CONF-950802--7

PHYSICS AND EXPERIMENTS AT RHIC

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— *Invited Paper* —
International Nuclear Physics Conference (INPC'95)
Beijing, China
August 21-26, 1995

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The Relativistic Heavy Ion Collider (RHIC), under construction at Brookhaven National Laboratory, will be the site of a series of experiments seeking to discover the quark-gluon plasma and elucidate its properties. Several observables should exhibit characteristic behaviors if a quark-gluon plasma is indeed created in the laboratory. Four experiments are now under construction for RHIC to measure certain of these observables over kinematic ranges where effects due to quark-gluon plasma formation should be manifest.

1 Introduction and Historical Background

The quark-gluon plasma (QGP) is a state of matter formed of "deconfined" quarks and gluons.[1] It is conjectured, in Big Bang cosmology, to have existed briefly during the end of the first microsecond of the universe's existence and to have been one in a natural progression of steps wherein the universe cooled from its initial singularity to its present state. The quark-gluon plasma is the state existing just before the universe cools to the point that hadrons (e.g., nucleons, hyperons, mesons, and such) are more likely to survive after formation than to be destroyed in a succeeding violent collision. The state consisting of free quarks and gluons is sufficiently different from the state consisting of a heated assemblage, or gas, of hadrons that the language of phase transitions is appropriate to describe the transition from one to the other. An expanding and thus cooling system will eventually enter the hadron phase (and upon further cooling, enter phases where nuclei, then atoms, then people, and even conference talks can exist, but that is beyond the scope of this talk). Thus it seems possible intuitively that if we could somehow heat nuclei sufficiently, we could reverse this QGP to hadron phase transition of so long ago, if only over a small space-time volume, and produce laboratory samples of quark-gluon plasma for further intensive study.

The favored field theory of the strong interactions, Quantum Chromodynamics, (QCD),[2] postulates that quarks carry a color charge and that interactions among quarks are mediated by an octet of colored field quanta known as gluons. In contrast to the situation in quantum electrodynamics wherein the field quanta themselves are not charged, the gluons do carry a charge and thus interact at first-order in the theory. Hadrons are postulated to be color singlet states formed either of a triplet of colored quarks (qqq), which are the baryons, or by a quark-antiquark doublet ($q\overline{q}$), which are the mesons. Confinement inside hadrons is evidently a property of colored quarks whose interactions are mediated by an octet of colored gluons. The vacuum state of QCD is a condensate of $q\overline{q}$ pairs and gluon pairs[3] which acts as a color dia-electric, confining the "field lines" connecting two quarks to a small region of space surrounding the quarks. A counterbalancing pressure is created at the boundary of this small "bag" containing the quarks; the pressure is related to the bag constant $B^{1/4} = 206\ \mathrm{MeV}/(\hbar c)^{3/4}$. This behavior is the dual of the behavior observed for a superconductor immersed in an external magnetic field (Meissner effect): in that case, the superconductor is a condensate of electron pairs, is perfectly dia-magnetic, and expels the magnetic flux lines outward from its volume.

Perturbative solutions for QCD in the high-energy limit have been known for some time, being developed since the discovery that QCD is asymptotically free was made in 1973 by Politzer[4] and by Gross and Wilczek.[5] The theory is more difficult to handle in the low-energy limit applicable to static properties of hadrons and properties of the quark-gluon plasma, in part because the strong-coupling constant is not small compared to one at such small momentum-transfer scales. Fortunately, studies of behavior of the theory on a lattice, using the techniques pioneered by Wilson, progressed to the point by the early 1980s that one could make confident predictions of the energy density, or temperature, that had to be reached for a system comprised solely of gluons to become deconfined. These studies more recently can treat systems with two or three flavors of quark as well as gluons on a lattice, which now allows refinement of the estimates of transition temperature and leads to an understanding of whether a phase transition from a hadronic to a quark-gluon plasma might be first or second order.

A novel method of developing solutions to theories such as QCD in the low-energy limit was developed by Wilson[6] in the 1970s and consists of developing solutions upon a discrete mesh of space–time points. Iterative methods can be used to converge to a stable solution for a given set of conditions. This is also quite useful in addressing problems such as behavior at high temperature using field-theoretic methods to map temperature onto the "time" dimension. An advantage of this "lattice" method is that solutions at varying densities of particles can be studied and values of, for example, correlation functions can be determined.

