SPIN PHYSICS
A NEW TWIST ON HEAVY-ION EXPERIMENTS AT RHIC [a]

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Operation of RHIC with two beams of highly polarized protons (70%, either longitudinal or transverse) at high luminosity $\mathcal{L} = 2 \cdot 10^{32}$ cm^{-2} sec^{-1} for two months/year will allow high statististics studies of polarization phenomena in the perturbative region of hard scattering where both QCD and ElectroWeak theory make detailed predictions for polarization effects. The collision c.m. energy, $\sqrt{s} = 50 - 500$ GeV, represents a new domain for the study of spin. Direct photon production will be used to measure the gluon polarization in the polarized proton. A new twist comes from W-boson production which is expected to be 100% parity violating and will thus allow measurements of <u>flavor separated</u> quark and antiquark (u, $\bar{u}$, d, $\bar{d}$) polarization distributions. Searches for parity violation in strong interaction processes such as jet and leading particle production will be a sensitive way to look for new physics beyond the standard model, one possibility being quark substructure.

1 Spin Physics with Polarized Protons at RHIC

Soon after the approval of the Relativistic Heavy Ion Collider (RHIC) in 1990, a group of experimental, theoretical and accelerator physicists formed the RHIC Spin Collaboration (RSC) to prepare the case for a program of physics using Polarized Protons at RHIC. [1,2] The project "came onto the mass shell" in September 1995 with the signing of the BNL-RIKEN Agreement on Spin Physics. RIKEN, The Institute of Physical and Chemical Research, a non-profit research institute supported by the Science and Technology Agency of Japan, is providing \$20M for the accelerator components (spin rotators, siberian snakes, polarimeters) and a second muon arm in PHENIX to implement the RIKEN-BNL RHIC/Spin Physics Collaboration.

At RHIC, both longitudinally and transversely polarized protons will be provided at the interaction regions. This facility would be unique in the ability to perform parity-violating measurements with hadrons and polarization tests of QCD including polarized structure function measurements of gluons and flavor-separated quarks and anti-quarks. Polarization will be exploited to test fundamental symmetries in strong interactions and to search for new effects beyond the standard model. Single spin transverse asymmetries, as well as the

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new physics of transversity—the fraction of transverse polarization of a proton carried by its quarks—will be studied. Also, the existence of $p-p$ collisions in the energy range $\sqrt{s} = 50 - 500$ GeV will permit the study of some classical reactions like the total cross section and elastic scattering [3] as a complement and extension of the CERN and Tevatron $p-\bar{p}$ measurements.

2 Helicity Asymmetry Measurements

Spin effects can be observed with fine precision since they involve the measurement of asymmetries. The effect of systematic errors in the detectors and accelerator can be minimized by frequent polarization sign reversal and careful preparation of the initial polarized beams to give equal luminosities in all polarization states. The goal is to polarize the beams for all proton runs including the possibly extensive $\sqrt{s} = 200$ GeV comparison runs for the Relativistic Heavy Ion (RHI) program. Experiments not interested in polarization will obtain the spin-averaged result to a high accuracy.

2.1 A_{LL}—Parity Conserving Two-Spin Longitudinal Asymmetry

The polarization of a longitudinally polarized proton beam has two possible states, parallel to the momentum ('+' helicity) or opposite to the momentum ('−' helicity). In asymmetry definitions at RHIC, care must be taken to account for the possibility of large parity violating effects. We use the notation $\sigma^{++} = N^{++}/(P_1 P_2 L^{++})$ for the measured cross section with both beams having '+' helicity—where N^{++} is the measured number of events for an integrated luminosity L^{++} and P_1 and P_2 are the polarizations of the beams[b]—with analogous notation for the other helicity combinations. The two-spin parity-conserving longitudinal asymmetry, A_{LL} is defined: [4]

$$A_{LL} = \frac{\sigma_{ll}}{\sigma_{uu}} = \frac{\frac{1}{4}(\sigma^{++} + \sigma^{--} - \sigma^{+-} - \sigma^{-+})}{\frac{1}{4}(\sigma^{++} + \sigma^{--} + \sigma^{+-} + \sigma^{-+})} \tag{1}$$

where the denominator is clearly the spin-averaged (unpolarized) cross section. If parity is conserved, the theoretical cross sections obey the relations $\sigma^{++} = \sigma^{--}$ and $\sigma^{+-} = \sigma^{-+}$, leading to the more conventional definition:

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \tag{2}$$

[b] P_1 and/or P_2 are dropped for unpolarized sums.

2.2 Parity Violating Asymmetries (PVA's)

The familiar single spin Parity Violating Asymmetry A_L for one polarized beam has a more interesting form at RHIC, where both beams are polarized:[4]

$$A_{Lu} = \frac{\sigma_{lu}}{\sigma_{uu}} = \frac{(\sigma^{--} + \sigma^{-+}) - (\sigma^{+-} + \sigma^{++})}{\sigma^{++} + \sigma^{--} + \sigma^{+-} + \sigma^{-+}} \tag{3}$$

with a corresponding definition for A_{uL}. Also discussed is the symmetric two-spin parity-violating asymmetry[5]

$$A_{LL}^{PV} = \frac{\sigma^{--} - \sigma^{++}}{\sigma^{--} + \sigma^{++}} = \frac{A_{Lu} + A_{uL}}{(1 + A_{LL})} \tag{4}$$

which can be twice as big as A_L for special cases.[5,6]

2.3 Statistical Errors on Asymmetries

Assuming equal integrated luminosity for each spin configuration, with N total number of events summed over the relevant spin configurations, e.g. $N = N^{++} + N^{--} + N^{+-} + N^{-+}$, the error on the measured asymmetry A is approximately:

$$\delta A_{LL} = \frac{1}{P_1 P_2} \sqrt{\frac{1 - A^2}{N}} \quad \text{and} \quad \delta A_L = \frac{1}{P} \sqrt{\frac{1 - A^2}{N}} \quad . \tag{5}$$

For the purposes of this article, it is assumed that the statistical error in the number of events is the dominant error, with much smaller systematic errors.

