# 1 Executive Summary **[Edits in blue by T.Kirk, 1-16-05]**

An action item from the June 30-July1, 2004 DOE Office of Nuclear Physics Science and Technology Review of the Brookhaven National Laboratory (BNL) Relativistic Heavy Ion Collider (RHIC) written Report, dated September 13, 2004, was *that "BNL should prepare a document that articulates its research plan for the RHIC spin physics program. A copy should be submitted to DOE by January 31, 2005."* This document is the response to that action item.

We provide here a plan that addresses: 1) the science of the RHIC spin program in a world-wide context; 2) the collider performance requirements for the RHIC spin program; 3) the detector upgrades required, including timelines; 4) time evolution of the spin program. The RHIC Spin Plan Group was charged to formulate the plan by Thomas Kirk, BNL Associate Director for High Energy and Nuclear Physics, who hereby submits the plan to the DOE Office of Nuclear Physics on behalf of the Laboratory.

The importance of the study of nucleon spin to nuclear physics and its co-evolution with heavy ion physics in the RHIC facility is discussed in the first section of this report. Here, we note that, of all the basic properties of the nucleons (protons and neutrons), the intrinsic spin angular momentum aspects are least well known. In particular, the contribution of the gluons to the net spin of the nucleons, as well as the role of orbital angular momentum among the quarks and gluons is almost totally unmeasured. Our plan will argue that the RHIC facility will provide the most comprehensive and precise measurements possible in the present and foreseen worldwide program of spin physics and will be able to accomplish this in a proposed program of 10 weeks (on average) of data taking per year through the year 2012. This scenario is labeled "the technically limited BNL spin plan". If budgetary constraints on the spin program evolution are imposed, the program will be stretched out accordingly and the results will be available later and at higher total cost.

The RHIC 100-250 GeV colliding beams of highly polarized protons, with arbitrary spin orientation at two interaction points around the RHIC ring (at the PHENIX and STAR detectors), are unique in the world and likely to remain so for the foreseeable future. The maximum polarization in each beam is expected to rise from 45% to ~70% in the 2005-2006 time frame. Exploiting this powerful accelerator and experimental detector capability, together with a steadily improving average luminosity at the interaction points, a unique and important program of spin physics measurements can be completed over the time period 2005-2012. Determination of the gluon's contribution to the proton spin, the '$\Delta G$ structure function', will be an early achievement of the program, followed by the direct measure the quark and anti-quark contributions to the proton spin, sorted by quark flavor. These results will be achieved in a later phase of the spin physics program via W-boson production measurements. In the same time frame, the power of lattice gauge physics, carried out on BNL supercomputers, is expected to be able to relate the spin results to the predictions of Quantum Chromo-Dynamics, now believed to be the fundamental theory of the strong nuclear interactions.

We summarize our findings on the four areas in the charge:

**Science:** Gluon polarization will be measured at RHIC using several independent methods: $\pi^0$, jet, direct $\gamma$ and $\gamma$+jet, and heavy quark production. Results from the different methods will overlap to allow us to test our understanding of the processes involved and expand the range of momentum fraction for the measurements. We want to learn both the average contribution to the proton spin of the gluons as well as a detailed map. We use first the higher cross section processes, $\pi^0$ and jet production and, as we reach higher luminosity and polarization, the clean but rarer process of direct $\gamma$ production. We plan to emphasize these measurements for $\sqrt{s}$ = 200 GeV collisions from 2005-2008. At that time, we expect to have reached a precision that can clearly distinguish between zero gluon polarization and a minimal (”standard”) gluon polarization. A large gluon polarization, consistent with the gluon carrying most of the spin of the proton, would be precisely measured. In this period we will also pursue the question of the transverse spin structure. Gluons, massless spin 1 particles, cannot contribute to the transverse spin. Large transverse spin asymmetries have been seen for deeply inelastic scattering (DIS) and now for RHIC, so this topic is also a potential window into a new understanding of the structure of the nucleons.

