was a quark-gluon plasma prior to 10 microseconds after the Big Bang.

QCD tells us that exciting the

vacuum to an energy density of something like 3 GeV/fm^3 should do the trick. From what is already known about high-energy collisions of heavy nuclei, RHIC is likely to produce vacuum energy densities as high as 10 GeV/fm^3 . That's generally thought to be a comfortable margin for achieving the quark-gluon plasma. RHIC will greatly exceed the nuclear collision energies achievable at existing heavy-ion accelerators, the most powerful of which is the Super Proton Synchrotron at CERN.

The SPS, which normally serves as a proton-antiproton collider, is occasionally given over to experiments with ion beams as energetic as 200 GeV/nucleon. (See *PHYSICS TODAY*, March 1988, page 17.) But these are all fixed-target (as distinguished from collider) experiments. The SPS, with its single ring of bending magnets, cannot store countercirculating beams of like charge. Therefore the center-of-mass collision energies, per nucleon, at RHIC will exceed those obtainable at the SPS in its heavy-ion runs by an order of magnitude.

Nonetheless, these CERN experiments, and lower-energy heavy-ion runs at Brookhaven's Alternating Gradient Synchrotron and the Berkeley Bevalac, have done much to clarify what we can expect at RHIC. Among other things, they have supported the expectation that nuclei become more and more transparent to one another with increasing collision energy. This transparency is an important aspect of the emerging picture of nuclear collisions at RHIC energies: Two 100-GeV/nucleon gold nuclei colliding head on would literally pass through each other in such a way that roughly 90% of their energy is accounted for by fragments of the incident nuclei emerging from the collision with little change of direction. That leaves about 10% of the incident energy to excite the region of vacuum left behind at the center of mass by the departing nuclear frag-

ments.

Although this "central region" will be left largely devoid of nuclear matter, the vacuum there will have been excited to an energy density high enough to produce mesons and baryon-antibaryon pairs in great profusion. That much is fairly certain. One wants to test the QCD assertion that these emerging hadrons—at least from some of the more violent collisions—will show themselves to be the cold vestiges of a fleeting quark-gluon plasma.

The vacuum plays two crucial roles in the standard model of the elementary particles. The peculiarities of the "QCD vacuum" are thought to be responsible for the confinement of quarks inside hadrons. "RHIC will be our very first opportunity to test the dynamical properties attributed to the QCD vacuum," says theorist T. D. Lee (Columbia). "This supposed interplay of the elementary particles with the vacuum is an extraordinary coupling of the microscopic to the macroscopic—the vacuum being everywhere—that has yet to be demonstrated by experiment."

Testing the other key role assigned to the vacuum, Lee points out, will probably have to wait until the Superconducting Super Collider collides 10-TeV/nucleon beams of heavy ions! (Such are the heady aspirations excited by the imminence of RHIC.) The electroweak component of the standard model makes the asymmetry of the vacuum responsible for the enormous mass difference between the photon and the vector bosons that mediate the weak interactions. But testing that conjecture will require vacuum excitations hot enough to generate $W^\pm$ and Z^0 bosons in profusion. These vector bosons weigh a hundred times more than the hadrons that will let RHIC test the QCD vacuum.

The machine

RHIC, like the SSC, will have a double

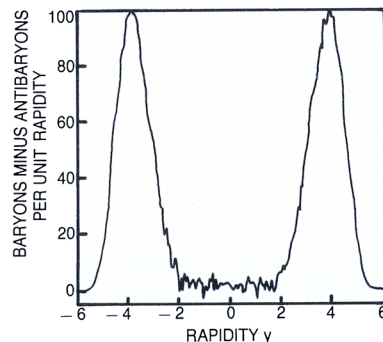
ring of superconducting bending magnets. But RHIC requires a modest bending field of only 3.5 tesla. That's about half the field-strength requirement that has given the SSC magnet designers so much trouble. Each RHIC bending magnet will be 9.7 meters long. After the successful testing of prototypes built at Brookhaven, the magnet design was essentially ready for mass production three years ago. All that was lacking was the go-ahead from DOE and Congress.

