RHIC SPIN PROJECT – OPENING A NEW ERA OF HADRON PHYSICS –

HIDETO EN'YO

RIKEN (The Institute of Physical and Chemical Research), Wako, Saitama 351-0198, Japan

and

RIKEN- BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973, USA

E-mail:enyo@riken.go.jp

Polarized pp collisions at 200 GeV of the center of mass energy will take place for the first time in December 2001, which opens a unique opportunity to study the spin structure of the nucleon and the symmetries in nature. This new field of physics is opened under the treaty between RIKEN and Brookhaven National Laboratory by adding necessary equipments in RHIC, Relativistic Heavy Ion Collider. The physics program with polarized beams at RHIC is overviewed

1. Introduction

Although we are still remembering the sudden termination of SSC, there was another collider called ISABELL abandoned in 1983 at Brookhaven National Laboratory leaving a tunnel with a circumference of 3.85 km. The project was reborn after more than 15 years of sleep as the first heavy ion collider and the first polarized proton collider. The new collider RHIC consists of two independent rings and is able to collide any nuclei on any other nuclei with the nucleon-nucleon center of mass energies $\sqrt{s_{NN}}$ of 48 - 500 GeV in proton-proton collisions and 22 - 200 GeV in gold-gold collisions. Luminosities are expected to reach 2 x 10^{32} in p-p and 2 x 10^{26} in Au-Au collisions.

In year 2000, the first collision was achieved for Au on Au at $\sqrt{s_{NN}}$ of 130 GeV, and commissioning of polarized proton acceleration was successfully done. In year 2001 at the time of this symposium we are already taking the data at $\sqrt{s_{NN}}$ = 200 GeV for Au-Au collisions, at the time of writing this manuscript the machine study of polarized proton acceleration is taking place, and we expect the first collision to be achieved in the middle of December of year 2001. This manuscript describes the RHIC spin project with physics highlights expected from this new Spin Collider.

2. Physics of RHIC spin project

Nucleon is a bound state composed of 3 valence quarks glued together with gluon. It has spin 1/2 so that the simplest spin picture of nucleon is that the three quarks are in the s state with spin directions of (1/2,1/2, -1/2) configuration. This picture was very naïve but quite successful in describing the magnetic moments of many baryons. In this picture the fraction $\Delta\Sigma$ of proton spin carried by quarks $(\Delta u, \Delta d, \Delta s)$ is unity,

$$\Delta\Sigma = 1 = \Delta u + \Delta d + \Delta s \,.$$

Sehgal already pointed out theoretically the fragileness of this simple picture in 1974[1]. He took the Bjorken sum rule[2] and neglected s-quark polarization, and concluded that ΔΣ=0.6. To convince this puzzle experimentally the spin structure of the nucleon has been studied for over two decades using deep-inelastic scattering of longitudinally polarized leptons off a longitudinally polarized nucleon target. Those measurements have reached the conclusive results around 1989[3,4],

$$\Delta\Sigma = 0.1 \sim 0.3\,,$$

namely this puzzle is even a crisis of our understanding of the nucleon spin structure. Apparently there is a significant spin carrier other than quarks, and we need to go back to the most basic spin sum rule;

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + L_z\,,$$

where Δg is the spin carried by gluon and L_z is the angular momentum of quarks and gluons. More generally, we need to understand the proton in term of the polarized parton distribution function;

$$\frac{1}{2} = \int dx[\frac{1}{2}\Delta u(x) + \frac{1}{2}\Delta d(x) + \frac{1}{2}\Delta s(x) + \Delta g(x)] + L_z\,,$$

to obtain a complete picture of the nucleon spin structure. Another important implication from the deep-inelastic scattering experiments was that $\Delta s \neq 0$, i.e. the strange quark polarization is not zero although the total strange content in the nucleon is zero. This also indicates the anti-quarks (sea quarks) are possibly be polarized as well. Thus the important questions remain are; 1) is the gluon polarized? 2) is the sea quark polarized? and 3) is there angular momentum exist in the nucleon?

The RHIC spin project is planned to solve most of the issues described above. Especially direct measurements of gluons and anti-quarks are the highlights over the deep-inelastic scattering, since virtual photons from an incident lepton can neither probe the neutral partons (gluons) nor identify antiquarks from quarks.

The other new category, to be measured at RHIC Spin Collider, is the transversity distribution, which is the parton structure function, to appear in the collision of a transversely polarized proton on a transversely polarized proton. Although this structure function is known to exist in the leading order, no experimental measurements are done so far. The measurements will become available in RHIC and complete Table 1, i.e. to complete our picture of the nucleon spin structure.

