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Physics of the STAR Experiment at RHIC

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1 RELATIVISTIC HEAVY ION PHYSICS

The primary motivation for studying relativistic heavy ion collisions is to gain an understanding of the equation of state of nuclear, hadronic and partonic matter, commonly referred to as nuclear matter. This endeavor is of cross-disciplinary interest to nuclear physics, astrophysics, cosmology and particle physics. Displayed in Fig. 1 is a schematic phase diagram of nuclear matter. The behavior of nuclear matter as a function of temperature and density (or pressure), shown in Fig. 1, is governed by its equation of state. Conventional nuclear physics is concerned primarily with the lower left portion of the diagram at low temperatures and near normal nuclear matter density. Here normal nuclei exist and at low excitation a liquid-gas phase transition is expected to occur. This is the focus of experimental studies using low energy heavy ions. At somewhat higher excitation, nucleons are excited into baryonic resonance states, along with accompanying particle production and hadronic resonance formation. In heavy ion collisions, such excitation is expected to create hadronic resonance matter. This region is presently accessible in heavy ion studies at the AGS accelerator facility at Brookhaven National Laboratory and at the SPS accelerator facility at CERN. As seen in the diagram, there is a possibility that some part of these collisions traverse the transition region into the quark-gluon plasma regime. Formation of a quark-gluon plasma, a deconfined state of quarks and gluons,[1] is the major focus of relativistic heavy ion experiments at higher energies. For this purpose the Relativistic Heavy Ion Collider (RHIC)[2] and associated experiments are presently under construction at Brookhaven for operation in 1999, and operation with heavy ions is also being planned for the LHC in 2005. As seen in the phase diagram, the anticipated temperature and density trajectories at RHIC (and for LHC heavy ions) lie close to that of the early universe, while those at the AGS and SPS occur at higher baryon densities.

A quark-hadron phase transition is predicted to have occurred at around ten micro-seconds after the Big Bang when the universe was at a temperature of approximately 150 to 200 MeV. This is the same transition as that from hadronic matter to a quark-gluon plasma, but in the reverse direction by cooling from a higher temperature as depicted in the phase diagram. Also of interest in cosmology is general nucleosynthesis and the long-term effects of the possible existence of fluctuations in the quark-hadron phase transition. The region of high baryon densities and very low temperatures is important for various aspects of stellar evolution. The nuclear matter equation of state governs neutron star collapse and supernova expansion dynamics.

[1] Author list on http://rsgi01.rhic.bnl.gov/star/starlib/doc/www/star.html

Collisions of relativistic heavy ions will allow an investigation of the perturbative vacuum of Quantum Chromo-Dynamics (QCD).[3] In such studies, a better understanding of symmetry breaking mechanisms and the origin of particle masses may be found. The QCD vacuum is predicted to have a complex internal structure, made up of a quark-antiquark condensate sea. This sea possesses energy and mass, and can undergo fluctuations about its zero point. However, isolated quarks are not expected. At low energy densities, quarks and gluons are confined in hadrons (baryons and mesons). Here the vacuum acts as a color dielectric. At the high temperatures anticipated in high energy collisions of heavy ions, the quark-antiquark condensate vacuum is expected to melt. The hadrons dissolve into freely propagating quarks and gluons, and the vacuum becomes a color conductor, or the true perturbative QCD vacuum. This is the quark-gluon plasma (QGP) phase. At such high temperatures another phase transition is predicted to accompany the QGP transition, this is the restoration of chiral symmetry.

