OAK RIDGE
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PHYSICS
DIVISION
PREPRINT

July 1991

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— *Invited Paper* —

*Fourth International Conference on Nucleus-Nucleus Collisions
Kanazawa, Japan, June 10-14, 1991*

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CONF-9106158--5

DE91 016220

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Physics and experiments at RHIC

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The Relativistic Heavy-Ion Collider (RHIC), presently under construction at Brookhaven National Laboratory in the U.S.A., will be the first colliding-beams machine designed expressly for the purpose of colliding heavy ions. It will be capable of colliding any two stable nuclear species at center-of-mass energies of up to 100 GeV/u on 100 GeV/u for the heaviest nuclei. It is being built for the express purpose of producing and studying a new state of strongly interacting matter, the so-called Quark-Gluon Plasma (QGP), which is predicted to be created in heavy-ion collisions at sufficiently high energy. I find it interesting to be asked to cover at this conference the various physics topics that first-round physics experiments will address, since it was at the first conference in this series (at Michigan State University in October, 1982), that my interest in actually studying such collisions experimentally, as opposed to just following the field in the literature, was sparked by a talk there by Miklos Gyulassy. At the time, Miklos had to content himself with regaling us with tales of interesting cosmic-ray events. RHIC will change all that.

A diagram of RHIC on the BNL site is shown in Figure 1. Protons are accelerated by the existing Linac to 200 MeV, and heavy-ions are accelerated by the existing Tandem Van de Graaffs to 1-3 MeV/u. Protons and/or heavy ions are then transferred to the newly constructed Booster Ring where they are bunched and accelerated prior to injection into the AGS. ¹⁹⁷Au ions leave the booster at 35 MeV/u and are stripped at the exit to $q = 77^+$. The particles are then transferred to the AGS ring and accelerated further for injection into RHIC; for example, gold ions leave the AGS at 10 GeV/u and are fully stripped at that point with nearly 100% efficiency. The particles are next transferred, maintaining their RF structure, through one of the two injection arcs and into one of the two rings of RHIC. Subsequent bunches are placed synchronously around the circumference (so-called "boxcar" stacking) until some 57 bunches are loaded into each ring. The magnetic field in RHIC itself is then ramped up and the particles are accelerated to their desired collision energy, which may range up to 100×100 GeV/u for Au ions and up to 250×250 GeV for protons. The beams are brought into collision; physics measurements ensue; and the process is repeated after the luminosity decays sufficiently, roughly 10 hours after filling.

* Managed by Martin Marietta Energy Systems, Inc., under contract DE-AC04-84OR21400 with the U.S. Department of Energy

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Figure 1. Layout of RHIC on BNL site.

RHIC is a colliding-beams machine designed to collide any two ions which can be made into beams, meaning collisions from $p - p$ to $Au - Au$ and including $p - Au$ can be realized. A key parameter of a collider is its luminosity, a quantity which,

when multiplied by the cross section of interest, gives the event rate. The luminosity for RHIC as a function of beam species and collision energy is shown in Figure 2, which also shows the number of central collisions per second (the ones most likely to create an observable QGP) on the right-hand ordinate. Tens to hundreds of central collisions/second are obtained even for the heaviest beams. The fact that RHIC is a colliding-beams machine also means it attains much higher center-of-mass energies than the present fixed-target experiments enjoy. This leads to much larger phase-space densities of produced particles and transverse energy, which should signal high energy densities. This large c.m. energy also yields a baryon-free zone of some 2-4 units extent at midrapidity, where one is free of the net baryon content of the beams (although the cautious experimentalist should take note of the talk by H. Stöcker in these Proceedings.) It is argued that such a region should be most easily amenable to theoretical description, as there is no net quark content.

Figure 2. Luminosity of RHIC vs. beam species, collision energy.

