Physics with RHIC Spin Collider

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The year 2002 has been very exciting and successful for the RHIC spin program, with the first collisions of polarized protons at $\sqrt{s} = 200$ GeV, which is an order of magnitude higher energy than any previous polarized proton collisions. The achievements in the first year of the polarized collider are reported.

1. INTRODUCTION

The first polarized proton collider started its operation at RHIC in December 2001, when RHIC became not only Relativistic Heavy Ion Collider to find a new state of matter, quark gluon plasma, but also the Spin Collider to solve the spin puzzle, how the spin of the proton is made of its constituents.

It is worthwhile to mention that the US-Japan collaborations have played essential roles toward this accomplishment. The collaboration between KEK and BNL made the KEK polarized proton source available as the ion source for RHIC, and the RIKEN-BNL collaboration made the snake and spin-rotator magnets available in the RHIC main ring.

In this manuscript, we describe how the machine behaved in the first year operation as a Spin Collider and why this machine built, *i.e.* the physics of the Spin program. Then we highlight some of the results from the first year of running.

2. OPERATION OF POLARIZED PROTON COLLIDER

Figure 1 shows a schematic view of the RHIC Spin Collider complex. Polarized protons are accelerated in a LINAC and then in a BOOSTER. Up to this point there are no depolarization resonances. In the AGS, the partial Snake made from a solenoidal magnet was newly introduced to preserve the proton polarization in the AGS. After the AGS, the protons are transferred to RHIC to be accelerated to 100 GeV in the last run, or eventually to 250GeV in future runs. Here some inventions and investments were required.

The key elements in the RHIC main ring, Siberian Snake, consist of four helical dipole magnets. The helical dipole was the major invention needed to realize the Spin Collider, because it rotates the spin of a proton by 180 degrees with minimum excursion of the proton's orbit. Two snakes in each ring have the snake axis orthogonal to each other. The snake axis is the vector around which spin is rotated. With this trick, the Larmor

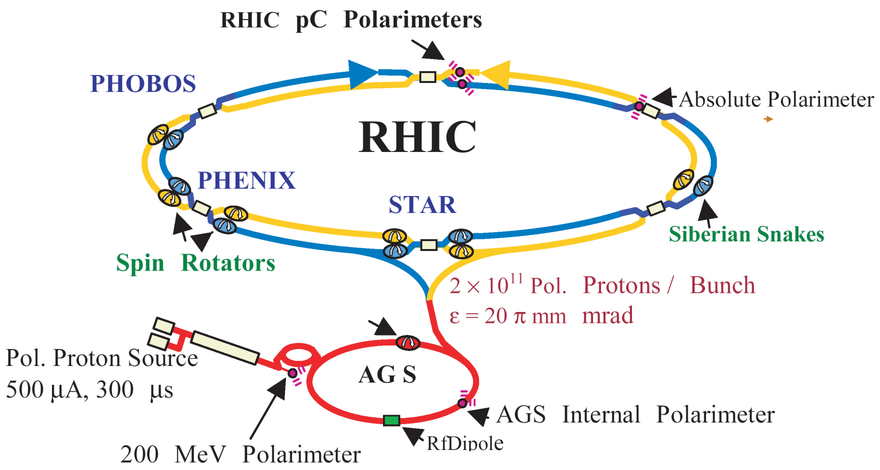

Figure 1. Layout of the RHIC Spin Collider

precession of the proton spin becomes π per turn independent from the energy of proton[1] so that the polarization can be kept up to the top energy of 250 GeV.

Another important invention was the RHIC polarimeter, located near the 12 o'clock interaction point. This polarimeter contains six silicon detectors in each ring, placed azimuthally about the beam. At the center, a very thin carbon filament is moved into the beam during the measurements. With this device, recoil carbons elastically scattered by protons in the beam to 90 degrees are detected. The scattered carbons with energy of a few hundred keV are sensitive to the proton spin due to the Coulomb-nuclear interference (CNI). Analyzing power of this device was measured at the AGS [2]. It is like one percent depending on t[1]. A wave form digitizer equipped with FPGA electronics selects these carbons and makes 0.5 MHz operation possible. So, in a minute, the amplitude and the orientation of the polarization vector are determined.

