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The Future of Spin Physics at BNL

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Abstract. The Relativistic Heavy Ion Collider (RHIC) at BNL is the world's only polarized proton-proton collider. Collisions at center-of-mass energies up to 500 GeV and beam polarizations approaching 70% (longitudinal or transverse) are provided to two experiments, STAR and PHENIX, at luminosities $\geq 10^{32}/cm^2/sec$. Transverse polarized beam has also been provided to the BRAHMS experiment. Measurements that bear on the important question of the spin content of the nucleon are beginning to appear. Over the next 10 years, as the performance of polarized proton running at RHIC is further developed, the Spin Physics program at RHIC will provide definitive measurements of the contributions to the proton's spin of the gluon, the sea quarks and the orbital motion of the partons in the proton's wave function. We plan to extend the reach of our study of the role of spin in QCD with the development of "eRHIC," which will provide polarized e-p collisions to a new detector.

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INTRODUCTION: PAST AND PRESENT SPIN PHYSICS AT BNL

The role of spin in nuclear and particle physics has long been a theme of research at BNL facilities for nuclear and particle physics. Important examples include a program[1] of fixed-target polarized proton experiments at the AGS, the muon g-2 experiment,[2] and the Laser Electron Gamma Source (LEGS) experiment[3] at the National Synchrotron Light Source.

With the advent of the Relativistic Heavy Ion Collider at BNL[4] came an opportunity to pursue the interest in spin physics on an unprecedented scale. Through collaboration between DOE, RIKEN, BNL and the RIKEN-BNL Research Center (RBRC, discussed below), RHIC was enhanced with accelerator and detector equipment to create the first and only polarized high energy p-p collider. Figure 1 shows a schematic of the RHIC facility with the major polarized collider components highlighted. As a result of this extension of RHIC's capabilities, the science scope and the breadth of the user community were significantly expanded: a much wider program of QCD physics can be and is being addressed.

In fact, it was the other way around: the desire of physicists to understand the role of spin in hadron structure drove the development of RHIC into a polarized proton collider. The key element in the realization of spin physics at RHIC was the interest and involvement of Japanese physicists at RHIC, through the creation of the RBRC at BNL. RBRC[5] was founded under the directorship of T. D. Lee by an agreement between RIKEN and BNL in 1996. Through this agreement Japan contributed scientists and resources to spin related developments in the accelerator complex and to PHENIX, one of the major experiments at RHIC.

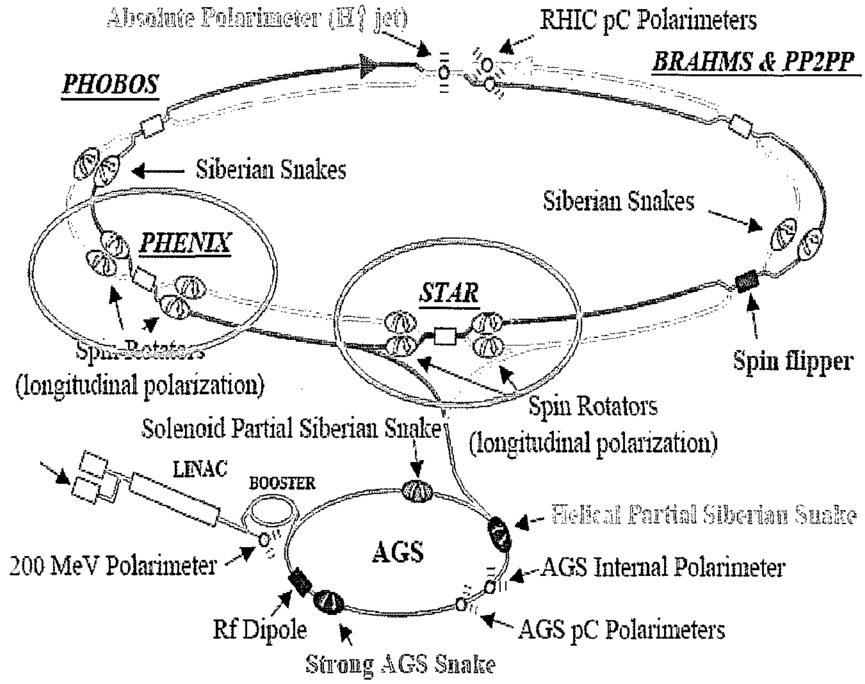

FIGURE 1. Schematic layout of RHIC with emphasis on the spin-related components

RBRC has also contributed greatly to the training of a new generation of strong interaction theorists and phenomenologists, through the RBRC Fellows Program, and has funded the construction and operation of a 10 Teraflops computer (called QCDOC) for lattice gauge theory simulations at BNL.[6] RBRC, now under the directorship of N. P. Samios, is completing 10 years of operation.