The purpose of RHIC is to produce in the laboratory a new (at least, new to physicists if not new to the Universe) state of strongly interacting matter consisting of "deconfined" quarks and gluons and often called a quark-gluon plasma. In such a plasma the color charge of the quarks in one hadron is no longer screened from that of quarks in other hadrons. The color-charged objects are crowded together as the hadron volumes overlap until they "forget" about the existence of a confining bag and become free to propagate over extended regions of space-time. RHIC provides the source of energy and strongly interacting matter; because one wants large space-time volumes populated, very heavy nuclei at very high energies are needed. The use of heavy nuclei also helps ensure that as much of the initial energy is "degraded" from the

initial motion as possible and that multiple collisions of the entrance channel partons take place. It also helps ensure that secondaries cannot escape easily by providing a small surface/volume ratio. Essential differences thus exist with low-energy heavy-ion collisions: created particles dominate the final state (circa 12000 created pions in central Au-Au collisions at 100x100 GeV/u, compared to 394 incident baryons); p_T is created due to string tension as created particles form, which is essential if the created particles themselves are to reinteract; and sufficiently high energy densities are created that a long proper time (circa 60 fm/c) must elapse before the system "cools" enough to relax back into hadronic modes.

After the ions pass through one another, a large gluonic number density ("string content") exists, not unlike the case for a high number density of photons (electric field). The quarks, antiquarks, and gluons are free to move over a large volume and will collide with one another, creating jets, photons and lepton pairs. The rate of such collisions and the energy of the final products reflect the temperature of the system and number densities in phase space of the objects undergoing collisions. While the amplitudes for these processes may be written down in perturbative QCD in the case of several GeV/c momentum transfers, rate calculations in the case of a plasma with a temperature of some 200 MeV are made difficult by the relatively low momentum transfer of most of these collisions and the to-be-elucidated phase-space densities of the collision partners (that is one of the things the experiments are trying to measure, after all).

After some proper time, the system has expanded and cooled sufficiently that deconfinement is "over." Hadrons are created at this time, meaning they carry information on the size and chemical composition of the system from that proper time. A very high temperature should manifest itself in a large system at hadronization, for example. It would be interesting to know if any information on critical fluctuations expected at a phase transition will be preserved through the hadronization transition.

One is then led to form a list of deceptively simple questions to ask about the matter which will be created at RHIC:

1. Is it deconfined?
2. How hot is it?
3. How big is it?
4. What is it made of? What is its flavor content?
5. Is it equilibrated?
6. Are the quarks still massive?
7. Is there a region of net baryon content?
8. Do interesting new objects get assembled?

Before listing the proposals, it is useful to recall the principal experimental issue for RHIC. The center-of-mass energy per particle is on familiar ground (viz. the Sp $\bar{p}$ S and Tevatron-I), the energies of the secondaries are in line with those from other colliders and, in fact, rather low compared with those in fixed-target experiments; and the collision rate (some 5-10 MHz beam-crossing rate) is familiar to any nuclear physicist who has worked at a cyclotron or tandem. The key issue is rather the multiplicity of secondary particles: in a central Au-Au collision at 100×100 GeV/u, 12,000-20,000 or more particles may be produced with rapidity densities dN/dy of 1000 or more. If this is translated into a number of particles per unit solid angle, and if one asks for a

1 cm² area to have only a 1% chance of being hit in a given event, then such a detector element has to be placed at 1.3 meters at 90° ($y = 0$), 1.9 m at 40.4° ($y = 1$), 4.8 m at 15.4° ($y = 2$), 12.7 m at 5.7° ($y = 3$), and a whopping 34.5 m at 2.1° ($y = 4$). (Recall that a 100 GeV/u beam has $y = 5.5$!) Thus without cleverness or concentration on a given kinematical region, a detector could grow quite unwieldy.

The following Letters of Intent were received by Brookhaven National Laboratory in October 1990. They are listed in the order received.

- RLOI-1 $p - p$ Total Cross Sections
- RLOI-2 Two-Arm Lepton/Photon/Hadron Spectrometer (TALES)
- RLOI-3 Dipole Time Projection Chamber (D-TPC)
- RLOI-4 Dimuon/Photon Spectrometer (DMS)
- RLOI-5 Solenoidal Time Projection Chamber (STAR)
- RLOI-6 Modular Apparatus for RHIC Spectra (MARS)
- RLOI-7 Open Axially-Symmetric Ion Spectrometer (OASIS)
- RLOI-8 Forward Angle Hadron Spectrometer (FAS)
- RLOI-9 High- p_T Photons and EM Jets (SPARHC)

Before proceeding with descriptions of these, a disclaimer must be made. As this is being written, all proposals are being updated. Several are in a state of flux, with redesigns, enhancements, cost-cutting measures, mergers between/among groups, and the like, all being pursued actively. Updated Letters-of-Intent are due at Brookhaven in July 1991 with proposals to follow in March 1992.