Most of the collider's 1600 superconducting bending, focusing and correcting magnets are to be built by industry. A request for bids from commercial manufacturers was issued in May. But Brookhaven itself will build 400 specialized magnets for the six regions where the countercirculating beams are to cross each other.

Being a heavy-ion machine, RHIC requires wider beam pipes than would a proton machine of comparable intensity. All the ions will be fully stripped of their electrons before injection into the collider ring. A stripped gold ion, for example, carries 79 times the charge of a proton. The adverse effects of Coulomb scattering between beam particles on the phase-space spread of the beam grow worse with increasing charge. Therefore the RHIC magnets must accommodate a beam-pipe diameter of 8 cm, almost twice as wide as one needs for the SSC magnets.

The higher the charge/mass ratio of the nuclear species, the greater is the maximum beam energy per nucleon allowed by the maximum bending-magnet field. But when RHIC runs in an asymmetrical mode, timing considerations impose an additional constraint: The magnets could, for example, store a 125-GeV/nucleon oxygen beam countercirculating against a 100-GeV/nucleon beam of gold nuclei. The velocities of these two beams would then, however, differ from each other (and the speed of light) by a few parts in 10^5 . That doesn't seem like much. But it's enough to ruin the synchronization of the countercirculating bunches of nuclei. RHIC will have six crossover points where the two beams can be brought into collision. To insure that opposing bunches keep arriving simultaneously at a collision point, countercirculating beams of different species must have the same velocity. In effect this means that both beams are limited to the energy per nucleon of the heavier species.

The acceleration of ions at the RHIC complex begins with one of Brookhaven's two existing tandem



Central region of low net baryon number is evident in this rapidity distribution of baryons (minus antibaryons) from a computer-simulated head-on collision between 100-GeV/nucleon gold nuclei. Rapidity, a useful measure of longitudinal velocity, is given by $y = \tanh^{-1}(p_z/E)$, where p_z is the momentum component along the beam direction and E is the energy. The incident nuclei had $y = \pm 5.4$. Nuclear fragmentation products appear as peaks beyond $y = \pm 2$, leaving a baryon-free region around the center of mass at $y = 0$. Not all computer models predict so clean a central region. (Adapted from letter of intent by D. Beavis *et al.*, Brookhaven).

Van de Graaff accelerators. After traversing the Van de Graaff, an ion emerges partially stripped of its electrons, with an energy of about 15 MeV times its net charge. A 700-meter-long transfer line will bring the ions to the new booster accelerator, just completed in June. Before the booster was built as an injector for the Alternating Gradient Synchrotron, the AGS could not accelerate ions heavier than sulfur. Now the limit is gold. The booster will also serve to raise the beam intensity of the AGS when it continues to do its traditional duty as a proton accelerator.

Emerging from the booster with energies on the order of 100 MeV per nucleon, the ions will be passed through a stripping foil that will remove all but the innermost electrons of the heaviest nuclei. Thus stripped, they will enter the AGS to be accelerated to energies ranging from 28 GeV (protons) to 10 GeV per nucleon (gold). At these energies the ions will be sent through one more foil to strip any remaining electrons before they enter the RHIC rings. It will take about a minute to fill each ring with 57 bunches of ions, each about 1 meter long and containing on the order of 10^9 ions. It takes just one more minute to shrink these bunches to 30 cm and accelerate them to their