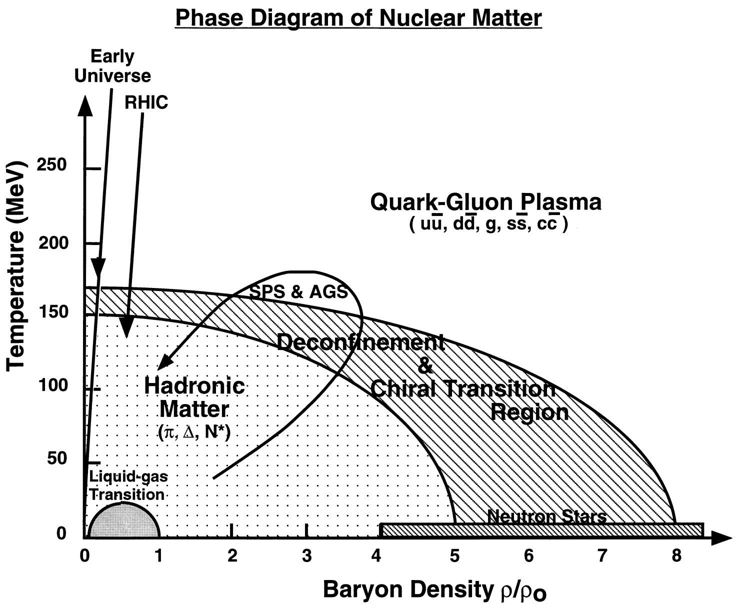

Figure 1: Schematic phase diagram of nuclear matter.

2 THE STAR EXPERIMENT

The STAR (Solenoidal Tracker At RHIC) experiment [4] is in its final year of construction prior to operation at RHIC beginning in June 1999. A schematic layout of the STAR detector systems is shown in Fig. 2. The initial configuration of STAR consists of high resolution tracking detectors, trigger detectors, and partial coverage of electromagnetic calorimetry inside a 0.5 T solenoid. The solenoid provides a uniform magnetic field for tracking, momentum analysis and particle identification via ionization energy loss measurements in the tracking detectors. These measurements will be carried out at mid-rapidity, over a large pseudorapidity range ($\mid \eta \mid< 4$) with full azimuthal coverage ($\Delta(\phi) = 2\pi$) and azimuthal symmetry. The tracking detectors are a silicon vertex tracker (SVT) covering $\mid \eta \mid< 1$, a large time projection chamber (TPC) covering $\mid \eta \mid< 2$, and a forward radial-drift TPC (FTPC) covering $2.5 <\mid \eta \mid< 4$. In addition to the tracking detectors, the electromagnetic calorimeter (EMC) will measure the transverse energy of events, and trigger on and measure high transverse momentum photons, particles and jets. Approximately 10% of the EMC is expected to be ready for initial RHIC operation, with the remainder being constructed and installed over the following three years. A time-of-flight system (TOF) surrounding the TPC to extend particle identification to higher momenta has been proposed for future construction. The following trigger detectors are under construction for STAR: a central trigger barrel (CTB) surrounding the outer cylinder of the TPC for charged-particle multiplicity triggering in the $\mid \eta \mid< 1$ region, a TPC endcap trigger for triggering on charged particle multiplicity over $1 <\mid \eta \mid< 2$, a vertex position detector (VPD) to identify and localize the interaction vertex, and zero-degree calorimeters (at large pseudorapidities, not shown in Fig. 2) for vetoing large impact parameter collisions with a large amount of energy remaining in the forward direction. The electronics, data acquisition and online monitoring systems for these detectors will also be installed.

Various proposals are being considered within STAR for construction and implementation of new detector systems for STAR. A proposal [5] is being considered by STAR for implementation of an additional layer of silicon tracking using a silicon strip detector barrel between the SVT and TPC. This layer would increase the efficiency of STAR tracking and improve its capability for measuring singly and multiply strange baryons. Another proposal [6] to provide level three trigger capabilities for STAR is being considered. Level three triggering would be implemented in STAR for special event selection to increase data rates for specialized triggers after initial running. A third proposal [7] has been made for construction and installation of a photon multiplicity detector. This detector would provide STAR with the ability to measure electromagnetic energy in the forward rapidity region covered by the STAR FTPC, and combined with the FTPC would allow a search for disoriented chiral condensates in this region.