We had 5 weeks of polarized proton run and in the latter half the accelerator delivered an average luminosity of $0.5 \times 10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ with the highest record of $1.8 \times 10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. During that period PHENIX got 150 nb^{-1} and STAR got 300 nb^{-1}.

Figure 2 shows the polarization of each ring(the Blue and the Yellow) over the run period, as measured with the RHIC polarimeter. Good news was polarizations are there in all the runs. So Snake worked well. Bad news was relatively low polarization like 15-20% while we have expected 70%.

The limitation of polarization was in the AGS. It was very unfortunate that, just before the run, the power generator for the AGS malfunctioned and had to be replaced by a less powerful spare. With this supply, the ramp up speed was reduced by two, so the effect of spin resonances was doubled. For the next year, the power generator has been fixed already and the ion source was improved from 70% to 80%. So, we expect about 50%

[1]Without the snake magnets, the precession angle is $2\pi G\gamma$ per turn, where G is the abnormal magnetic moment of proton. Depolarization resonance occurs when $G\gamma$ becomes integer (every 523MeV). The snake magnets eliminate those resonaces by canceling the precession in each turn.

[2]The energy dependence of the CNI analyzing power is expected to be small. A polarized proton gas jet target is under development to calibrate it in an absolute scale.

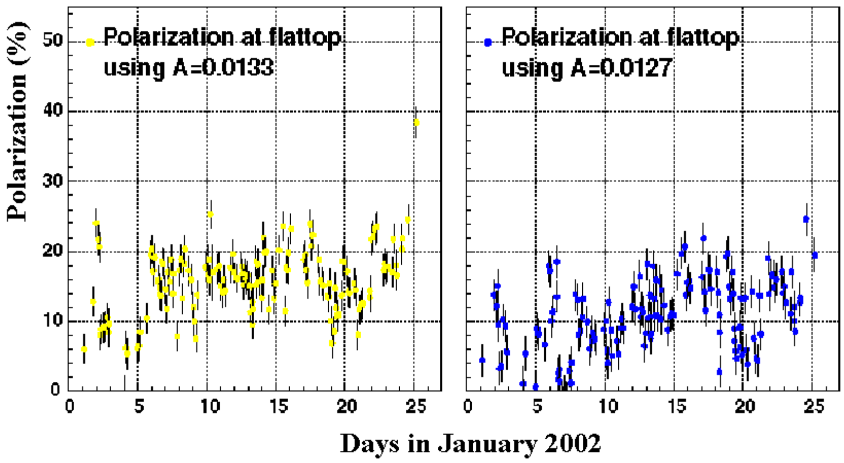

Figure 2. Polarization of the Yellow(left) and Blue(right) beams throughout the run, January 2002.

of polarization in the coming run. In the future, a new AGS helical snake is under development. With the new AGS snake, we do not have any polarization losses in the AGS. We will have 70-80% polarization in the RHIC ring.

Next year we will have more ions in a bunch, the number of bunches will be increased from 55 to 110 as designed, the β^* tune was 3 m which will be 1 m as designed. So, we anticipate almost a factor of ten increase in the luminosity for the next run with the polarization of about 50%. It will take some time to get higher luminosity as all the accelerators in history, and both the experiments and accelerator are on a great learning curve.

3. PHYSICS WITH SPIN COLLIDER

There are 3 spin experiments at RHIC. STAR and PHENIX are the larger ones. PP2PP2 is a smaller one [3]. Both STAR and PHENIX are equipped with spin rotators, almost same device as the snake magnet. Any type of the spin direction can be chosen at these collision points without any interference to other experiments. PP2PP is to measure elastic scattering. They use silicon detectors in two Roman Pots in the both sides of the collision point. To reach small t below 0.004 GeV/c^2, they require a different setting of beam, larger β^* like 10m. So they cannot always run together with others.