There are at least three suggestions on the market for looking for deconfined matter. One is to take advantage of the fact that a QGP will exhibit the color-charge analog of a Debye-screening radius and thus tend to block the formation of certain objects, particularly heavy vector mesons such as the J/ψ and ψ' , which have radii larger than the screening radius [Ma86]. This has become known as J/ψ "suppression." One looks for large objects, such as the ψ' ($r = 0.56$ fm), to disappear first, followed by the J/ψ ($r = 0.29$ fm) or the Υ' ($r = 0.30$ fm), as collisions with successively higher transverse energy production per unit volume, and thus presumably higher temperature, are selected. In contrast, the small Υ ($r = 0.13$ fm) is expected to be too small to be screened and thus acts as a control. Vector meson cross sections would be measured by the DMS, OASIS, TALES, and SPARHC proposals. The Dimuon/Photon Spectrometer, which includes a large-acceptance muon spectrometer for detecting vector mesons by their leptonic decay branches, is shown in Figure 3. The muon spectrometer part of this relies on a low- Z inner absorber to remove most hadrons, followed by a toroidal tracking spectrometer and an active muon-identifier to tag muon candidates.

A second suggestion [Gy90] is to look for energy-loss of high- p_T jets as they propagate through matter. Jets are made in the initial stage of the collision and thus have to propagate through whatever matter is created during the collision, so they act as a built-in probe. The energy loss for a jet traversing a QGP should be markedly larger than for one traversing a hadron gas, attaining 3–5 GeV/fm in a plasma, leading to measurable changes in jet spectra and in jet-jet energy and angle correlations. The STAR and OASIS proposals would be able to address this.

A third suggestion is to look at spectra of charmed mesons [Sv89]. Charmed quarks are heavy and thus tend to be created only in the initial stage of the collision. As is the

Figure 3. Dimuon/Photon Spectrometer.

case for jets, they then must propagate out through the matter created in the collision. They are strongly degraded in energy if they have to traverse boundaries between QGP and HG regions, which should result in a marked softening of the spectrum for charmed mesons (such as D 's) from a QGP, as compared to that seen in $p-p$ collisions. Detection of D 's is formidable in a heavy-ion collider.

The energy density, or temperature, of a deconfined phase could be determined by measuring spectra of lepton pairs or photons resulting from scatterings between the quarks, antiquarks, and gluons present [Ka86]. There are two basic classes of processes: quark-antiquark annihilation, which leads to a lepton pair or a photon+gluon in the final state (or two soft jets), and "Compton" scattering of a gluon from a quark (antiquark), leading to a photon plus quark (antiquark) final state. The lepton pair signature may be somewhat "cleaner," but suffers from two powers of the fine structure constant in the cross section; whereas, the cases leading to photons + gluons or quarks (either of which fragment into a jet in the final state) have larger cross sections because they have one vertex in the Feynman diagram which, instead, brings in a power of the strong coupling constant. However, detection of photons is complicated due to the large background of decay photons from hadrons such as π^0 , η , and η' . The TALES, DMS, OASIS, and SPARHC proposals would address this physics. The TALES detector, which includes two arms for precise $e^\pm$ and photon detection, is shown in Figure 4.

Figure 4. TALEs Detector.

look at like-particle correlations in momentum space. The system sizes expected at RHIC range up to 60 fm. It has been suggested by Cramer to consider looking at 3-pion and 4-pion correlations as an alternative way of examining this issue. It has also been suggested [Pr86, Be88, Ru88] to examine like-particle correlations as a function of the relative orientation of the relative-momentum vector and total momentum vector of the pair. A long proper time to hadronize would be reflected in a specific elongation of the apparent source along the "outward" axis. The STAR, D-TPC, OASIS, and MARS proposals would address this issue. The OASIS detector, which includes a long flight path and open-field geometry to allow precise momentum measurements and particle identification over a large area, is shown in Figure 5. It includes a TRD for e^+e^- tagging and tracking, Cerenkov and TOF cells for particle ID, and a liquid-argon

It incorporates Cerenkov counters for e^+e^- tagging, followed by a magnetic spectrometer and an EM calorimeter.