Production of W bosons, the carrier of the weak interaction, has an inherent handedness. At RHIC we plan to use this ”parity violation” signal to directly measure the polarization of the quark and anti-quark that form the W boson. To do this we will run at the top RHIC energy, $\sqrt{s}$ = 500 GeV. This will provide the first direct measurements of anti-quark polarization in the proton, with excellent sensitivity. We plan to begin these measurements in 2009. The W measurements will require the prior completion of certain detector improvements for both PHENIX and STAR.

The RHIC spin results will provide precise measurements of gluon and anti-quark polarization. With these results we will also understand the role of the remaining contributor to the proton spin, orbital angular momentum. We will have also explored our understanding of the interconnected results from the different RHIC spin probes, and from the DIS measurements. The sensitivity at RHIC for gluon polarization is shown in Figure 1, where we also include the sensitivity for the ongoing DIS experiment at CERN, which measures gluon polarization by the production of hadrons. From the figure, we see that RHIC will provide precise results over a large range in momentum fraction, characterizing the gluon contribution to the proton spin.

Figure 1: $\Delta G/G(x)$ vs. log x with a model showing the x range for various RHIC processes with expected uncertainties; 200 and 500 GeV data are shown with experimental uncertainties in RHIC and COMPASS for $Q^2 > 1$.

The sensitivity of RHIC for anti-quark polarization is shown in Figure 2. We will measure the ubar and dbar anti-quark polarizations to about ±0.01, as well as u and d quark polarizations. The measurement is direct and very clean, using parity violating production of W bosons. DIS measurements also yield the anti-quark polarizations. The method has the disadvantage of theoretical uncertainties in modeling the fragmentation and the advantage that the method is accessible today. The RHIC and DIS methods probe the proton at very different distances, ($Q^2$ range) where RHIC corresponds to X Fermi and DIS to Y Fermi, compared to the proton radius of 1 Fermi. The theory of QCD prescribes how to connect the results from different probing distances — the description of unpolarized DIS results over a very large distance range is one of the major successes of QCD. Both the anti-quark and the gluon results from RHIC and DIS test the QCD assumption of universality, namely that the physics for both proton and lepton processes can be described with the same underlying quark, anti-quark, and gluon distributions.

Figure 2: $\Delta Q/Q(x)$ vs. log x with a model for u, d, ubar and dbar; with RHIC and DIS expected uncertainties (or show $A^p_1$ with DIS measurements and RHIC sensitivities?).

We emphasize that the planned RHIC program will make major contributions to our understanding of matter. Our results will complement the DIS measurements, completed and planned. We include in our report expectations from a next stage of DIS–colliding polarized electrons with polarized protons and neutrons which probes still further into the structure of matter. As we develop theoretical tools to apply QCD to understand this structure, these spin results will provide a deep test of our understanding of the fundamental building blocks of matter.

**Collider Performance Requirements:** The spin physics program requires RHIC beams with high polarization, and high integrated luminosity. For the sensitivities assumed above, we have used P=0.7 and luminosity 300 $pb^{-1}$ at $\sqrt{s}$ = 200 GeV and 800 $pb^{-1}$ at $\sqrt{s}$ = 500 GeV. (Note that this would be "delivered" luminosity, while the figures use "recorded" luminosity. We comment on this point in the body of the report.)

The polarization level is presently P = 0.45 and is expected to reach 70% polarization by 2006. This improvement is expected using new Siberian Snake Magnets installed in the AGS in 2004 and 2005. The average luminosity at store must be increased by a factor 15 to reach the integrated luminosity goals for three years of running at 10 physics weeks per year. To achieve this level of performance will require completion of the planned vacuum improvements in RHIC, expected for 2007. The luminosity increase then comes from reaching a bunch intensity of $2x10^{11}$. A limit will be caused by beam-beam interactions that change and broaden the betatron tune of the machine, moving part of the beam into a beam resonance region where beam is then lost. Work in 2004 discovered a new betatron tune for RHIC that greatly improves losses from the beam-beam interaction. RHIC at our luminosity goal will be above previously reached tune-spread limits and will be close to vacuum limits from the onset of electron clouds.

Reaching these goals requires "learning by doing". We plan to study limits and develop approaches to improve the polarization and luminosity during physics runs by including beam studies for one shift per day. It is also important that a sustained period of running and development be followed, if possible each year. It is this approach that has led to the major improvements for heavy ion luminosity and to our improvements to this date in polarization and proton luminosity.