THE GOALS OF THE RHIC SPIN PROGRAM

Understanding the spin structure of the nucleon is expected to shed light on the larger questions of the structure of strongly interacting matter and of the phenomenon of confinement in QCD. The fundamentals of the spin structure of complicated objects like nucleons are not well understood. For example, the spin of the proton cannot be understood simply as the quantum sum of the spins of the valence quarks in the proton. Deep inelastic lepton scattering from nucleons and nuclei have shown[7] that the valence quarks contribute no more than 20-30% of the proton's spin. Understanding the contributions to the proton's spin from other constituents (gluons, sea quarks) and from dynamical effects (orbital motion of the protons constituents) are subjects of intense experimental and theoretical study (and of this Conference). Both fixed-target and collider experiments are involved in this effort and a high-energy collider is ideally suited for much of this research. In particular, the polarization of the glue in the proton can be measured with longitudinal double-spin asymmetries in polarized p-p collisions. The polarization of the sea (sorted by quark flavor) can be measured with single-spin asymmetries of hadrons arising from the decay of $W^{\pm}$ bosons. The contribution to the proton's spin coming from the orbital motion of partons in the proton can possibly be probed through asymmetries in particle production in the collisions of transversely polarized protons. RHIC can provide collisions with any configuration of polarization, change the configuration bunch by bunch, and thereby maintain very tight constraints on the systematic errors between different configurations.[8]

In the next two sections we discuss current progress toward the goals of the RHIC spin program and its future prospects.

CURRENT PROGRESS ON RHIC'S SPIN GOALS

Over the past several polarized proton runs at RHIC the performance of the accelerators has improved markedly, leading to excellent data sets for the BRAHMS[9], PHENIX[10] and STAR[11] experiments in 2005 and 2006. The highlights of this program of technical development and physics research are summarized below.

Gluon polarization

To date, the main thrust of physics research on the spin of the nucleon at RHIC has been the gluonic contribution to the spin of the proton. RHIC is no routinely delivering proton-proton collisions at $\sqrt{s}$ = 200GeV with 60-65% longitudinal polarization of both beams at luminosities averaging $2\times10^{31}/cm^2sec$. Measurement of the double spin asymmetry A_{LL} in the production of π^0 (by PHENIX) and of jets (by STAR) is sensitive to Δg, the polarization of the glue. Figure 2 shows recent results of A_{LL} as a function of transverse momentum of the produced particle or jet, together with curves which show the theoretical expectation for different values of Δg. The significance of these asymmetries at RHIC are fundamentally different than those double spin asymmetries seen so far in DIS. Interpretation of asymmetries in terms of polarized gluon distribution requires use of pQCD framework. This has been convincingly been shown to work in the kinematic region associated with the asymmetries in Figure 2, while has not been done so far in the case of fixed target DIS experiments[12].

Although there is more to be done on this important measurement, the data suggests that Δg is "small," i.e., seems to rule out models which assume an anomalously large gluon polarization. It remains to be seen if the spin crisis is partially or fully explained by the gluon's contribution.)