The quark flavor content can be studied by measuring cross sections for production of hadrons carrying other than up and down quarks and/or antiquarks. The strange quark mass is of the order of the expected critical temperature for QGP formation. Thus, strange and anti-strange quarks are expected to be produced copiously in a plasma [Ra82, Sh85]. In a deconfined or mixed phase, their production is further favored because of their near-absence in the initial state, which has only up and down valence quarks (i.e., no Pauli-blocking). It is, thus, of interest to measure cross sections for hadrons (mesons and hyperons) carrying strangeness and anti-strangeness, particularly those with multiple s or $\bar{s}$ quarks. For example, it would be interesting to compare the production rates of anti-Cascades, anti- Λ 's and antiprotons, with the latter serving as a "normalization," being an object not present in the entrance channel but also not carrying strange (anti-strange, actually) quarks. The STAR, D-TPC, OASIS, TALES, MARS, DMS, and SPARHC proposals all would address various aspects of this physics.

The prevalent suggestion for measuring the size of the system produced is to

calorimeter for electromagnetic calorimetry and jet detection via detection of leading particles.

Figure 5. OASIS Detector

It is a difficult matter to establish if a system is equilibrated. There are several suggestions for observables. These include equal p_T slopes of different hadrons and isotropic angular distributions of thermal lepton pairs [Ho87]. Hadron spectra necessarily give information about conditions at hadronization. However, the entire collision process may well be highly nonequilibrium, with there being only sufficient proper time to equilibrate if a QGP is formed and then has a long time to revert to hadrons. If only a hadron gas is formed, it is quite likely to be highly nonequilibrated, so observing hadrons might give an experimentalist a handle on this issue. One wants to measure hadron spectra on an event-by-event basis if possible so that averaging over events does not confuse things. Both TPC proposals, STAR and D-TPC, would exploit their large acceptance for hadrons to do this. The STAR detector, which includes a large TPC immersed in a solenoidal magnetic field, as well as external calorimetry to pursue

jet measurements as mentioned above, is shown in Figure 6. It accomplishes particle identification via multiple dE/dx measurements in the TPC coupled with TOF from a barrel just outside the TPC.

Figure 6. STAR Detector.

It has been suggested that masses of quarks (and perhaps hadrons also) may shift down markedly if a QGP is formed or if chiral symmetry is restored. The suggestions for observing this, to date, deal with looking for mass shifts and width increases for the lighter vector mesons, particularly the ρ , ω , and ϕ [Pi82]. The ω is very narrow and perched on top of the broad ρ resonance, so it will only be visible in e^+e^- spectra. The OASIS and TALES groups have proposed looking at all of these mesons at midrapidity, and the DMS group has proposed observing the ϕ over several units of rapidity using a combination of techniques.

The baryon-rich region at rapidities near the beam rapidity should be a good place to look for unusual objects heralding QGP formation. These include antinuclei and strange-matter objects which have a much larger strange-quark content than is the norm for nuclei. This is also the region in phase-space where measurements of baryon

distributions need to be made in order to test our ideas of how excitation energy transfers in such reactions (i.e., is the Lund string picture correct, or should we expect to find baryons spread over a very wide range in rapidity, as discussed by H. Stöcker in these Proceedings?). A specialized spectrometer to make measurements at forward rapidities has been proposed by the Forward Angle Hadron Spectrometer Group. This consists of a quite long (some 28 meters) spectrometer, shown in Figure 7, which includes small TPCs for tracking and pattern recognition in the densely populated environment near the beam direction. The spectrometer has two sections, one following the other and both having a pair of dipoles, tracking chambers, Cerenkov counters, and TOF walls. Both of these come into play at the most forward-angles. Larger angles can be studied by using only the first of these.

Figure 7. Forward Angle Spectrometer.

The initial round of proposals for RHIC is thus aimed at investigating questions of deconfinement, temperature, size, flavor content, equilibration, chiral symmetry restoration, and final state chemistry. The nine letters of intent have over 350 signatories. The RHIC project began in FY 1991 with \$15M in funding and is expected to receive \$45M in construction funding in FY 1992. A call for proposals will be issued in the fall of 1991 with decisions expected by early summer of 1992 and colliding beams expected by 1996/97. It should be an interesting time.

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