Such lattice gauge methods applied to a pure gluon theory gave the first encouraging indications that a deconfinement phase transition from hadronic matter to a quark-gluon plasma could be observed. These calculations led to estimates of the required energy densities, of order 1.5–2.5 $\mathrm{GeV/fm^3}$, to achieve deconfinement, what the latent heat of a first-order transition might be ($\sim 1\ \mathrm{GeV/fm^3}$), and led to the first ideas on what observables might be affected by such a transition. A gluon gas

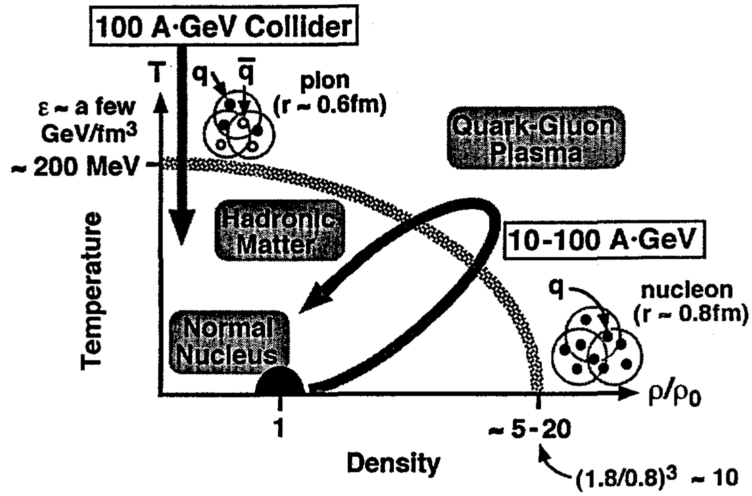

Figure 1: Phase diagram of nuclear matter and nuclear collisions (figure courtesy of S. Nagamiya).

follows a Stefan–Boltzman law, meaning energy density scales as the fourth power of temperature. These results led, when coupled with information from experiments as noted below, to the realization that the deconfinement transition might well be observable in experiments at high-energy heavy-ion colliders which could actually be built. Thermodynamic considerations of what happens to such a system at finite baryon chemical potential, and thus at finite baryon number density, then allow one to construct a phase diagram of nuclear matter as shown in Figure 1.

The estimated temperature at which such a transition occurs is in the range of 150–200 MeV. Temperatures of such magnitude, while not achieved in any naturally occurring process in the present-day universe, are, in fact, not more than a factor of two higher than those known from experimental work in the 1970s at the ISR studying *pp* collisions at center-of-mass energies up to 60 GeV and at the Bevalac studying heavy-ion collisions at center-of-mass energies of 1–2 GeV/nucleon. Hagedorn suggested from thermodynamic arguments that 160 MeV represented a limiting temperature achievable in a hadronic system; creation of any higher energy density just results in creation and "boiling off" of pions, which then reduce the temperature back below the limit.

Extrapolation from these existing bodies of *pp* and *AA* collision data then indicated that heavy-ion collisions between nuclei of mass 200 at center-of-mass energies of somewhere from 10–100 GeV/nucleon should create energy densities high enough for deconfinement to occur. Much of the energy density produced in the collision comes in the form of produced particles, which severely crowd one another just by their presence. (If the created particles were hadrons, their individual confinement volumes overlap almost completely in such collisions, making a description in terms of hadrons seem unplausible — to which hadron does any given quark or gluon "belong"?) Higher center-of-mass collision energies help increase the total "rapidity gap" between the baryons in two incoming nuclei, a consideration which gained considerably in importance after Busza and Goldhaber's[7] analysis of the nuclear stopping of 100-GeV protons by a lead nucleus showed that there is a long, lower-rapidity tail of slowed baryons extending some two units down from the rapidity of the incoming baryon. These "slowed" baryons might well obscure the midrapidity region where a plasma of zero net baryon number is most likely to be created. This "baryon-free" central region is most likely to lend itself to tractable theoretical description. Thus it was argued that a collider for heavy-ions should produce high enough energies to make this clean central region possible.

The above consideraions then led in 1983 to the choice of scale for RHIC, the Relativistic Heavy Ion Collider now under construction at Brookhaven National Laboratory, as being 100 GeV/nucleon + 100 GeV/nucleon. This center-of-mass energy corresponds to a rapidity separation of the colliding partners of 11 units, allowing for a central region of 2 or 3 units extent, and is estimated to produce energy densities of at least 5–10 GeV/fm^3, well above those needed for deconfinement.

2 The Relativistic Heavy Ion Collider at BNL

RHIC[8] is a colliding-beams machine being constructed on the BNL site just north of the existing Alternating Gradient Synchrotron (AGS) complex's north neutrino area, as shown in Figure 2. It consists principally of two independent, six-sided, intertwined rings of superconducting magnets which guide the beams around their orbits and bring them into collision. These rings are installed in the tunnel constructed for the former ISABELLE/CBA project. The magnets will be cooled to liquid helium temperatures using the helium refrigerator built and commissioned for ISABELLE. The magnets' rigidities are such that beams of 100 GeV/nucleon A = 200 nuclei can circulate, which translates into 125 GeV/nucleon for Z/A = 1/2 nuclei and 250 GeV for protons. Luminosities of 2 x $10^{26}/\mathrm{cm}^2/\mathrm{s}$ for ^{197}Au + ^{197}Au collisions and of 1.4 x $10^{31}/\mathrm{cm}^2/\mathrm{s}$ for $p + p$ collisions during early operation are expected.