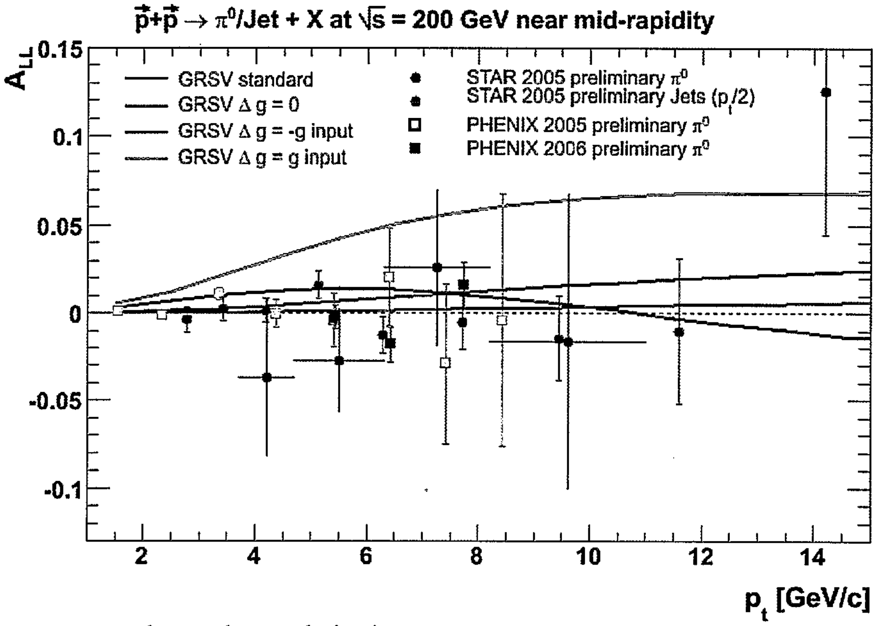

FIGURE 2. Recent results on gluon polarization vs. transverse momentum from STAR and PHENIX

Transverse spin asymmetries

About a 30% of the integrated physics operation with polarized p-p program to date has been with transversely polarized protons. The main thrust of investigations in transverse collisions has been to understand the origin of transverse physics asymmetries observed for many decades and over a wide range in center of mass, but which still remains to be understood in QCD. In fact, at leading order QCD predicts that none of the single spin transverse asymmetries should exist. Different scenarios of the transverse spin asymmetries have been speculated upon, ranging from those associated with initial state effects, indirectly or directly connected with the orbital angular motion of the partons, or final state effects, associated with asymmetries in fragmentation processes of the observed final particles in p-p collisions. There is also a fundamental transversity structure function, which is associated with the probability distribution of transversely polarized partons in a transversely polarized proton. Utilizing the simplicity and elegance of measurement of transversely polarized proton collisions, the program which has begun at RHIC seems to be one of the most potent in terms of understanding and distinguishing between the different effects mentioned above.

Figure 3 shows the single spin asymmetries measured by STAR in inclusive neutral pion production. Also shown is a selection of measurements by BRAHMS in inclusive charged pions/kaons. PHENIX has made these measurements in very different kinematic region, around zero rapidity, has seen no asymmetries of this kind. This provides another clue to the understanding of these phenomena in the high energy domain of RHIC.