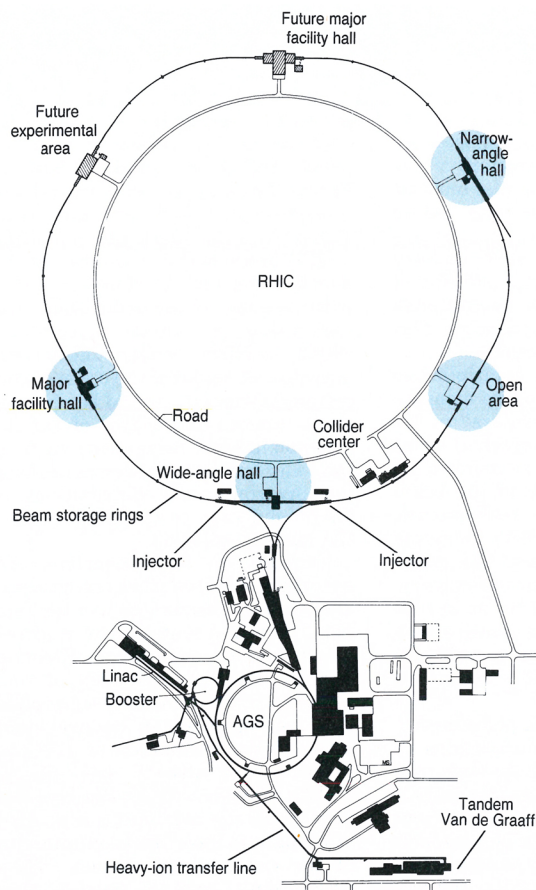
full RHIC energies. After that the two beams will continue to circulate for hours, coming into continual collision at any of the crossover points at which detectors are operating.

Detectors

Detector designers for RHIC face unique problems. A typical head-on collision between 100-GeV/nucleon heavy ions will engender ten thousand charged particles! That's a lot more than one expects from collisions between 20-TeV protons at the SSC. On the other hand, most of the interesting particles centrally produced in RHIC collisions will emerge with modest energies of no more than a few GeV. A 100-GeV/nucleon gold nucleus has just about as much total energy as a 20-TeV proton, but it's shared among 197 nucleons. Furthermore, the most energetic collision products—the nuclear debris that goes off at small angles relative to the beams—are the least interesting for the study of quark-gluon plasmas emerging from the excited vacuum.

Facing collisions of such complexity, no one is seeking to build a "hermetic" detector that can account for almost all the energy coming out. To the extent that one is dealing with a thermal process, such a complete accounting is not necessary. Nor is one looking for neutrinos by means of "missing" energy and momentum. But there is a class of proposed "large acceptance" detectors that aspire to reconstruct all charged particles emerging in a sizable chunk of central phase space—that is to say all particles with momentum components along the beam axis (in the center-of-mass frame) small enough to avoid overlap with the fast-moving fragments of the incident nuclei. (See the figure above.) In this central region thousands of particles, mostly pions, can show up in a single event, making it possible to characterize individual events as statistical ensembles. This is important when one is looking for a thermodynamic phase transition to the quark-gluon plasma.

Nuclei in RHIC will collide at all sorts of impact parameters. Glancing collisions are of little interest (except for some conventional nuclear-physics studies or when RHIC runs as a pp collider). The experimenters will be looking for head-on collisions that generate the highest energy densities. A simple "multiplicity" trigger, looking for events that produce far more particles than the average, can provide a fast first cut to identify events that might be interesting. Satoshi Ozaki, head of the RHIC project, expects that about one event in a



RHIC, the relativistic heavy-ion collider under construction at Brookhaven. The large, rounded hexagonal loop indicates both RHIC storage rings, carrying two countercirculating beams of energetic nuclei around the 4-km circumference of the collider. The beams will cross, and can be brought into collision, at six points equally spaced around the collider: four existing halls or pits (tinted blue) that are ready to receive detectors of various sizes and shapes, and two crossover points set aside for future facilities (shaded). The acceleration and stripping of the ions will begin at the Tandem Van de Graaff accelerator and continue in the new booster and the venerable Alternating Gradient Synchrotron before injection into the RHIC rings.

Detectors specializing in muons accomplish this by means of a thick hadron-absorbing barrier surrounding the collision point so close in that very few hadrons have time to decay into muons before being absorbed. Thus one is assured that almost anything getting through to the outside tracking chambers is a prompt muon. But the price one pays for this assurance is that there's very little room to measure the hadrons adequately before they're absorbed.

Detector designs specialized for electron-positron pairs are less incompatible with hadron measurement, but high-energy electrons are harder to identify than muons. To distinguish them from the much heavier hadrons, the RHIC detector schemes propose to employ time-of-flight counters, ring-imaging Čerenkov counters and transition-radiation detectors.