The beams originate and receive their initial acceleration in the BNL Tandem Van de Graaff accelerator (protons, however, originate in the AGS linac), are then sent to the AGS booster synchrotron ring and subsequently to the AGS itself for acceleration to 11 GeV (for ^{197}Au ions, more for lighter ions) prior to injection onto stable orbits in the RHIC rings. The ions are accelerated to their final collision energies in RHIC, then "squeezed" to increase the luminosity at collision points, and finally allowed to coast and collide for some ten hours before new beams are injected. Improvements have already been identified that should lead eventually to an order of magnitude increase in these luminosities. A joint U.S.–Japan project to accelerate and store polarized protons in RHIC has also recently been funded. The proton polarizations can be longitudinal or transverse, with luminosities of up to 2 x $10^{32}/\mathrm{cm}^2/\mathrm{s}$ expected for polarized proton operation. The orientation of the polarization of the protons in any given bunch in the circulating beam may or may not be reversed from that of the preceding bunch, as desired, for control of systematic errors.

Because RHIC has two independent rings of magnets, collision of unequal species is possible. RHIC is a bunched-beam collider, which does mean that the energy per nucleon, or more precisely the Lorentz γ, of the two beams must be matched so that their collision point does not slowly precess about the rings' circumference. This capability is of great benefit to the program, since a robust program of $p + A$ physics can also be carried out at the same center-of-mass energies as the heavy-ion program. Such physics is of interest in its own right and also provides a baseline of behavior against which any signal of QGP formation should be compared to see if truly new phenomena have been observed or merely extrapolations of familiar ones to more complex collision geometries.

The RHIC project is now past its midway point in construction. It was started in January 1991 and is expected to be completed in March 1999. The tunnel enclosure and service buildings are complete and being fitted out. Over 90% of the major procurements for the collider are under contract. The superconducting magnets are in routine commercial production, by Northrop–Grumman, and have all exceeded field-level, field-quality, and training specifications. The dipoles and quadrupoles are being installed around the ring; in fact, this installation is nearly complete. There have been no failures of magnets nor rejections of magnets. The injection lines from the AGS to RHIC are complete. The needed Au beams have been accelerated in the AGS and will be injected into and carried around one sextant of RHIC during 1996. Tests to date indicate it will be straightforward to achieve the desired goal of 4000 hours per year of colliding-beams operation.

The beams in RHIC will be brought into collision in up to six regions equipped with collision halls to accommodate detectors. Four of these halls were built as part of ISABELLE/CBA and two more built as part of RHIC. There are presently four approved experiments being built to operate at RHIC. They are described in the following sections.