3 STAR PHYSICS OVERVIEW

STAR will search for signatures of QGP formation and investigate the behavior of strongly interacting matter at high energy density in central collisions of relativistic nuclei. The STAR detector system will simultaneously measure many experimental observables to study signatures of the QGP phase transition as well as the space-time evolution of the collision process over a variety of colliding nuclear systems. In addition, STAR will investigate very peripheral

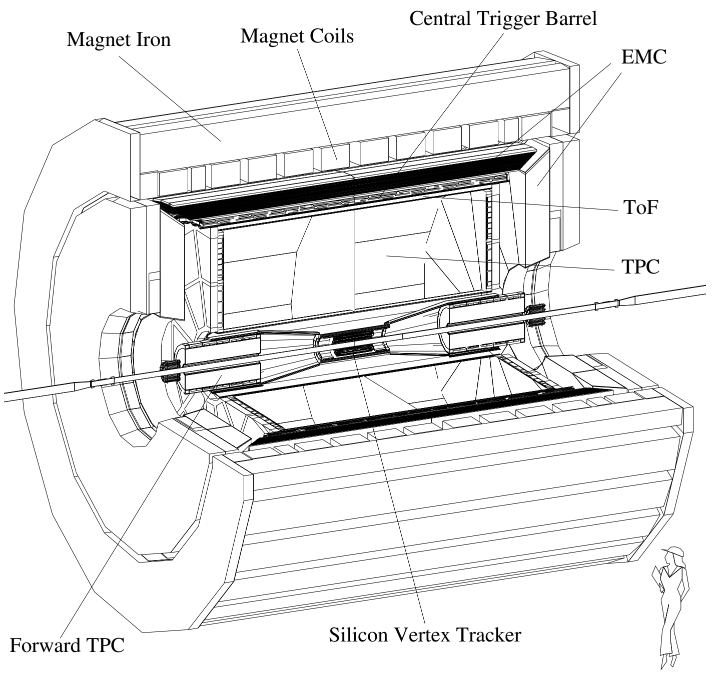

Figure 2: Layout of the STAR experiment at RHIC.

collisions of relativistic nuclei to study photon and pomeron interactions resulting from the intense electromagnetic fields of the colliding ions and colorless strong interactions, respectively. [8] STAR will also have an active program of spin physics studies of the interactions of polarized protons at RHIC. [9]

4 STAR RELATIVISTIC HEAVY ION PHYSICS PROGRAM

4.1 Initial Conditions - Colliding Nuclei

The STAR physics program is outlined in Fig. 3. The three primary categories of physics in STAR (relativistic heavy ion, polarized proton, and photon/pomeron) are listed individually. The physics observables are listed on the left and the quantities measured in STAR are listed on the right. The relativistic heavy ion program is depicted as a function of time during the collision process, with initial collision impact listed at the top with time proceeding downward. The initial conditions will be studied in order to understand the structure functions of the quarks and gluons of the colliding nuclei. This will require 1) measurement of the nuclear structure functions of quarks and gluons in proton-proton interactions at RHIC energies, and 2) measurement of the structure functions of quarks and gluons in proton-nucleus interactions to determine the degree of nuclear shadowing of quarks and gluons at RHIC energies. Each of these studies will involve measurements of the elementary Compton process (gluon + quark $\rightarrow \gamma$ + quark jet) and other jet production processes. This will determine the initial flux of quarks and gluons within the incident nuclei. Such determinations are necessary as input to calculations of the production yields of various processes.

STAR

STAR Physics at RHIC

(* denotes event-by-event measure)

	STAR
Initial Conditions	
Nuclear structure functions / nuclear shadowing (quark and gluon)	γ-jet jets
Early Gluon-dominated Plasma	
Temperature (radiation)	Open Charm?
Quark Gluon Plasma Transition & Mixed Phase	
Thermalization	$d^3\sigma/dp_t d\eta d\phi$ *
Flavor equilibrium	strangeness *
Deconfinement	(J/ψ suppression?)
Order of phase transition	T, entropy, HBT
Fluctuations	$d^2E/d\eta d\phi$ *, $d^3\sigma/dp_t d\eta d\phi$*
Space-time evolution	$\pi\pi$ *, KK - HBT($R_{/\!/}$, $R_{\perp o}$, $R_{\perp s}$)
Mini-jet and jet propagation/attenuation	high p_t particles jets *
Chiral Symmetry Restoration	
Resonance widths, masses, branching ratios	$\phi \rightarrow$ KK, (e^+e^-?)
Disoriented chiral condensates	charge/neutral * low p_t *
Hadronization Transition	
Freeze-out conditions	HBT *, T *
Strangeness Distillation	K^+, K^- *
Collision Dynamics	
Stopping & baryo-chemical potential	$d^3\sigma/dp_t d\eta d\phi$ *
Expansion dynamics (long./transverse flow)	flow, $d^3\sigma/dp_t d\eta d\phi$ *
Spin Physics	
Spin-dependent parton distributions	jet-jet, γ-jet, γ, $W^\pm$, Z^o
Peripheral Collision Physics ($\gamma\gamma$, γg, pomerons)	
$f_2(1270)$, $f_0(975)$, $\rho^0\rho^0$, $\gamma g \rightarrow c\,\bar{c}$, pomeron int's	resonance decays ($\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-$,...)
New Physics	TBD

Figure 3: Schematic representation of the STAR physics program. See text for description.