The RHIC spin collider was born to solve the spin puzzle. To obtain a complete picture of the spin structure of the nucleon, it is essential to combine spin-dependent hadron-induced reactions with different probes. In the lepton deep inelastic scattering, virtual photons are only sensitive to electric charge. Therefore, it is difficult either to separate flavors or to probe gluons.

The first target with RHIC is Δg, the gluon polarization in nucleon. With Spin Col-

[3]Another experiment BRAHMS is planning to measure A_N at forward x_F over a broad p_T range in the coming runs.

lider, we are also able to measure anti-quark polarization, and transversity, the structure function in transversely polarized nucleon. As a kind of bi-products, we have a lot of new tool to understand the strong interaction. The entire scope of RHIC spin physics is well described in the reference[2].

The unpolarized gluon distribution has been studied using the cross sections for prompt photon, jet, and heavy quark productions in hadron collisions, by both fixed target and collider experiments. In addition, Q^2 evolution of the structure function $F_2(x, Q^2)$, obtained in lepton scattering experiments, has been used to constrain the gluon distribution in the small-x region. These efforts have led to a gluon distribution with a reasonable precision. For the polarized case, by the Fermilab E704 experiments, helicity asymmetries A_{LL} for high-mass multi-γ pair production in polarized pp collisions has been measured at $\sqrt{s}$=19.4 GeV[3]. The data were compared with the model calculation of A_{LL} and provided a restriction on Δg, but the statistical significance was marginal.

In lepton scattering experiments, $\Delta g(x)$ has been determined through Q^2-evolution of the spin dependent structure function $g_1(x, Q^2)$ but the uncertainty is still too large and leaves a room for any models. Recently, a proposal to use pairs of oppositely charged hadrons to probe the photon-gluon fusion process to access gluons in lepton scattering experiments has been made[4]. The HERMES experiment at DESY has measured such an asymmetry and gave the first finite Δg values but with large errors[5]. The interpretation, however, is still controversial due to a difficulty of theoretical treatments. At RHIC, the best Δg measurement will be done with prompt photon production via longitudinal double-spin asymmetry.

To visualize the importance of the RHIC gluon measurements, Figures 3 explain how well the gluon polarization is determined by DIS experiments up to now, and how it becomes better after 100 days of direct photon measurement at RHIC at $\sqrt{s}$=200 GeV with the designed luminosity. One can find that a great improvement is expected for the determination of the gluon polarization. It is worthwhile mentioning that this study even assumes a shape of $\Delta g(x)$, which is still not known at all.

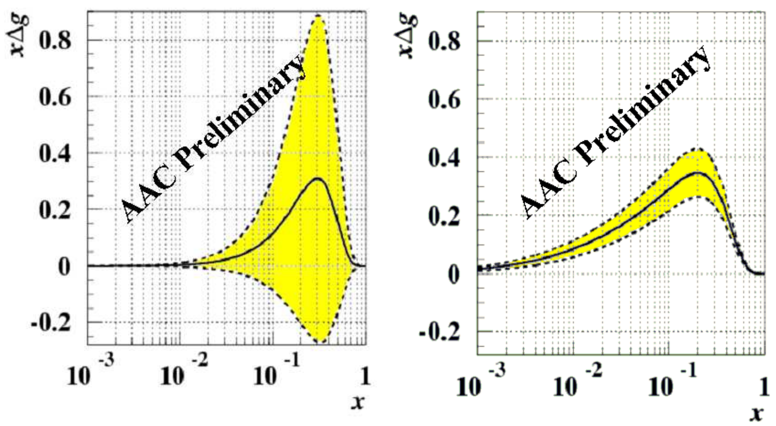

Figure 3. Left) Present precision of the gluon helicity distribution restricted from all the available DIS data. Right) Precision to be achieved after 1-year data in RHIC. These graphs are given from the Asymmetry Analysis Collaboration and are preliminary[6].