**Experimental Detector Capabilities:** The PHENIX and STAR detectors are complete for the gluon polarization program. Improvements to both detectors are required to carry out the W physics program. Both experiments also plan upgrades that benefit both the heavy ion and spin programs, significantly extending the range of physics probes for spin.

W-Program Upgrades
PHENIX - The present online event selection for muons, the channel used for W physics, will need to be improved for the W luminosity. New resistive plate chambers (RPC) are being proposed to provide the tighter event selection, along with electronics changes to the muon tracking readout. The RPC proposal was submitted to NSF in January 2005, with a cost estimate of $1.8M. The tracking readout proposal has been submitted to the Japan Society for the Physical Sciences, with a cost of $1.0M. The planned timeline for both is to complete for the 2008 run.

STAR - New tracking for forward electrons from W decay is necessary for the W program. It is planned to propose this upgrade in 2006 to DOE, with an estimated cost of $5M, although research and development on the technology (GEM detectors) is proceeding and the cost estimate is rough at this time. The forward tracking detector is to be completed for the 2010 run, with part of the detector in place earlier.

Heavy-Ion/Spin Program Upgrades

PHENIX plans a barrel micro vertex detector that provides access to heavy quark states and to jet physics based on tracking. The heavy quark data will add a new probe for gluon polarization at lower momentum fraction (shown on Fig. 1). The jet information will be used in correlated ($\gamma$+jet) measurements, which better determine the sub-process kinematics for gluon polarization measurement. A second upgrade being planned is to change the brass "nose cones", used as a filter for the muon arms, to active calorimeters that will measure photons, $\pi^0$ and jet energy. The nose cone calorimeters would provide a larger momentum fraction range for the gluon polarization measurements. Both are important upgrades for the heavy ion physics program. The vertex detector is planned for the 2008 run, and the nose cone calorimeter proposal is being developed now.

STAR will propose expanded forward calorimeters to NSF in January 2005. The calorimeters will measure the gluon density for proton-gold collisions and will also provide very significant spin measurements. With the calorimeters, forward $\pi^0$, $\gamma$ and jet events can be observed, yielding sensitivity to gluon polarization at lower momentum fractions, as shown on Fig. 1. A second upgrade driven by the heavy ion program, a barrel inner tracker, will give access to heavy quark measurements for spin. The forward calorimeters are to be in place for the 2007 run. The barrel inner tracker is to be completed for the 2010 run.

**Time Evolution:** In order to indicate the pace of spin program evolution under different budget assumptions, we provide two examples with an average of 10 weeks and 5 weeks of spin physics data taking per year. We note that the actual running plan will continue to be developed, year-by-year, from the experiment beam-use proposals. The time evolution cases provided here indicate paths for reaching the spin program's strategic goals under two example scenarios.

We show in Fig. 3, the impact of 10 and 5 averaged spin physics weeks per year. The "technically-driven schedule" represents the luminosity used for the sensitivities shown in the figures above. With 10 weeks per year, we achieve the $\sqrt{s}$ = 200 GeV target in 3 years, assuming that we successfully climb the accelerator learning curve to reach the target store luminosity. The 500 GeV running target is also expected to be achieved in 3 years (there is a natural luminosity improvement for 500 GeV of a factor of 2.5 over 200 GeV from the smaller cross section beams).

With 10 averaged spin physics weeks per year, technically driven, our proposed target sensitivities can be reached running at $\sqrt{s}$ = 200 GeV from 2005-2008, and at $\sqrt{s}$ = 500 GeV from 2009-2012. We have assumed that 2009 will be an engineering run for W physics (new detector systems and higher luminosity), with a full detector in place for PHENIX and a partial detector for STAR. 2010-2012 will provide full-functionality W physics runs at high luminosity for both detectors. This is the preferred scenario from BNL.