4.2 Early Gluon-Dominated Stage

Once a RHIC collision begins, hard scattering of quarks and gluons dominates the collision process.[10] This stage is dominated by gluon interactions due to the shorter mean-free path of gluons as compared to quarks and due to the predominance of gluon producing reactions over quark producing ones. It is predicted that a gluon-dominated plasma forms.[11]

It is important to determine the characteristics of this early stage of the collision at RHIC. Since hard processes will dominate this stage of the collision, measurements of products of the hard scattering are necessary. STAR will measure high transverse momentum ($p_\perp$) photons, charged particles and jets. In addition, STAR is investigating ways of performing an open charm measurement via the hadronic or semi-leptonic channels of the decays of D-mesons. At present, no techniques have been found to accomplish these measurements in STAR, without the addition of new detectors. Since a measurement of the charm production cross section is essential to be able to determine the charm contribution to the background for charmonium production, and thus understand the suppression of charmonium states and possible formation of a deconfined phase in relativistic heavy ion collisions, investigations into the possibility of measuring open charm in STAR will continue.

4.3 Quark Gluon Plasma Transition and Mixed Phase

4.3.1 Strangeness and Particle Yields.

To determine the degree of equilibration of the system and to investigate fluctuations, STAR will measure triple differential cross sections for production of various types of particles as a function of transverse momentum ($p_\perp$), pseudorapidity (η) and azimuthal angle (ϕ). Since the hadrons that are measured in the final state are formed in the hadronization process after a possible QGP phase, the final state spectra of hadrons are a product of the various stages of evolution of the system. For a QGP to have formed, the yields of produced particles must be representative of a system in equilibrium at a temperature and baryochemical potential regime beyond that sustainable in hadronic matter (see Fig. 1). To ascertain information on the high density phase, strange hadrons (K^+, K^-, K^o) and singly- and multiply-strange baryons ($\bar{\Lambda}, \Lambda, \Xi^-, \bar{\Xi}^-, \Omega$) will be measured in STAR over a wide rapidity interval about mid-rapidity.[12] These measurements will be used to determine the degree of saturation of the strangeness degree of freedom. An enhancement in the production of strange particles resulting from chemical equilibrium of a system of quarks and gluons was one of the first predictions for a signature of QGP formation.[13] From the measurements and ratios of strange particles and other hadrons, the baryo-chemical potential, temperature and degree of saturation in strangeness can be determined for various ensembles of events (impact parameter selections) and colliding systems in STAR. Coupled with theoretical predictions, this information can be used to determine whether a QGP has been formed. Some strangeness observations that are anticipated to accompany the formation of a QGP are an enhancement in the strange antibaryon content [14] and an increased sensitivity of multiply-strange baryons ($\Xi^-, \bar{\Xi}^-, \Omega$) compared to singly-strange hadrons [15] to the presence of a QGP.

4.3.2 Parton Propagation and Attenuation.

The products of hard scattering processes in the early stages of a relativistic heavy ion collision must traverse distances of several fermi through highly excited matter. The energy loss of these propagating quarks and gluons is predicted [16] to be sensitive to the medium through which they travel, and may be a direct method of observing the excitation of the medium. As a result the spectra of high $p_\perp$ particles and jets will be modified due to attenuation in the medium. The resulting spectra will represent the energy-loss history of the hard-scattered parton as it traverses the medium. If there is a large difference in the energy loss between highly excited hadronic matter and the QGP, then this quenching effect should be visible in the high $p_\perp$ spectra of particles and jets. A systematic study of pp, p-nucleus and nucleus-nucleus collisions will be necessary to unravel the degree to which shadowing and quenching contribute to the particle spectra.