Table1: parton distributions of the nucleon in the leading order. Horizontal and vertical arrows denote spin direction of parton in helicity and transverse direction, respectively.

	Quark	Gluon
Spin average distribution	$q(x) = \vec{q} + \overleftarrow{q} = q^{\uparrow} + q^{\downarrow}$	$g(x) = \vec{g} + \overleftarrow{g}$
Helicity distribution	$\Delta q(x) = \vec{q} - \overleftarrow{q}$	$\Delta g(x) = \vec{g} - \overleftarrow{g}$
Transversity distribution	$\delta q(x) = q^{\uparrow} - q^{\downarrow}$	Not applicable

Once these spin structure functions are measured to a reasonable precision, the polarized proton beams can be regarded as quark and gluon beams with known luminosities and energies, which can be used to explore searches of new physics. Especially parity violating effects can be extracted by using longitudinally polarized quark beams, which can potentially reveal the substructure of a quark[5].

3. The first polarized collider: RHIC

The layout of the RHIC polarized collider is shown in Figure 1. The major machine parameters are listed in Table 2. There are five experiments, Brahms, Star, Phenix, Phobos, and pp2pp. Amongst those, Star, Phenix, and pp2pp are to perform spin physics measurements, and the potential of spin physics with Brahms and Phobos is also being studied. It is worth mentioned that the energy region covered with this program is more than a factor of 10 higher comparing to previous fixed target experiments.

To realize polarized proton collisions at such energy, many aspects are changed and added to the original RHIC design. The optically pumped polarized ion source was supplied from KEK, modified in TRIUMPH and moved into the BNL Linac. A solenoidal magnet and an RF dipole were installed in AGS (Alternate Gradient Synchrotron) to keep the polarization up to 24GeV of the injection energy to the RHIC main ring.

As the most important equipment for the spin collider, technology to fabricate a super-conducting helical dipole magnet was developed. This device is essential to realize the Siberian Snake magnets and the Spin Rotators in RHIC. The Snake magnets are used to maintain polarization in accelerating and storing beams by flipping spin direction by 180^{o} around the beam in every half or full revolution to cancel the accumulated spin precession. The Spin Rotators are used to change the spin direction at collision points as needed for the experiments and to return it back to the original direction. Those Spin Rotators are to be installed for the two large experiments, Phenix and Star.

Figure 1: Outline of RHIC polarized collider

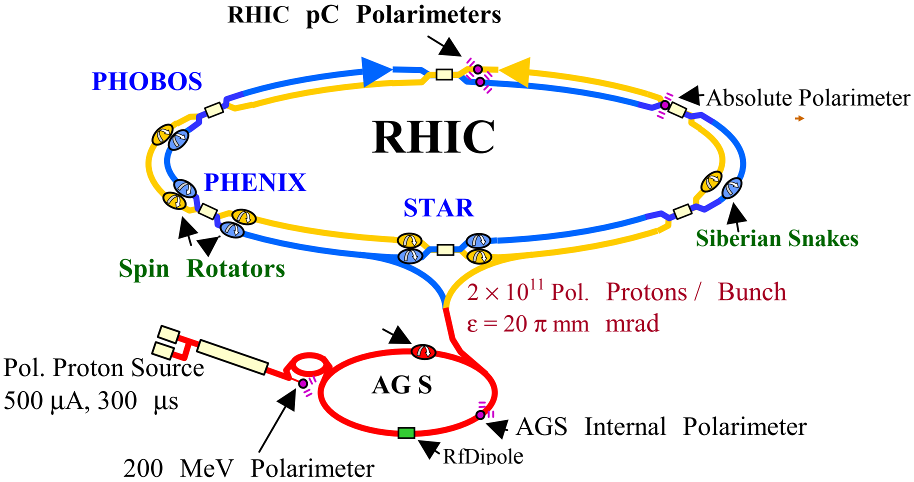


Table 2: RHIC accelerator specification.