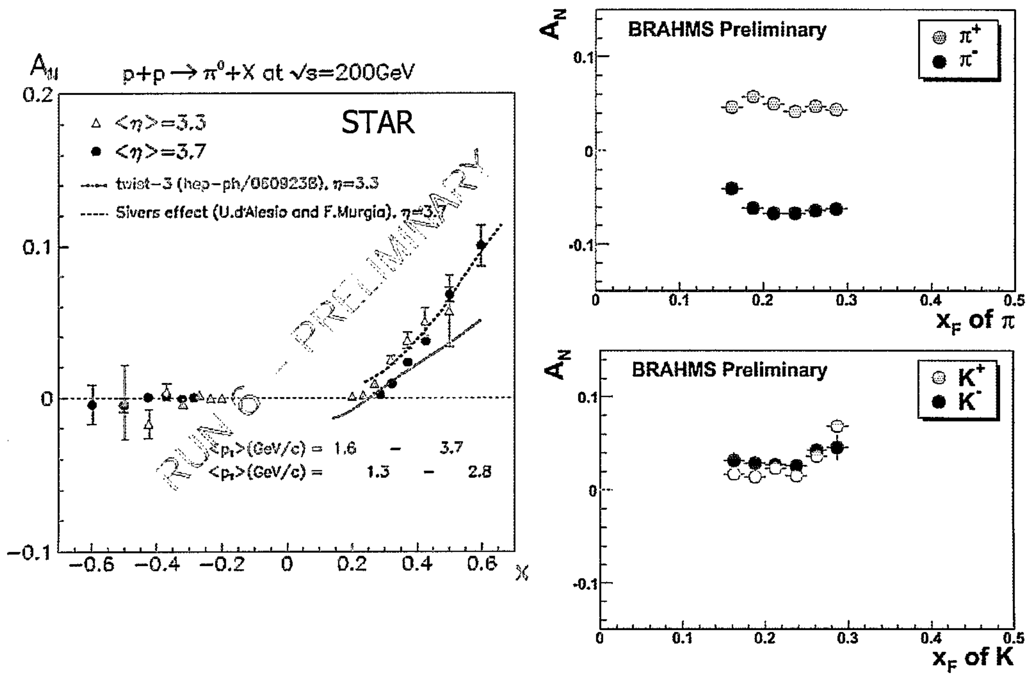

FIGURE 3. Recent results on transverse spin asymmetry vs. x from STAR and BRAHMS

Polarized p-p collisions at √s = 500GeV

RHIC can deliver polarized p-p collisions at √s up to 500 GeV. The importance of the higher center-of-mass energy, which provides good production rates for $W^{\pm}$, is discussed below. The most recent run included a brief machine development period aimed at achieving good polarization at the higher √s. Though brief, it was successful in accelerating both beams to 250 GeV and in developing beam polarization up to about 40%. This important step paves the way for future spin physics at RHIC, discussed below.

THE FUTURE OF SPIN PHYSICS AT BNL

The future of spin physics at BNL is focused on RHIC and has two main components:

- Continuous improvement of the polarized p-p program through better machine performance (polarization and luminosity) and upgraded detectors
- Development of a new capability, called eRHIC, whereby polarized e and polarized p can be collided at high luminosity and studied in one or more new detectors.

These proposed new capabilities and their associated physics programs are detailed below.

Polarized p-p

We plan[13], with annual running of the polarized proton configuration at RHIC to develop the ongoing program with the following capabilities:

- Accelerator parameters: $\sqrt{s}$ = 500 GeV, beam polarization P = 70% and luminosity $\mathcal{L} = 1.5\times10^{32}/\mathrm{cm}^2\mathrm{sec}$
- Integrated polarized p-p luminosity over the next five years $\int\mathcal{L}dt \approx 800\mathrm{pb}^{-1}$
- Polarized He^3 beams with RHIC's new electron beam ion source (EBIS), enabling the study of the neutron's spin structure
- Detector upgrades to STAR and PHENIX, including silicon micro vertex detectors and enhanced forward tracking, calorimetry and triggering

Figure 4 shows the projections for integrated luminosity performance of the RHIC Spin program over the next six years.

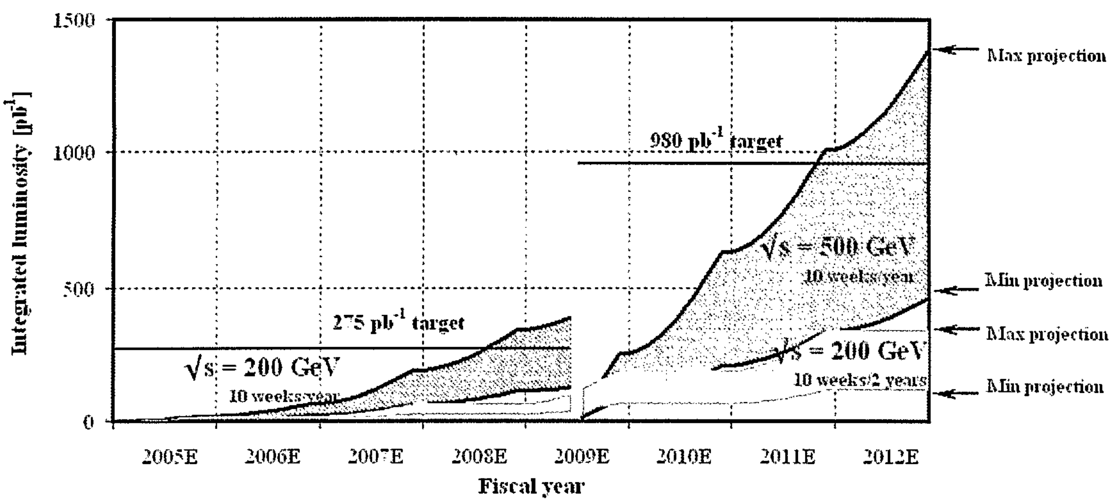

FIGURE 4. Integrated p-p luminosity history and projections at $\sqrt{s}$ = 200 and 500 GeV

The goals for this program are to extend our understanding of the "spin budget" of the nucleon. This includes looking at the polarization of sea-quarks and looking at dynamical effects (orbital angular momentum of the partons). Of course, a more precise understanding of the gluon polarization is part of the program as well.