4.3.3 Hanbury-Brown and Twiss (HBT) Interferometry.

Correlations between identical bosons provide information on the freezeout geometry, the expansion dynamics and possibly the existence of a QGP.[17] STAR will measure the parameters of the pion-emitting source via pion correlation analysis on an event-by-event basis and will correlate them with other event observables. Moreover, the correlations of like-sign charged kaons or pions will be measured on an inclusive basis to high accuracy. The dependence of the source parameters on the transverse momentum components of the particle pairs will be measured with high statistics. Measurement of correlations between unlike-sign pairs will provide information for Coulomb corrections and on effects of final state interactions. The KK correlation is less affected by resonance decays after hadronic freeze-out than the $\pi\pi$ correlations. The K's are expected to freeze out earlier [18] than π's in the expansion. Depending upon the baryo-chemical potential and the existence of a QGP, the K^+ and K^- freeze out at different times.

By reconstructing the decay topologies of $K^o_s \rightarrow \pi^+\pi^-$, STAR will measure $K^o_s K^o_s$ correlations.[4] In this case the absence of Coulomb repulsion, as compared to like-sign charged particle correlations, will enable a more precise measurement of the large source dimensions expected at RHIC. Since the K^o_s is not a strangeness eigenstate, the $K^o_s K^o_s$ correlations will contain an interference term which should provide additional space-time information and exhibit strangeness distillation effects in regions where the baryochemical potential is significant.[19]

4.3.4 Fluctuations in Energy, Entropy, Multiplicity and Transverse Momentum.

It has long been known that a general indicator of a phase transition is the appearance of critical dynamical fluctuations in a narrow range of conditions. Such critical fluctuations can only be seen in individual events where the statistics are large enough to overcome uncertainties (N) due to finite particle number fluctuations. The large transverse energy and multiplicity densities at midrapidity in central collisions allow event-by-event measurement of fluctuations in particle ratios, energy density, entropy density and flow of different types of particles as a function of $p_\perp$, rapidity, and azimuthal angle. Fluctuations have been predicted to arise from the process of hadronization of a QGP.[20]

4.4 Chiral Symmetry Restoration

4.4.1 Resonance Widths, Masses, Branching Ratios.

The production cross section of ϕ-mesons will be measured inclusively in STAR via the decay $\phi \rightarrow K^+K^-$. Measurement of the yield of the ϕ, which is an $s\bar{s}$ pair, places a more stringent constraint on the origin of the observed flavor composition [21] than the K/π ratio and is expected to be more sensitive to the presence of a QGP. The ϕ mass, width and production rate are also expected to be extremely sensitive to changes in the quark masses [22] due to a possible chiral phase transition at high energy densities. STAR will measure $\phi \rightarrow K^+K^-$ and with lower statistics $\phi \rightarrow e^+e^-$ in order to determine the yield, mass, and width of the ϕ produced in central collisions at RHIC.

4.4.2 Electromagnetic/Charged Particle Energy Ratio.

The measurement of EM energy vs. charged-particle energy is an important correlation to measure in STAR in the search for the QGP and other new physics. The imbalance between charged particle and neutral energy observed in Centauro and other cosmic ray events emphasizes the need for EM/charged particle measurements.[23] Such abnormal ratios of neutral to charged-particle energy and multiplicity have been associated with the formation of disoriented chiral condensates.[24]

4.4.3 Spectra at Low $p_\perp$.

Using the silicon vertex tracking, STAR will measure the spectra of charged pions at low $p_\perp$ in order to investigate effects of the presence of a disoriented chiral condensate. A summary of STAR's capabilities and the sensitivities to parameters of the DCC domain size can be found in Ref. [25].