After reviewing the letters of intent in April, Brookhaven associate director Melvin Schwartz urged that these nine proposals, with their many overlapping features, be consolidated by mergers into a smaller number of proposals to be reviewed at the end of August. (Schwartz returned to high-energy physics at the beginning of this year after a decade in the entrepreneurial wilderness. See *PHYSICS TODAY*, January 1989, page 17.) The \$400 million total RHIC budget includes \$80 million for detectors. "We plan to devote \$60 million of that to the big detectors, holding back \$20 million for small detectors to be proposed later," says Thomas Ludlam, associate RHIC project head for detectors and experimental support. "That means two or three big detectors, depending on how much money comes in from foreign user groups and other non-DOE sources." Small, highly specialized detectors can run parasitically with a large detector at the same collision point.

How will the plasma look?

The QCD prediction that a quark-gluon plasma must exist at sufficiently high energy density is quite firm. What the actual transition should look like is much less obvious. Enormous number-crunching efforts at making the theory divulge its predictions in detail—the so-called lattice-gauge calculations—have yet to say unambiguously whether the quark-gluon plasma is separated from ordinary nuclear matter by a first- or second-order thermodynamic phase transition, or by something much more gradual. The experimenters will be looking for both: signatures of the existing plasma and, if nature is

hundred will be interesting enough for the detector to measure and store. With RHIC running at full intensity, that would require a detector and its on-line computers to deal thoroughly with about 10 events per second—a very modest event rate, much slower than what the SSC detectors will have to confront. That makes the prospect of ten thousand particles in a single event somewhat less daunting.

By last October Brookhaven had received nine "letters of intent" from various collaborations proposing to build RHIC detectors of different sizes and shapes. Most of the proposals fall into two general categories: detectors designed to look at the distribution of hadrons radiated off the surface of a quark-gluon plasma, and those seeking to probe the interior of the plasma by looking at emerging leptons and gammas. It's difficult to do both these things well with the same detector.

The most ambitious hadron-detector schemes propose to cover a large solid angle around the collision point, to see how the emerging hadrons are distributed over the central phase

space. They would follow all the tracks out to considerable distances in order to measure momenta accurately and distinguish between pions, kaons, protons, antiprotons and hyperons. These various hadrons are thought to radiate from the surface of the thermalized plasma when it has expanded and cooled sufficiently for the quarks to revert to their wonted confinement. A large time-projection chamber, with its excellent tracking and ionization-measuring capabilities, would appear to be the instrument of choice.

But if one wants a glimpse deep inside the plasma before the hadrons begin to "freeze out," one must look for lepton pairs (e^+e^- or $\mu^+\mu^-$) or gammas. Unlike hadrons, these deep probes can make their way out of the cauldron relatively unscathed. It's a bit like using solar neutrinos to study the interior of the Sun. Lepton detectors must distinguish between prompt leptons direct from the collision and the much larger background of hadrons and secondary leptons from hadron decay.

so inclined, signatures of an abrupt phase transition.

When a quark-gluon plasma cools enough to congeal into hadrons, Lee points out, its entropy density decreases greatly as it loses the degrees of freedom of the unfettered quarks and gluons. "But the second law of thermodynamics won't let the overall entropy decrease," he reminded us. Therefore the hadronization of the cooling plasma must be accompanied by an expansion such that the product of the entropy density and the volume will have increased despite the loss of all those degrees of freedom. The diameter transverse to the beam axis might expand to 30 or 40 fermis.

How can one measure the size of the plasma? One borrows a trick from the astronomers. In the 1950s Robert Hanbury Brown (University of Manchester) and Richard Twiss (University of Sydney) developed a new interferometric method for measuring the angular diameters of stars. Photons, being bosons, tend to be positively correlated in phase space. The two-particle correlation function peaks when the momentum difference Δp between two photons goes to zero. Hanbury Brown and Twiss pointed out that the rate at which the correlation vanishes with increasing Δp is a measure of the source size. The smaller the source, the larger is the Δp at which one still sees correlation.

Pions, also being bosons, have the same clustering tendency. The idea of using pions to do Hanbury Brown-Twiss interferometry goes back to Gerson and Shulamith Goldhaber, Wonyong Lee and Abraham Pais at Berkeley in 1962. But only with the advent of RHIC will multiplicities be so large that one can make a statisti-

cally significant measurement of the source size in an individual event.