At RHIC, the parity violating asymmetry in W productions will directly measure the polarization of flavor-identified quark and antiquark. These measurements will be done at $\sqrt{s}$=500 GeV by detecting high p_T leptons. Similar quark identification is not possible in lepton scattering experiments without additional model assumptions, while the W production explicitly separates them. In addition to the helicity distributions of quarks and anti-quarks, RHIC Spin is also sensitive to the transversity distributions. One of the cleanest measurements will be provided by the Drell-Yan production of lepton pairs. Recent theoretical work suggested another effective measurement for transversity using two-pion correlation[7], which will be tested in RHIC and will possibly improve our sensitivity to large extent.

4. HIGHLIGHTS FROM THE FIRST YEAR DATA

As a consequence of the low polarization, the entire physics data taking was performed with vertically polarized beams [4]. Thus the goal of the first year was to commission the detectors for polarized proton collisions, to determine the unpolarized pp cross section as a reference for spin and heavy ion physics, and most interestingly to perform the first measurements of single spin left-right asymmetries (A_N) at $\sqrt{s}$ = 200GeV.

PHENIX has measured the π^0 cross section from 1GeV/c to 13GeV/c of p_T [8]. Over 10^8 of magnitude, the spectrum was nicely reproduced by a NLO-pQCD calculation within the uncertainties from the scale dependence[9]. Although the statistics were limited, PHENIX has measured J/ψ's[10] with a consistent rapidity distribution to PYTHIA and the total cross section consistent to the color evaporation model.

The left- right asymmetry, A_N, is expected be small in high x_T due to the nature of pQCD. Previous experimental studies showed so far zero-consistent results, which will be revisited by the new data from RHIC. In the large x_F region, however, story is different. The data from FNAL E704 at $\sqrt{s}$=20 GeV[11], taken about 10 years ago, showed beautiful asymmetries for π^+, π^0, and π^-. The measured asymmetry reaches a level of 10% in the x_F region larger than 0.3. Recently a lot of theoretical work have been performed to relate this effect to the transversity, spin effect in the fragmentation function, K_T effect, or orbital motion of quark[9]. Theoretical interpretation for this phenomena is, however, not settled yet[5]. Nevertheless, there were enough reasons to believe this dependence is scale to x_F, and the region to watch is not covered by the main detectors of STAR and PHENIX so that some new detectors were added for such measurements. If the asymmetry exists it will be a wonderful tool - called local polarimeter - to determine the polarization at the interaction points.

Figure 6 illustrates the kinematical coverage of the spin experiments. STAR has prepared the Forward π^0 Detector (FPD) to cover the same x_F region as E704. PHENIX has developed new zero degree calorimeters. And pp2pp covers the elastic scattering region by its nature.

STAR FPD has measured the L-R asymmetries of π^0 production at the pseudo-rapidity

[4]Because the sensitivity of the double spin asymmetry, A_{LL}, is diluted by $1/P^2$.

[5]The essential but unknown ingredient is the spin effect in the quark fragmentation process. Recently, a team comprising PHENIX and STAR members joined the Belle collaboration at KEK to determine the spin dependent fragmentation function in two-quark jet events in the $e^+ + e^-$ collider.

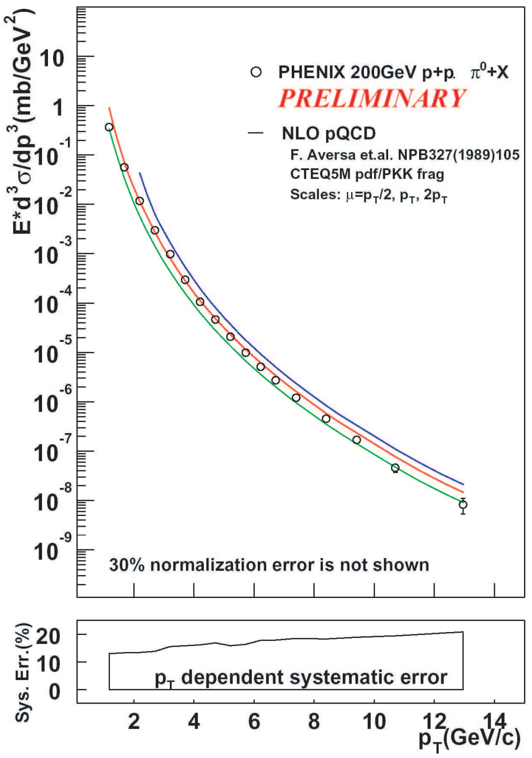

Figure 4. The transverse momentum spectrum of $p + p \to \pi^0 + X$ at mid rapidity, measured at $\sqrt{s} = 200$ GeV by the PHENIX experiment. The data are compared to NLO pQCD calculations.