The polarization of the sea-quarks in the wave function of the nucleon can be measured as a function of quark or antiquark flavor through the production and decay of $W^{\pm}$ mesons to hadrons. Measurement of the single (longitudinal) spin asymmetry A_L yields determinations of $\Delta f/f$, where $f = u$, $\bar{u}$, d or $\bar{d}$ as shown in figure 5.

A couple of different models are shown in figure 5 and serve to illustrate the discrimination power of the projected experimental precision of these measurements.

As now appears likely, the polarization of the partons in the nucleon wave function will not fully account for the nucleon's spin. Determination of the spin contribution of dynamical effects can also be accessed at RHIC though the measurement of higher twist mechanisms (such as Sivers and Collins effects) utilizing single (transverse) spin asymmetries A_N. This is an emerging study at RHIC; numerous inclusive A_N measurements were reported by BRAHMS, PHENIX and STAR at this meeting.

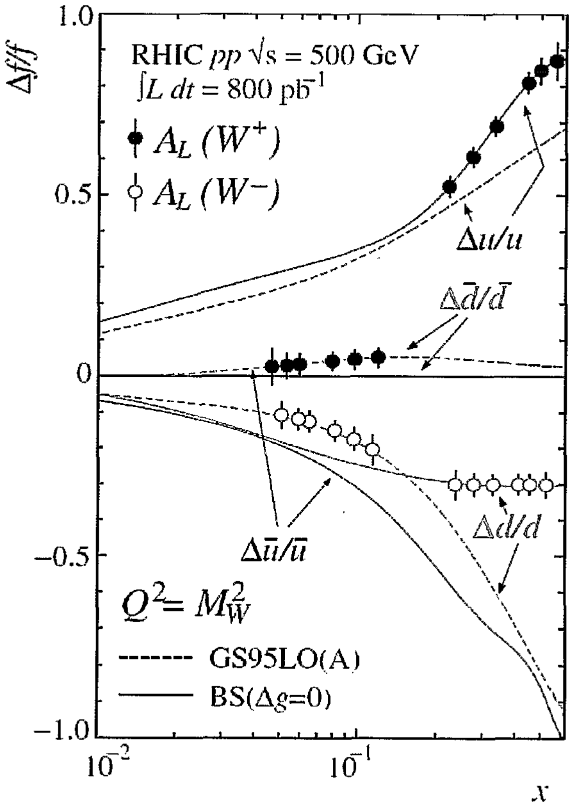

FIGURE 5. Projected sensitivity for sea-quark polarization at RHIC

eRHIC

The future of fundamental studies in QCD appears to lie in an extension of the program pursued at HERA (DESY),[14] namely in high luminosity electron-hadron interactions in collider mode. For example, the construction of a high energy, high intensity polarized electron (and positron) beam to collide with the existing heavy ion and polarized proton beams would significantly enhance RHIC's ability to probe fundamental, universal aspects of QCD[15]. In particular, the existing RHIC polarized proton beam plus a polarized electron beam of 10 GeV or more could cover a significant fraction of the (x, Q^2) kinematics of HERA with polarized beams and 100 to 1000 times the HERA luminosity. This would provide polarized deep inelastic e-p scattering in a wholly new kinematic regime (Compare the red-outlined areas in Figure 6).

eRHIC provides another unique capability, namely electron-ion collisions for any A up to Uranium. This program has its own new and important nuclear physics agenda. A summary is provided elsewhere.[16] Of note for the spin program, however, is the ability, mentioned above, to accelerate and collide polarized He^3 nuclei.