4.5 Hadronization Transition

4.5.1 Freeze-Out Conditions.

Both two-particle interferometry (discussed above) and single particle inclusive transverse momentum distributions provide information on the freezeout geometry and the expansion dynamics of the collision. As a consequence of the high multiplicities in central collision events, the slope of the transverse momentum ($p_\perp$) distribution for pions and the $\langle p_\perp \rangle$ for pions and kaons can be determined event-by-event in STAR. Thus, individual events can be characterized by a pion slope parameter T_o (effective "temperature") or $\langle p_\perp \rangle$, and a kaon $\langle p_\perp \rangle$ in order to search for events with extremely high temperature, predicted [26] to result from deflagration of a QGP. The determination of $\langle p_\perp \rangle$ for pions can be made very accurately on the single event basis in this experiment, over the expected range of multiplicities in central collisions from Ca + Ca to Au + Au. For kaons, with $\sim$ 200 charged kaons per event in the acceptance for central Au + Au events, $\langle p_\perp \rangle$ can be determined accurately for single events.

4.5.2 Strangeness Distillation.

The spectra of K^+ and K^- will be measured accurately in STAR and compared for regions of different baryo-chemical potential in order to determine if effects of strangeness distillation are present. These distillation effects are predicted to occur in the presence of a QGP. [19]

4.6 Collision Dynamics

4.6.1 Expansion Dynamics, Stopping, and Baryo-Chemical Potential.

Inclusive $p_\perp$ distributions of charged particles will be measured with high statistics in STAR to investigate various effects. These include collective radial flow and critical temperature at low $p_\perp$, and mini-jet attenuation [27] at high $p_\perp$. The $p_\perp$ spectra of baryons and anti-baryons at midrapidity are particularly interesting for determining the stopping power of quarks. Measurements of the net baryon number and net charge are important for establishing the baryo-chemical potential at midrapidity.

5 STAR SPIN PHYSICS PROGRAM

The STAR spin physics program will focus on measurements using colliding beams of polarized protons at RHIC to understand the spin structure of the proton. This program is described elsewhere in this workshop.[9]

6 STAR PERIPHERAL COLLISIONS PHYSICS PROGRAM

Nuclei colliding at ultra-relativistic velocities produce intense electromagnetic fields, which can act as a coherent source of photons for the study of $\gamma\gamma$ interactions. Likewise, the colorless strong force fields of the interacting nuclei can act as a coherent source of pomerons. These allow the possibility of also studying γ-pomeron and pomeron-pomeron interactions by investigating the possible final state couplings and hadronic final states resulting from collisions of relativistic heavy ions. Since the photon flux will be enhanced by a factor of the square of the nuclear charge, the high photon-photon luminosities at RHIC will allow a thorough study of many vector meson final states in the 1 to 2 GeV mass range. This is of particular interest since the results of e^+e^- and proton-proton interaction experiments have exhibited many more particles in this mass range than can fit into SU(3). STAR will measure charged-particle exclusive final states with few particles in order to reconstruct the final state of the interaction. Peripheral collisions will be studied to decrease the background of particles from nuclear interactions. The initial program in STAR will involve a study of $\gamma\gamma \rightarrow e^+e^-$ and $\gamma\gamma \rightarrow \mu^+\mu^-$ to measure the incident flux for $\gamma\gamma$ interactions. Then various final states, e.g. $f_2(1270)$ or $\rho^o\rho^o$, will be measured and compared to their expected couplings to the two-photon incident state. This will lead to an investigation of more exotic states that have been seen in e^+e^- and proton-proton interactions, e.g. candidates for multi-quark(gluon) and/or mixed states. Thus, additional information can be learned about these exotic states based upon their anticipated couplings to two-photons. In addition, vector meson states formed in γ-pomeron interactions will be studied. More detailed information on this program in STAR can be found in Ref. [8].

7 CONCLUSION

A broad physics program is anticipated in STAR. The primary focus of STAR is the "conventional" RHIC program involving the study of nuclear matter under extreme conditions, such as high temperature and pressure. In addition, STAR will also undertake a spin physics program with polarized proton colliding beams and study photon/pomeron physics utilizing peripheral collisions of heavy ions at RHIC. This paper has focussed on the conventional RHIC program in STAR. In this program, it should be emphasized that the capability of measuring several different observables event-by-event is unique to STAR. Events will be characterized event-by-event by their temperature, strangeness content, transverse energy density, multiplicity density, entropy density, degree of fluctuations, occurrence of jets and source size. The presence of a QGP may not be observed in an average event, nor in a large fraction of events. Since there is no single clearly established signature of the QGP, access to many observables simultaneously may assist in identifying events in which a QGP is formed.

8 ACKNOWLEDGEMENTS

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