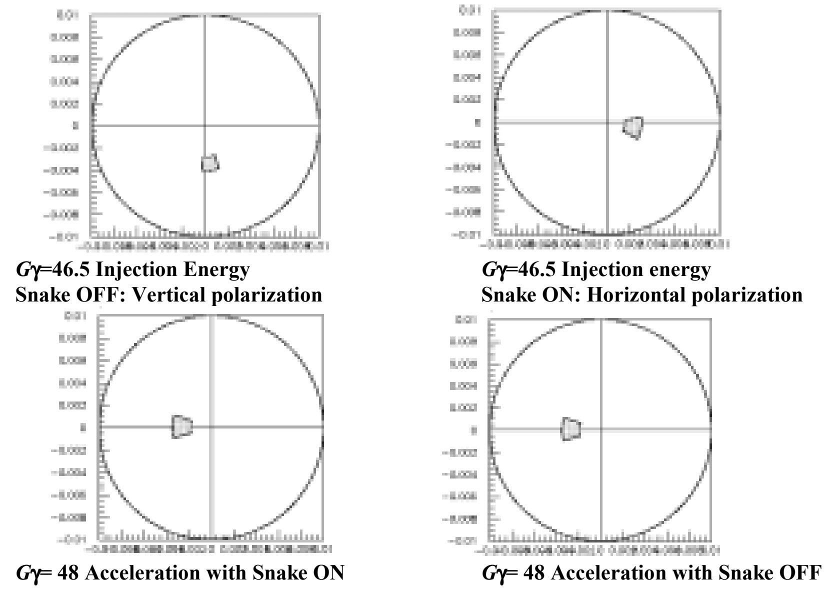
Configuration	Two Concentric Super-conducting magnet Rings	
Circumference	3.8 km	
Interaction point	6	
Number of Bunches	60; 120 in enhanced mode	
Ion Species	Ranges from proton to Gold, p+A /A'+A are possible	
	p+p	Au+Au
Injection &	Linac-Booster-AGS	Linac-Booster-AGS
E_{cm}(Maximum)	500 GeV	200 GeV
Luminosity	$2x10^{32}/cm^2/s$	$2x10^{26}/cm^2/s$
Polarization	70%	

In year 2000, following a successful physics run with gold ion beams, we commissioned one RHIC ring with a polarized proton beam. In the commissioning, the polarimeter is the most critical device to tune the machine for the maximum polarization. We have developed the polarimeter basing on proton-Carbon elastic scattering in the Coulomb-Nuclear Interference (CNI) region and installed in the RHIC ring. The analyzing power A_N is expected to be as large as 4% at $t = 3x10^{-3}$ $(GeV/c)^2$. The recoiled Carbon was detected with Si-strip detectors which are placed 15 cm from a carbon target surrounding azimuthally around the beam line at $\phi = 45^o$, 135^o, 225^o and 315^o. This configuration allows us to measure the direction of the polarization vector.

The proton beam with vertical polarization was injected to the RHIC ring at 24.3GeV ($G\gamma$=46.5)[1] with the Siberian Snake off. In this case, the stable spin direction is vertical, and the measured asymmetry clearly showed vertical polarization. The polarization is estimated to be $19 \pm 1\%$ (see Figure 2). Then we turned the Snake on adiabatically to rotate the spin to the horizontal direction.

The beam was accelerated to 25.1GeV ($G\gamma$=48), where we expected the spin direction to be rotated by 180^o, and we observed the spin vector as expected. It is also demonstrated that no polarization was maintained with the snake off. Through this test the principle of the snake magnet operation was proven.

Figure 2: Measured asymmetries during the spin commissioning. Measured polarization vectors are shown in (top left) $G\gamma$=46.5 with the Snake off, and (top right) with the Snake on, (bottom left) $G\gamma$=48.0 with the Snake on and (bottom right) with snake off.



$G\gamma$=46.5 Injection Energy
Snake OFF: Vertical polarization

$G\gamma$=46.5 Injection energy
Snake ON: Horizontal polarization

$G\gamma$= 48 Acceleration with Snake ON
Horizontal polarization

$G\gamma$= 48 Acceleration with Snake OFF
Polarization lost

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[1] G is anomalous magnetic moment of the proton and γ is a Lorentz factor. $G\gamma$ is often used rather than beam energy, because it represents the number of spin precession per turn.

4. The highlights of physics outputs for the first few years

Here we review the physics highlights assuming the integrated luminosities of 800pb^{-1} for $\sqrt{s}$ =500GeV and 320pb^{-1} for $\sqrt{s}$ =200GeV, which correspond to 100 days of running with 50% efficiency with full luminosities. We are expecting to obtain such integral luminosities in the first few years of the RHIC operation.

Measurements in the RHIC spin program

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. On the other hand in hadron collision the Drell-Yan process producing lepton pairs guarantees the main contribution come from quark-antiquark annihilation. Prompt photon production is dominated by gluon Compton scatterings, which measures gluon-quark collisions. The gluon-fusion process dominates open heavy flavor productions. Such selectivity is fascinating merit of hadron-induced interaction.

Spin asymmetries for various reaction channels in polarized p+p collisions are listed with the primary goals of their measurement in Table 3.

Table 3: Spin asymmetries for various pp reaction channels with major goals of their measurements. References shown do not necessarily represent the initial work.