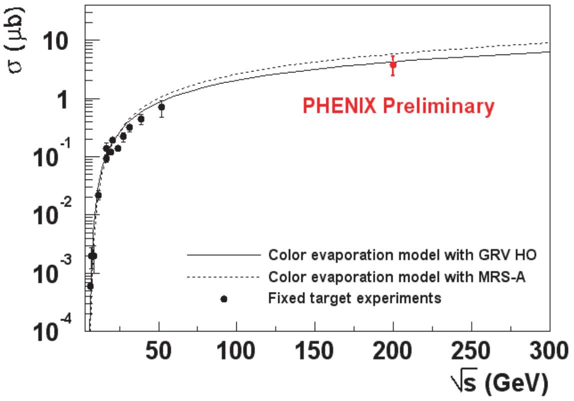

Figure 5. The production cross section of J/ψ at $\sqrt{s} = 200$ GeV is compared to previous experiments. The curve is the prediction of the color evaporation model.

region $3.4 \leq \eta \leq 4.1$, As shown in Figure 7[12] the x_F dependence looks similar to the E704 data as well as the theoretical predictions[13]. This means such an effect still existing at 10 times larger $\sqrt{s}$.

Finally a surprise from 12 o'clock should be mentioned. There, developments of the PHENIX local polarimeter has been performed. Before and after the collision point there are dipole magnets to steer both beams into parallel. So, beyond these magnets only neutral particles can be measured. There they placed a hadron-calorimeter type counter in one end and an EM calorimeter type in the other end. Both of them were segmented to measure left-right asymmetries. The kinematical coverage is schematically shown in Figure 6 as the detectors covered very small p_T below 300 MeV/c in the x_F region larger than 0.3.

Figure 8 shows the measured asymmetry for forward neutrons. Large asymmetry in neutron ($\sim$-10%) was consistently observed in the both calorimeters. The γ events have small asymmetry ($\sim$ -1%), and π^0's showed no significant asymmetry. They have confirmed that the neutron asymmetry as shown in Figure 9 has the expected angular dependence for a true left-right asymmetry. Such neutron asymmetry has never been observed before. Its existence and its amplitude are both unexpected. It is a bit ironical that the device

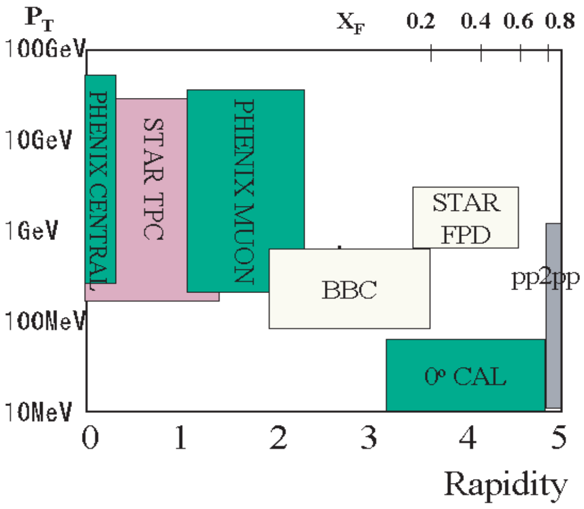

Figure 6. The kinematical coverage of the RHIC spin experiments (very schematic).