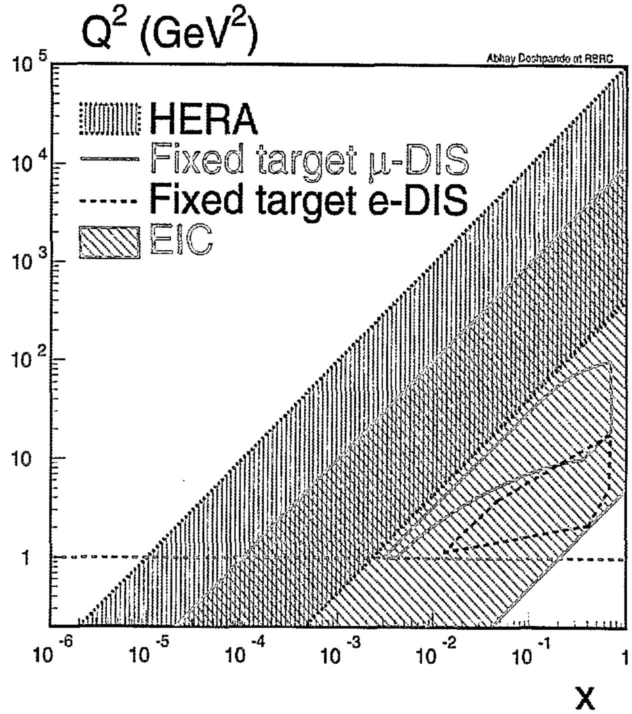

FIGURE 6. (x, Q^2) coverage for eRHIC (EIC) compared to HERA and fixed target experiments

The spin physics agenda enabled by eRHIC would be extremely powerful. Highlights of this agenda include[16]:

- Precision understanding nucleon structure and its spin, including the role of quarks and gluons in nucleon, low-x phenomena and Deeply Virtual Compton Scattering
- Unique QCD measurements, such as the partonic spin structure of the photon and the heavy flavor contribution to nucleon spin
- Fundamental tests of QCD, leading to precision measurements of Standard Model QCD parameters

Significant work on the conceptual design of eRHIC has been performed by BNL and its collaborators (MIT-Bates, BINP, DESY and others) over the last several years, leading up to a Zeroth Order Design Report.[17] Two versions of the concept have been worked out and reviewed in 2005 by external committees – one based on a ring design for the electron beam and one based on a superconducting ERL. Sketches of the two concepts are shown in Figure 7.

Ongoing work is aimed at refining the design(s) including the challenging Interaction Region (IR) design, identifying/performing the critical R&D tasks and developing the basis for reliable cost estimates. Among the R&D tasks are those related to superconducting ERLs; this work benefits from ongoing superconducting ERL R&D at BNL for a RHIC electron cooler.[18]

Also prominent in the ongoing eRHIC effort is the development of detector concepts for the IR. General-purpose, hermetic detectors[19] like Zeus and H1, as well as more special-purpose detectors which focus on the high-rapidity region[20] are among the options under study.

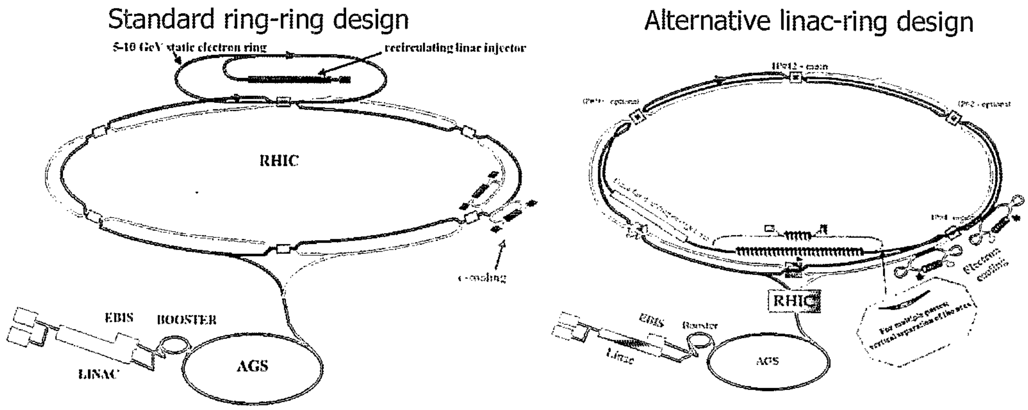

FIGURE 7. Schematic layouts of eRHIC with two electron options as described in the text

BNL's plans for the construction and operation of eRHIC during the next decade depend on the roadmaps for Nuclear Physics over that period, both in the US and worldwide. As of this writing, a US Nuclear Physics Long Range Plan[21] process is starting; it will provide the roadmap for the period 2008-2017. Also ongoing is a 10-15 year Roadmap exercise for Nuclear Physics worldwide, conducted under the auspices of The Organization for Economic Co-operation and Development (OECD) and led by the US.[22] With appropriate national and international support, BNL would be able to construct and start operating eRHIC during the next 10 years.

SUMMARY

Spin physics has been a vital component of BNL's programs in nuclear and particle physics for decades. Spin provides sensitive tests of our understanding of QCD in the structure of nucleons. BNL intends to provide world-class facilities to enable research in.this important area through continuous improvement of RHIC and the development of eRHIC.

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