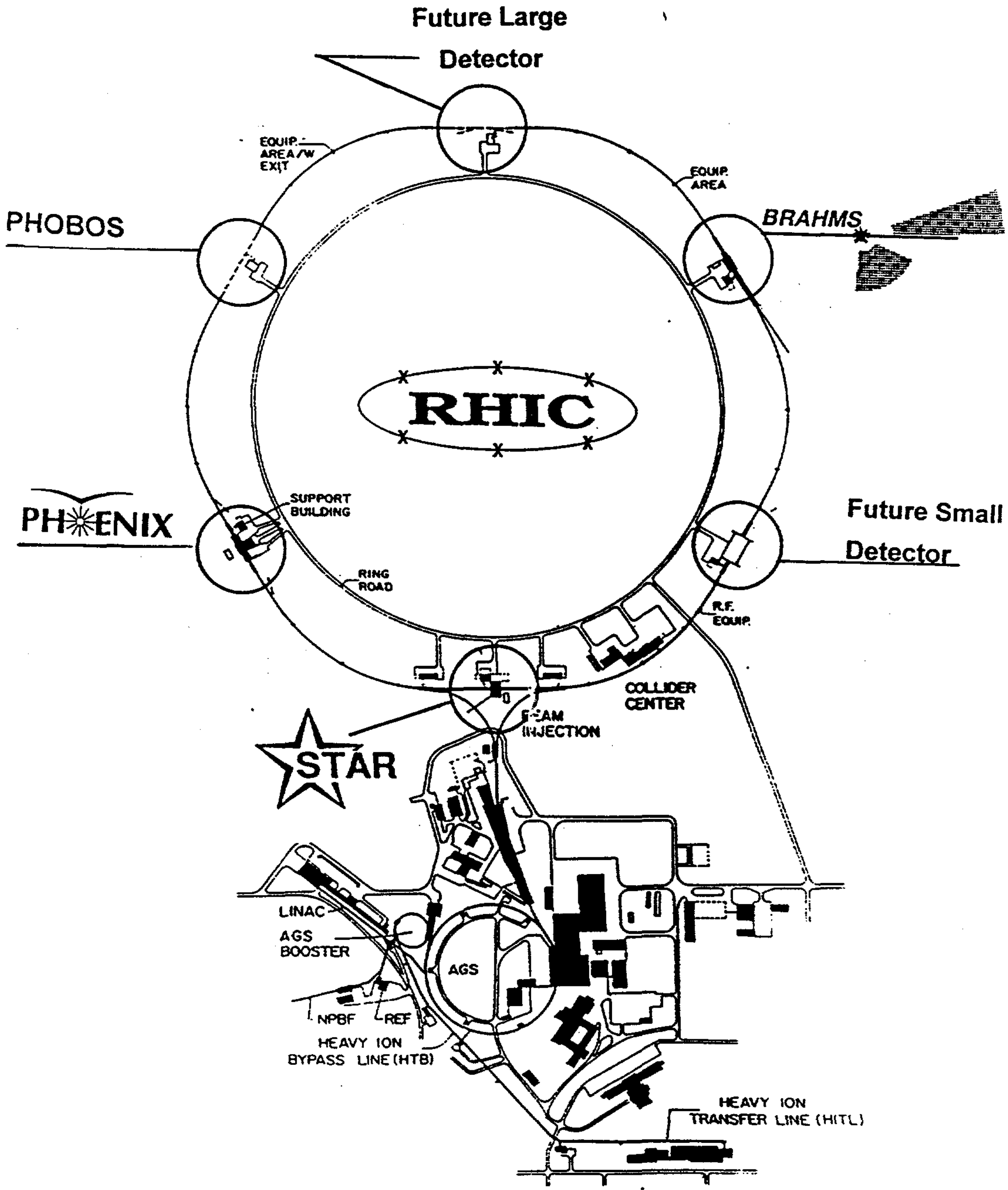

Figure 2: Diagram of RHIC on the BNL site, showing the rings, collision areas, and the Tandem Van de Graaff + AGS complex of injector accelerators.

3 The STAR Experiment

A diagram of the STAR detector[9] is shown in Figure 3. The detector consists of a large time projection chamber (TPC) enclosed in a solenoidal magnet. The TPC provides three-dimensional space points along charged-particles' trajectories. A high degree of segmentation is needed because over 4000 charged particles enter STAR for central Au + Au events. This particular TPC is also instrumented with pulse-height electronics so that a measurement of any given particle's specific ionization can be obtained by an appropriate truncated average of many dozen dE/dx samples taken along its trajectory. Surrounding the TPC are a time-of-flight barrel made up of scintillator slats and an electromagnetic (EM) calorimeter made up of alternating layers of lead and scintillator tiles. The time-of-flight barrel extends in momentum the charged-particle identification power of STAR, and the EM calorimeter measures energy carried by photons, which is likely to be one-third of the total energy emitted around midrapidity. Inside the TPC, surrounding the collision point, is a micro-vertex detector constructed from silicon-drift detectors. This device, coupled with the TPC, provides precise localization of the decay vertices of particles living longer than 10^{-10} seconds, which includes most of the multi-strange hyperons which are a focus of one part of the STAR physics program.

The physics program of STAR concentrates in four main areas. They are:

- Initial conditions achieved in heavy-ion collisions at RHIC. This is addressed by measuring quark and gluon structure functions at the time of the initial collision by means of measuring jet production cross sections and photon-jet correlations. Both of these observables are expected to reflect any modifications to the structure functions during early stages of the collision, when large momentum transfers are still likely. One can also look for any evidence for shadowing of these same structure functions in nuclei, i.e., any in-medium static modification of parton distributions in nuclei due to the presence of all the other quarks and gluons present. This would be studied in $p + A$ collisions.
- Early gluon-dominated plasma. One looks for objects produced by the copious "hot" gluons present early on, preferably objects such as charmed quarks which are difficult to produce later when the system has cooled. STAR will look for mesons carrying open charm, such as D's.
- Quark-gluon plasma. STAR addresses this by looking for evidence of thermalization (measured by looking at triple-differential momentum distributions for single events), for flavor equilibrium among the three light quarks (measured by looking at strange particle production cross sections), for evidence of an order parameter of the phase transition (measured by looking at temperature scaling with particle rapidity density and by looking at triple-differential small-relative-