Pion interferometry of a quark-gluon plasma yields the expanded size at which the pions start to freeze out. The transverse diameter of the plasma *before* this expansion is essentially given by the diameters of the incident nuclei. One can also imagine measuring the plasma size before expansion by doing the Fermi-statistics analog of pion interferometry with the much smaller population of leptons. But that is a questionable prospect not contemplated in the first round of detector proposals.

The enormous pion multiplicities will also make it possible to measure accurately the "temperature" of the central region in an individual event from the distribution of momentum components transverse to the beam axis. The higher the temperature, the greater the transverse momenta of the emerging hadrons. The multiplicity itself is a measure of entropy. Therefore one can look for an abrupt phase transition to the quark-gluon plasma by plotting the pion multiplicity of the central region against its temperature.

Some thermodynamic phase transitions are signaled by fluctuations on all scales. One can look for such wild fluctuations by dividing the central phase space into bins of different longitudinal momentum and comparing the multiplicities or energy densities of the different bins in an individual event.

Flavored and massless quarks

The quark-gluon plasma arising out of the excited vacuum should have a higher fraction of "nonvalence quarks" (antiquarks and strange

quarks) than one sees in more mundane collisions between nuclei. The RHIC experimenters will therefore look for an increase in the relative yield of kaons and antihyperons with increasing temperature. Kaons are also expected to freeze out before pions. Therefore a smaller Hanbury Brown-Twiss source size from kaon interferometry would be regarded as evidence for the quark-gluon plasma.

QCD predicts that the onset of the quark-gluon plasma closely coincide with another phase transition: the restoration of "chiral symmetry," which, in effect, renders the quarks massless. A signal of the onset of this restored symmetry would be changes in the masses and widths of various common meson resonances such as the ρ and ϕ , which are seen as peaks in the invariant-mass distributions of lepton and kaon pairs emerging from the nuclear collisions.

Further up the invariant-mass spectrum of lepton pairs one comes to exotic-quark resonances like the famous J/ψ bound state of the charmed quark and its antiquark. Theorists expect that the production of such mesons will be noticeably suppressed by screening effects in a quark-gluon plasma. Some evidence of J/ψ suppression was already seen in the CERN heavy-ion runs. But this preview of coming attractions is no longer thought to have been a glimmering of the quark-gluon plasma. These CERN data seem to have a more mundane explanation.

"Perhaps more important than all these things the theorists are telling us to expect," says Ozaki, "is the search for the totally unexpected in this *terra incognita*."

—BERTRAM SCHWARZSCHILD

INTERNATIONAL TEAM EXAMINES HEALTH IN ZONES CONTAMINATED BY CHERNOBYL

Glasnost notwithstanding, the Soviet Union has faced a credibility gap regarding its public pronouncements about the health effects from the explosion of a nuclear reactor at the Chernobyl atomic power station in 1986. While rumors have abounded in the affected republics of excess cancers or thyroid abnormalities, the central government has not found any clear evidence for maladies attributable to the accident. (See *PHYSICS TODAY*, July 1990, page 62.) In October 1989, the Soviets asked the International Atomic Energy Agency to review government assessments of the radiological and health situation

in the areas affected by the accident and to evaluate measures to protect the population. The resulting report, released at the end of May, largely validates the Soviet assessments to date. The study team did not find any significant health abnormalities that might be associated with radiological exposures except for high levels of stress and anxiety caused by concern over the radiation. Because of the limited scope of the study and the long latency period of cancers, the team could not determine whether there are any excess cancers in the populations examined. The report contains some recommendations for improve-

ments in the ongoing assessments.

Limitations

The study launched in response to the Soviet request, called the International Chernobyl Project, eventually involved six agencies besides the IAEA and enlisted the help of 200 experts from 25 countries. The project sponsored 50 missions to the USSR between March 1990 and January 1991. Substantial though this effort was, it was not sufficient to evaluate comprehensively an accident of the scale of Chernobyl. Constrained by the limited time that the experts could devote to the job and