As can be seen in Fig. 3, running 5 averaged spin physics weeks per year (we have interpreted this as running 10 spin physics weeks every two years to reduce end effects), each program, 200 GeV and 500 GeV, takes more than 6 years. Under this scenario RHIC would run roughly 25% of the year and both the heavy ion and spin programs would be stretched a factor of greater than two in calendar time. We hope that such a slow and relatively inefficient program can be avoided.

Fig. 3: pp luminosity projections for 10 and 5 physics weeks per year (5=10/2).

# 2 The case for RHIC Spin

## 2.0 Proton Spin Physics and the RHIC Facility Spin Program

The RHIC spin physics program contributes to a developing understanding of the known matter in our universe. This matter is predominantly nucleons, protons and neutrons of atomic nuclei. Deep inelastic scattering of high energy electrons from protons established in the 1960s that the nucleons are built from quarks.Quantum chromodynamics (QCD) is now believed to be the theory of the nuclear force, with protons built from quarks and the QCD force carrier, the gluons.Unpolarized studies have verified many predictions of QCD, probing deeply inside the proton using unpolarized colliders at very high energy. These experiments have determined with great precision the unpolarized structure of the nucleons, the distributions of quarks, gluons, and anti-quarks.

There has also been considerable progress, and a major surprise, studying the spin structure of the nucleons. *Polarized* deep inelastic experiments (DIS) from the 1980s to now, done at the SLAC, CERN, and DESY accelerator laboratories, have shown that the quarks and anti-quarks in the proton and neutron carry very little of the spin of the nucleon, on average. Roughly 75% of the nucleon spin must be carried by its gluons and by orbital angular momentum. This was seen as quite surprising in 1989 when it was first discovered. Although the QCD theory does not yet provide predictions for this structure, it was expected that the quarks would carry the nucleon spin. This polarized DIS result indicated that the proton and neutron have surprising spin structure, and probing this structure has become a major focus in our field. The DIS experiments probe the nucleon using the electromagnetic interaction. The electromagnetic interaction scatters through electric charge, directly observing the effect of the charged quarks and anti-quarks in the nucleon, but not the electrically-neutral gluons.

The RHIC spin program, colliding polarized protons at ps=200 GeV and above, uses the strongly interacting quarks and gluons from one colliding proton to probe the spin structure of the other proton. The RHIC program is particularly sensitive to the gluon polarization in the proton, which will be independently measured with several processes. In addition, parity-violating production of W bosons at RHIC will offer an elegant method to directly measure the quark and anti-quark contributions to the proton spin, sorted by type of quark. These measurements explore the structure of longitudinally polarized protons. The transverse spin structure of the proton can be different from longitudinal, and this is also a major topic at RHIC, and large spin asymmetries have already been observed.

The RHIC spin program is underway. Highly polarized protons, P=45%, have been successfully accelerated to 100 GeV, using unique sets of magnets called Siberian Snakes in the RHIC accelerator. The first polarized collisions at ps=200 GeV took place in 2001, and polarization and luminosity have been increased substantially since then. The RHIC spin accelerator complex includes a new polarized source providing very high intensity polarized (P=80%) $H^-$ ions, new ”partial” Siberian Snake magnets in the AGS accelerator, four ”full” Siberian Snakes in RHIC, and eight sets of Spin Rotator magnets in RHIC. Polarization is measured with new devices in the LINAC accelerator, the AGS, and in RHIC. Absolute polarization was determined at 100 GeV using a polarized atomic hydrogen gas ”jet” target in RHIC in 2004. Progress in polarization and luminosity has been made by combining machine work with periods of sustained collisions for physics.

The two large RHIC detectors, PHENIX and STAR, have photon, electron, charged hadron, and muon detectors, all important for the spin program. Measurements of the unpolarized cross sections for _0 and direct production, reported by the RHIC experiments, are described well by QCD predictions. These predictions are based on a perturbative expansion of QCD and calculations have been carried out to two orders for all important RHIC spin processes. Theoretical understanding of these important probes for spin physics at RHIC is robust. First spin measurements from RHIC have been published, showing a large spin asymmetry for _0 produced in the collision of transversely polarized beams, and a helicity asymmetry for _0 production, sensitive to gluon polarization, consistent with zero.

## 2.1 Introduction: what we know so far, what else we would like to learn, and why