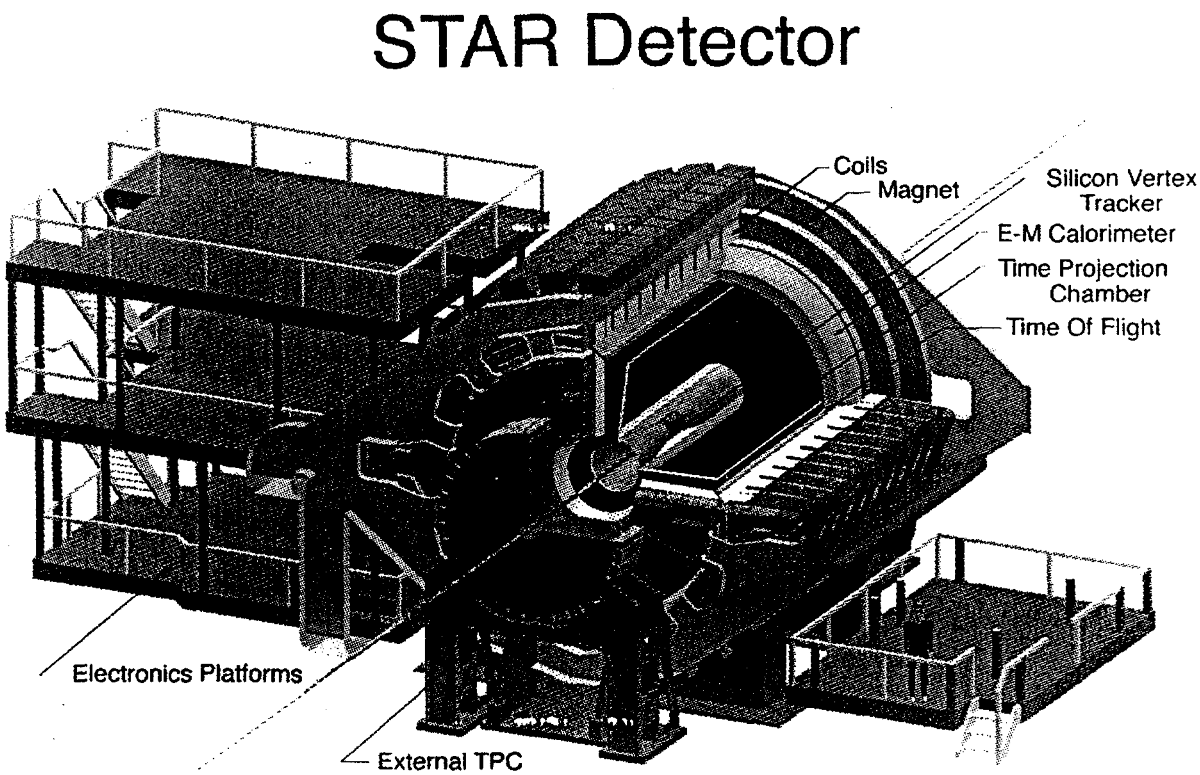

Figure 3: Diagram of the STAR detector under construction for RHIC. The various components are noted in the cutaway view.

momentum correlations), for fluctuation phenomena that might signal critical behavior, and at propagation of and possible attenuation of jets and high-p_T particles as they traverse the system produced.

- Chiral symmetry restoration. One looks for modifications to the masses, widths and branching ratios of particles. Vector mesons are appealing for this because their leptonic branches are not likely to be affected. STAR measures the hadronic decays of the ϕ meson.

4 The PHENIX Experiment

A diagram of the PHENIX detector[10] is shown in Figure 4. The detector consists of two distinct regions — the central arms and the forward arms. The central arms are placed in an axial magnetic field and equipped with precision magnetic spectrometers designed to identify electrons and photons. The particular design also gives excellent identification for hadrons. Tracking is provided by a package of drift chambers for precise momentum resolution, pad chambers for pattern recognition, and a time expansion chamber (i.e., a planar TPC) for pattern recognition at large radius (after the RICH counter) and for specific ionization by means of multiple sampling of dE/dx. Photon detection is provided by a finely-segmented EM calorimeter. Electron identification is provided by rings seen in a ring-imaging Cerenkov counter, electromagnetic shower-shape cuts in the EM calorimeter, time-of-flight measurements by the EM calorimeter and time-of-flight wall, and specific-ionization *vs* momentum cuts from the time expansion chamber. Global event characteristics and vertex finding are provided by a combination of silicon strip and silicon pad counters located near the collision vertex. PHENIX requires a multitude of electron identification methods because the momentum range covered at midrapidity is too wide to be covered by any pair of techniques and because redundant identification is required in the high-multiplicity environment to be encountered at RHIC.

The forward/backward arms of PHENIX are specialized for the detection of muons. Each includes a "piston and lampshade" magnet configuration which causes charged particles to bend in azimuth. The muon spectrometers are equipped with interpolating cathode-strip chambers to obtain space-point resolutions of 100 μ, necessary at forward angles where particle momenta are high. Muon identification is accomplished by requiring particles to penetrate several layers of steel, located downstream of the tracking spectrometer, without showering. Some 99% of the flux of primary hadrons from the collision vertex is removed by requiring all muon candidates to first traverse the yoke steel of the central-region magnet.

A comparison of the rapidity and azimuthal angle coverages for STAR and PHENIX is shown in Figure 5. PHENIX's polar angle range is larger, while STAR covers all azimuth for the central rapidity region, as required by their different physics programs.