Channel	A_{LL}	A_L	A_{TT}	A_N
$pp \to \gamma X$	$\Delta g \times A_1^P$[6]	-	0 [7]	Twist-3 [8]
$pp \to jet \cdot X$	$\Delta g \times (\Delta g + \Delta\Sigma)$[9]	Sub quark [10]	0 [7]	-
$pp \to Q\overline{Q}$	$\Delta g \times \Delta g$[11]	Z, Higgs doublet[12]	-	-
$pp \to W^+ \cdot X$	$\Delta u \times \Delta\overline{d}$ [13]	$\Delta u \times \Delta\overline{d}$ [13]	~ 0[14]	-
$pp \to W^- \cdot X$	$\Delta\overline{u} \times \Delta d$ [13]	$\Delta\overline{u} \times \Delta d$ [13]	~ 0[14]	-
$pp \to \gamma^* \cdot X$	$\Delta q \times \Delta\overline{q}$ [15]	γ^*/Z mixing[16]	$\delta q \times \delta\overline{q}$ [17]	Twist-3 [18]

Gluon Helicity Distribution

The unpolarized gluon distribution has been studied using the cross sections for prompt photon, jet and heavy quark productions in hadron collisions, both in 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 $\sqrt{s_{NN}}$ =19.4 GeV[19]. 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, Δg(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[20].

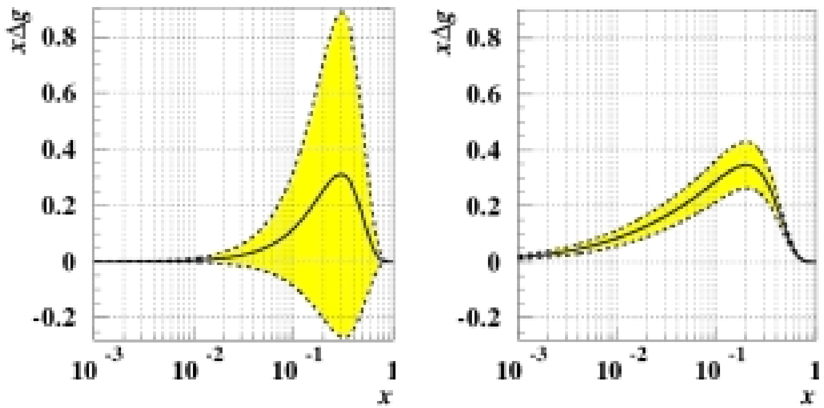
Recently a proposal to use pairs of oppositely charged hadrons to probe the photon-gluon fusion process to access gluons in lepton scattering experiments has been made [21]. The HERMES experiment at DESY has measured the asymmetry and gave the first finite Δg values with large errors[22]. The interpretation, however, is still controversial due to a difficulty of theoretical treatments.

At RHIC, the best Δg measurement will be done with prompt photon productions. Its longitudinal double-spin asymmetry is expressed as;

$$A_{LL} = \frac{\sigma(++) - \sigma(+-)}{\sigma(++) + \sigma(+-)} \approx \frac{\Delta g(x_1)}{g(x_1)} \frac{\Sigma_q e_q{}^2[\Delta q(x_2) + \Delta\overline{q}(x_2)]}{\Sigma_q e_q{}^2[\Delta q(x_2) + \Delta\overline{q}(x_2)]} \widehat{a}_{LL}(qg \to \gamma q),$$

where $\widehat{a}_{LL}$ is the partonic level asymmetry and is calculable in perturbative QCD, and the quark part is well knows as $A_1{}^P$ from lepton deep-inelastic scatterings (DIS). The only unknown, Δg(x)/g(x), is thus deduced from the measurement.

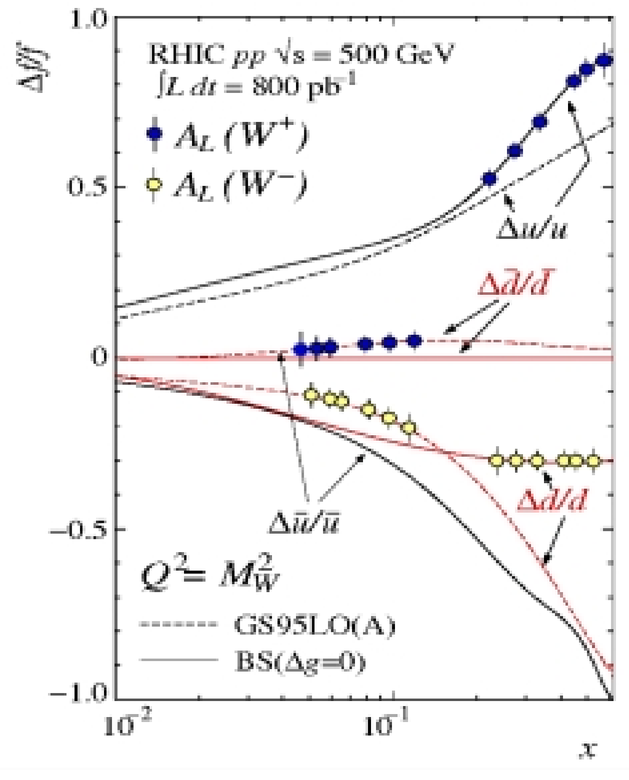
Figure 3: Left) Present precision of the gluon helicity distribution restricted from all the available DIS data. Right) Precision to be achieved after 1-year data in RHIC. These graphs are given from the Asymmetry Analysis Collaboration (AAC: M. Hirai *et al.*) and are preliminary .