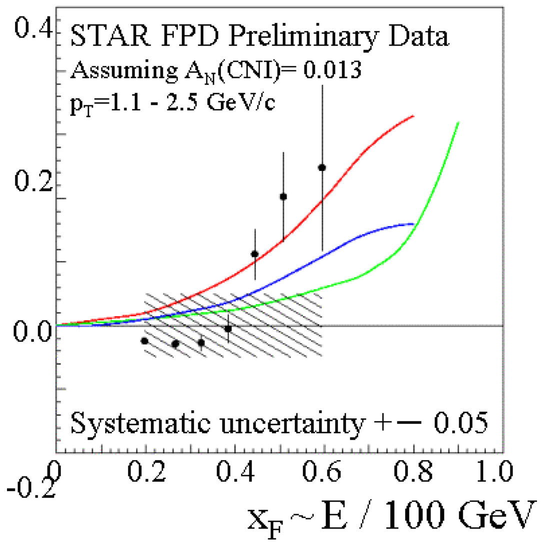

Figure 7. The analyzing power of π^0 production measured by STAR FPD, at the pseudo-rapidity region $3.4 \leq \eta \leq 4.1$. The curves are the theoretical predictions[13].

was developed aiming to see the π^0 asymmetry, but the nature is apparently beyond our imagination. We hope to have a consistent picture for all these A_N measurements, which is now under consideration by many theorists.

In the low x_F and the high x_T region where our 100M$ detectors are situated, STAR reported the analyzing power of charged hadrons up to p_T=5 GeV/c[14]. The results are consistent with zero as expected from pQCD. It should be stressed that measurements in this region become very important in the next year with longitudinally polarized beams. Both jet measurements in STAR and leading hadron measurements in PHENIX will access Δg directly.

5. SUMMARY AND OUTLOOK

The RHIC spin program has begun. We have a series of programs over 5 years to go. In Year 2002, the first polarized proton collision was successfully carried out with transversely polarized beams, producing even unexpected spin phenomena which may relate to unknown behavior of QCD (transversity, *etc.*). With spin-state averaged beams, the validity of pQCD calculation is being confirmed over a broad range of p_T.

In Year 2003, the first measurements of helicity asymmetry will soon be performed at 200 GeV. Sizable Δg would generate surprises in the data.

In Year 2004 or later, statistics will be much improved at 200 GeV, ensuring the determination of Δg. The spin puzzle will hopefully be solved by then. Also weak bosons will be produced at RHIC at 500 GeV, the new flavor sensitive tool for anti-quark/quark polarizations and unpolarized structure functions of anti-quark measurements.

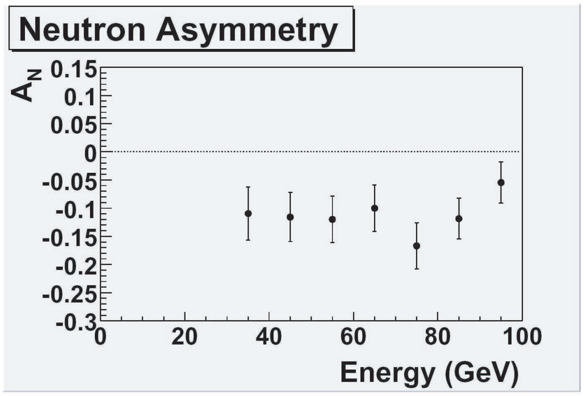

Figure 8. The asymmetry observed for neutrons in the local polarimeter development for PHENIX (preliminary).

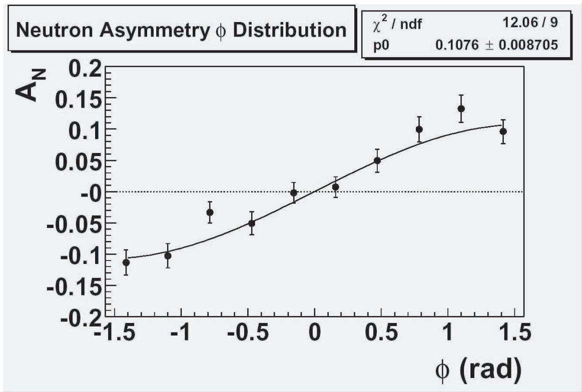

Figure 9. Angular dependence of the neutron asymmetry (preliminary). The abscissa is angle with respect to the spin direction of the incoming beam.

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