The physics program of PHENIX concentrates on the following areas:

- Deconfinement. It is predicted that the presence of a dense assemblage of quarks and gluons will "screen" a quark-antiquark pair trying to create a heavy vector meson, hindering formation of the pair. The resulting degree of "suppression" should depend on the radius of the particular state. PHENIX measures production cross sections of several members of the ψ and Υ families to address this.
- Chiral symmetry restoration. PHENIX measures production of ρ, ω, and ϕ mesons via their e^+e^- decay channel plus that of the ϕ via its K^+K^- decay channel to address this.
- Early gluon-dominated plasma. PHENIX measures charmed meson production by looking for semileptonic decays and taking advantage of the fact that such

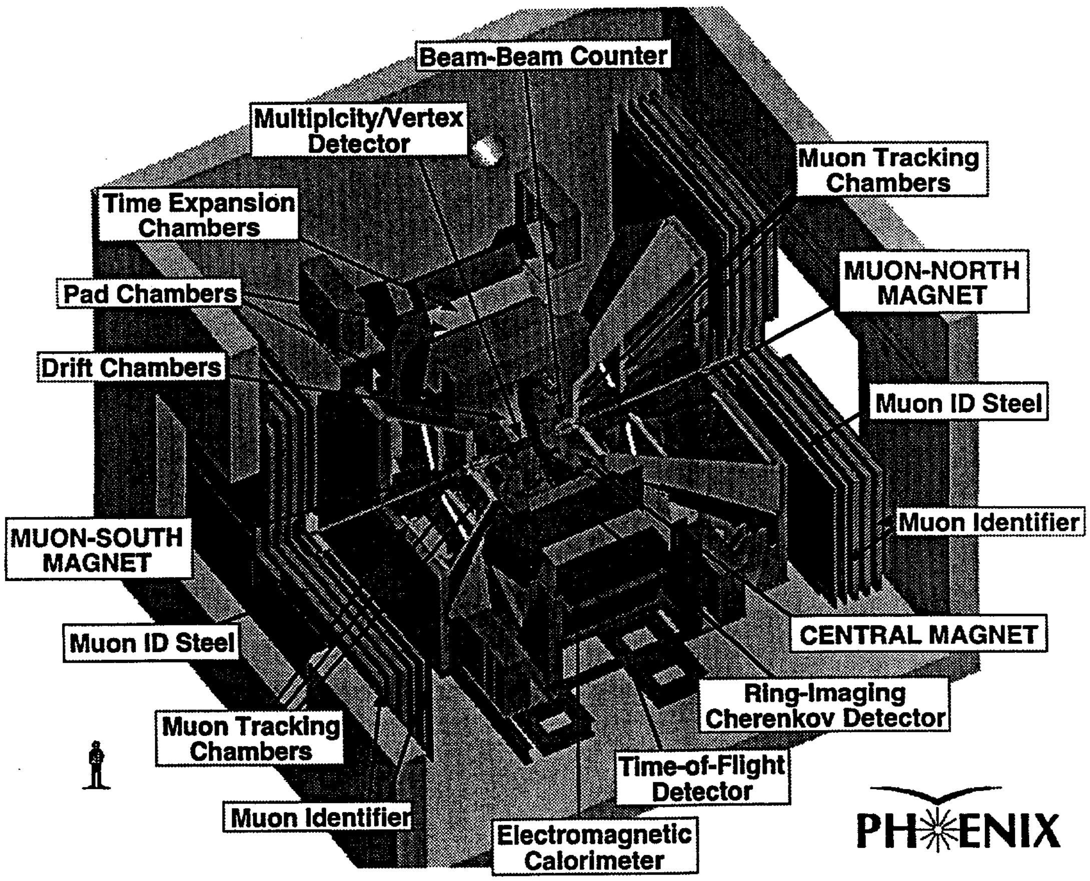

Figure 4: Diagram of the PHENIX detector under construction for RHIC. The various components are noted in the cutaway view.

decays of a D-$\overline{D}$ pair can lead to unlike-flavor lepton pairs, specifically μ-e pairs which can be detected by using both the central and forward arms of PHENIX.

- Radiation from a quark-gluon plasma, from a gluon-dominated plasma, and/or from a hot hadron gas. PHENIX searches for this by measuring the cross section for production of directly-radiated photons as a function of p_T and by simultaneously measuring opposite-sign lepton pairs (e^+e^- and $\mu^+\mu^-$) as a function of pair mass and p_T. Measuring both channels together provides an important check on any model for the production of such radiation.
- Order of any phase transition. This is addressed by means of hadron correlations at small relative momentum using, in particular, the part of PHENIX equipped with the time-of-flight wall. Hadron identification out to in excess of

2.5 GeV/c is employed to see if any signal behaves with p_T as expected for a phase transition.

- Structure functions and spin structure functions in the nucleon and nucleus. PHENIX addresses these by means of a program of $p + A$ physics using its lepton-pair and identified-photon measurement capabilities to measure cross sections for Drell–Yan pairs and direct photon production. Additionally, for polarized proton collisions, PHENIX will measure cross sections for $W^{\pm}$ and Z^0 production via their leptonic decay channels.