To visualize the importance of the RHIC gluon measurements, Figure 3 illustrates the present situation of Δg(x)/g(x) determination (left) and the one after 1 year of RHIC measurements (right). The left figure shows the Δg(x)/g(x) uncertainty constrained by all the available data up to now. One can find a great improvement is expected for the determination of the gluon polarization. It is worth mentioned that this analysis even assumes a shape of Δg(x), which is still not known at all.

Flavor Decomposition of Quark and Anti-Quark, Transversity

Figure 5:Polarization of $u, d, \bar{u}, \bar{d}$ quarks as functions of *x,* modeled by Bourreley-Soffer, and Gehrmann-Stirling. Sensitivities of the RHIC Spin *W* measurements are shown.



At RHIC, the parity violating asymmetry in *W* productions will directly measure the polarization of identified quark and antiquark, namely;

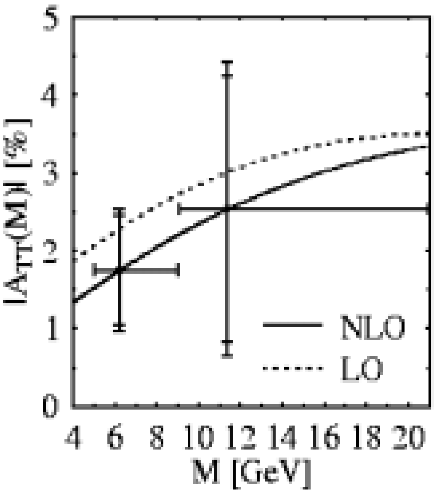
$$A_L(W^+) = \frac{\Delta u(x_1)\overline{d}(x_2) - \Delta\overline{d}(x_1)u(x_2)}{u(x_1)\overline{d}(x_2) + \overline{d}(x_1)u(x_2} \quad \text{and}$$

$$A_L(W^-) = \frac{\Delta d(x_1)\overline{u}(x_2) - \Delta\overline{u}(x_1)d(x_2)}{\overline{u}(x_1)d(x_2) + d(x_1)\overline{u}(x_2}.$$

These measurements will be done at $\sqrt{s_{NN}}$ =500GeV by detecting high p_T leptons. The sensitivity with Phenix Muon Arms is shown in Figure 5. 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. One year sensitivity in Phenix Muon Arm at $\sqrt{s}$ =200 GeV is shown in Figure 6. Although the sensitivity seems marginal in this plot, the measurement will serve as the first and cleanest measurement and will become powerful when the proposed upgrade in luminosity and energy are achieved. Recent theoretical work suggested another effective measurement for transversity using two-pion correlation[23], which will be tested in RHIC and will possibly improve our sensitivity to large extent.

Figure 6: Double transverse-spin asymmetry for Drell -Yan dimuon production at $\sqrt{s_{NN}}$ =200GeV. Phenix Muon Arm sensitivity of 1-year measurements is shown.



5. SUMMARY

We have reviewed the physics highlights with the first polarized proton collider, RHIC, and its status towards the first spin physics runs in 2001. Further descriptions can be fond in the reference[24]. With the RHIC spin program we will see the deep insight of nucleon that has been unknown over 20 years, and with the original plan of heavy ion collision we will create the new state of matter, Quark Gluon Plasma. The both programs together are opening a new era of hadron physics in the beginning of 21st Century.

Acknowledgments

The idea of RHIC spin collider emerged in 1990. Since then so many people contributed to realized the project for over 10 years. The author is very much grateful to those who have supported the project from various aspects. We are finally taking off. It should be noted again that without RIKEN this project has never been in life. The author would like to thank the organizers of this symposium and whishes to have more Italian friends participating in RHIC spin physics

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