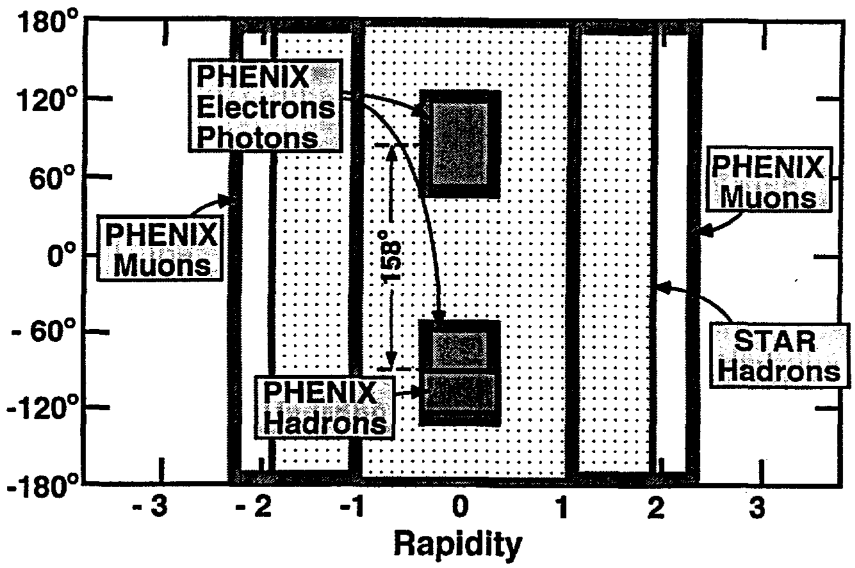

Figure 5: Comparison of the rapidity and azimuthal angle coverages of the STAR and PHENIX experiments.

5 The PHOBOS Experiment

A diagram of the PHOBOS detector[11] is shown in Figure 6. It consists of a precision tracking spectrometer constructed entiredly from silicon microstrip and silicon pad detectors. The spectrometer is immersed in a high magnetic field provided by a pair of superconducting magnets, whose pole tips can be seen in Figure 6. Event characterization is provided by an external set of silicon pad detectors arrayed along the beam line in order to measure the multiplicity of charged particles produced over a wide rapidity range and all azimuthal angles. A time-of-flight wall to identify hadrons and fast trigger counters complete the apparatus.

A diagram of the rapidity and momentum coverage for PHOBOS, delineating regions over which particles are identified, is shown in Figure 7.

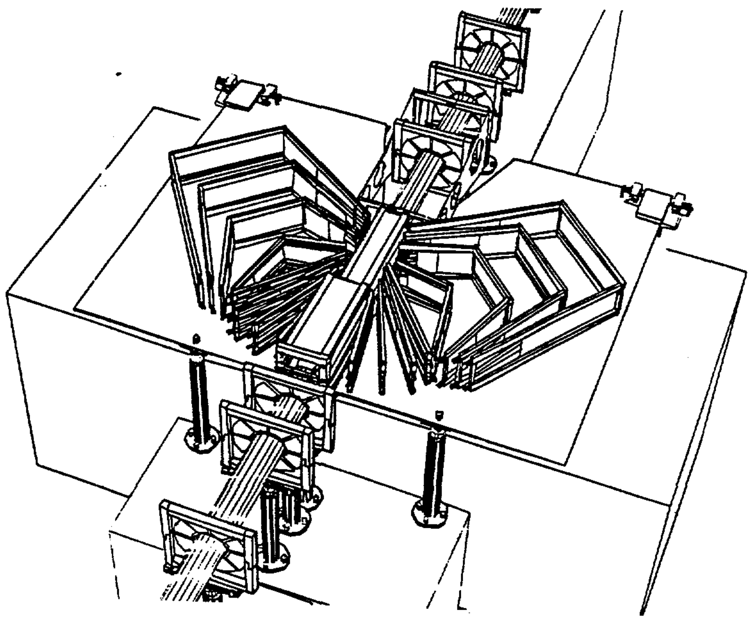

Figure 6: Diagram of central region of the PHOBOS detector under construction for RHIC.

The physics program of PHOBOS concentrates on the following areas:

- Formation of quark-gluon plasma. This is accomplished in part by measuring small-relative-momentum correlations of like particles, and in part by measuring particles at very low transverse momenta where effects from a large emitting zone may be manifest. Measurement of decays such as $\phi \rightarrow K^+K^-$ may also be possible.
- Global event characteristics in 4π. This leads to estimates of the energy density and entropy achieved in the collision and is a method to search for evidence of fluctuation phenomena as expected near a phase boundary. This is accomplished by the full complement of detectors in PHOBOS.

6 The BRAHMS Experiment

A diagram of the BRAHMS detector[12] is shown in Figure 8. BRAHMS includes two small-aperture magnetic spectrometers which may be moved to cover a range of polar angles, and thus rapidities, and which have a complement of particle identification devices for hadron identification. Particle identification is provided by time-of-flight hodoscopes, threshold gas Cerenkov counters, and ring-imaging gas Cerenkov counters. BRAHMS is the only detector at RHIC which will investigate the forward rapidity region, from $\eta = 2$ to $\eta = 4.0$, where one may hope to learn details about

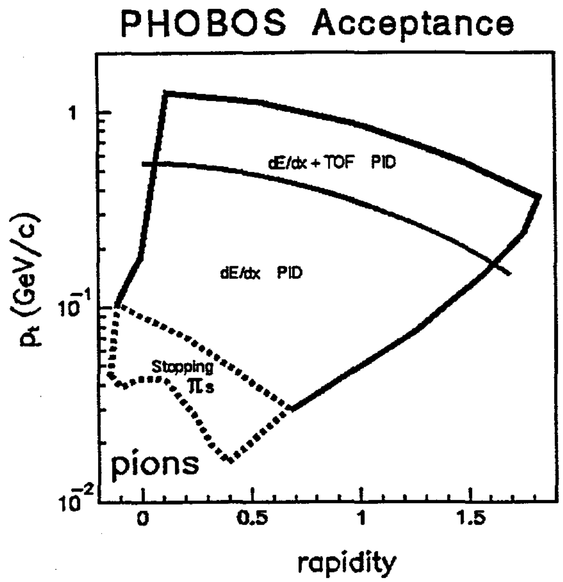

Figure 7: Diagram of coverage of the PHOBOS detector for various identified particles.

baryon stopping at such high energies. Our understanding of the physical mechanism by which baryons are slowed via their collisions with other hadrons is quite incomplete and leads to sharply different predictions of the rapidity distributions of baryons in the final state at RHIC. BRAHMS will also be able to study small-relative-momentum correlations of like particles (pions and kaons) at forward rapidities. This is in contrast to the coverage provided by the other three experiments and should establish the rapidity extent of any emitting source shaped as one might expect for a long-lived phase transition.

Acknowledgments

I am indebted to Tim Hallman for information about STAR, Shoji Nagamiya for information about PHENIX, Mark Baker and Bolek Wyslouch for information about PHOBOS, Flemming Videbaek for information about BRAHMS, and Tom Ludlam for information about RHIC. Oak Ridge National Laboratory is managed by Lockheed Martin Energy Research Corp. for the U.S. Department of Energy under contract number DE-AC05-96OR22464.

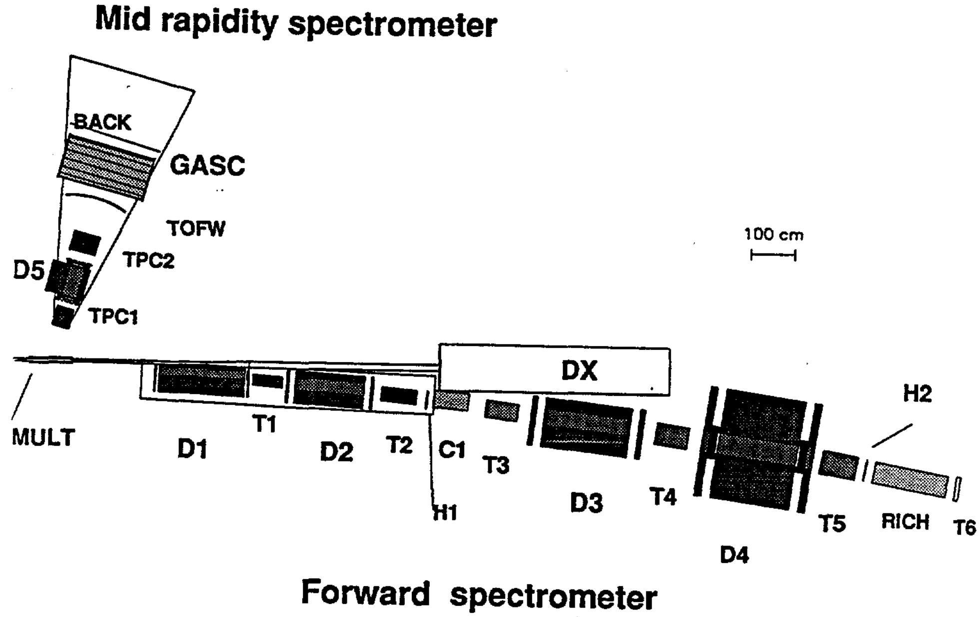

Figure 8: Diagram of the BRAHMS detector under construction for RHIC.

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