3 Luminosities for Rate Calculations and Sensitivity Estimates

The expected luminosities for polarized proton at RHIC are $\mathcal{L} = 2 \times 10^{32}$ cm^{-2} sec^{-1} at $\sqrt{s} = 500$ GeV, ~ 1 event/crossing, and $\mathcal{L} = 8 \times 10^{31}$ cm^{-2} sec^{-1} at $\sqrt{s} = 200$ GeV. It is assumed that the $\sqrt{s} = 500$ GeV run is dedicated for spin physics and, since the goal is to polarize the beams for all proton runs, the 200 GeV data are collected during comparison runs for the RHI program. The polarization of both beams is taken as $P_1 = P_2 = 70\%$. The physics sensitivity calculations at each $\sqrt{s}$ are based on runs of 4×10^6 seconds, or about 100 days with a duty factor of $\sim 50\%$, which leads to the integrated luminosities $\int \mathcal{L} dt = 8 \times 10^{38}$ cm^{-2} at $\sqrt{s}$=500 GeV and $\int \mathcal{L} dt = 3.2 \times 10^{38}$ cm^{-2} at $\sqrt{s}$=200 GeV. These initial runs are planned to be accomplished during the first five years of RHIC operation which begins in 1999.

4 QCD and Hadron Collisions

The cross section for hard processes in $p-p$ collisions at c.m. energy $\sqrt{s}$ is taken to be a sum over the constituent reactions, $a+b \rightarrow c+d$

$$\frac{d^3\sigma}{dx_1 dx_2 d\cos\theta^*} = \frac{s d^3\sigma}{d\hat{s} d\hat{y} d\cos\theta^*} = \sum_{ab} a(x_1) b(x_2) \frac{\pi\alpha_s^2(Q^2)}{2\hat{s}} \Sigma^{ab}(\cos\theta^*) \qquad , \tag{6}$$

where (in lowest order (LO) of α_s) $a(x_1)$, $b(x_2)$, are the differential probabilities for constituents a and b to carry momentum fractions x_1 and x_2 of their respective protons, e.g. $u(x_1)$, and $\Sigma^{ab}(\cos\theta^*)$ are the characteristic QCD subprocess scattering angular distributions.[7] The quantities $a(x_1)$ and $b(x_2)$, the "number" distributions of the constituents, are related (for the electrically charged quarks) to the structure functions measured in Deeply Inelastic lepton-hadron Scattering (DIS), e.g.

$$F_1(x,Q^2) = \frac{1}{2}\sum_a e_a^2 \, a(x,Q^2) \quad \text{and} \quad F_2(x,Q^2) = x\sum_a e_a^2 \, a(x,Q^2) \tag{7}$$

where e_a is the electric charge on a quark.

4.1 Spin QCD

The two-spin longitudinal asymmetry for a $p-p$ collision is the sum of the helicity differences for the individual terms in Eq. 6 divided by the overall cross section. If one subprocess dominates, a reasonable estimate of A_{LL} is:

$$A_{LL} \simeq \frac{\Delta a}{a}\frac{\Delta b}{b}\hat{a}_{LL}(a+b \rightarrow c+d) \qquad , \tag{8}$$

where $\Delta a(x)$ is the helicity asymmetry of the constituent structure function

$$\Delta a(x) = a^+(x) - a^-(x) \tag{9}$$

and the '+' and '$-$' refer to constituents with the same or opposite helicity as the parent proton. The spin asymmetry of the subprocess[7] $\hat{a}_{LL}(a+b \rightarrow c+d)$ is a fundamental prediction of QCD, **which has never been verified—to my knowledge.**

5 Direct Photons—The Spin Structure Function of the Gluon

A_{LL} in direct photon production should be a clean measurement of the spin dependent gluon structure function since the dominant subprocess in $p-p$ collisions is

$$g+q \rightarrow \gamma+q \qquad , \tag{10}$$

with $q\bar{q} \to \gamma + g$ contributing on the order of 10%. This small contribution from the annihilation channel can be neglected in the first measurements of $\Delta G(x)$. Predictions[8] for A_{LL} (in NLO) are surprisingly large, in the range 5% to 20%. For inclusive γ detected at 90°, $x_1 = x_2 \simeq x_T$ (PHENIX), the gluon structure function $G(x_T)$ and its spin asymmetry $\Delta G(x_T)$ can be measured:

$$\Delta G(x_T) = \frac{A_{LL}(p + p \to \gamma + X)}{A_1(x_T) \times \hat{a}_{LL}(g + q \to \gamma + q)|_{\theta^* = 90^\circ}} \tag{11}$$

where $A_1(x)$ is a measured spin asymmetry from lepton-proton DIS. [9]. For instance, 120K events are expected in the range $10 \le p_T \le 15$ GeV/c at $\sqrt{s}$ =200 GeV.

6 Structure Function Measurements using Parity Violation

At RHIC the conventional parity violating effects are large. In inclusive single jet production—the leading strong interaction process at RHIC—A_{LL}^{PV} due to the interference of gluon and W exchange at the constituent level is $\sim$ 1%. (See Fig. 1 MS). Of course, a more spectacular effect at RHIC concerns the direct production of the Weak Bosons $W^\pm$ and Z^0. The peak from $W \to$ Jets is evident in Fig. 1. The cleanest channel is the leptonic decay $W^\pm \to e^\pm + X$,

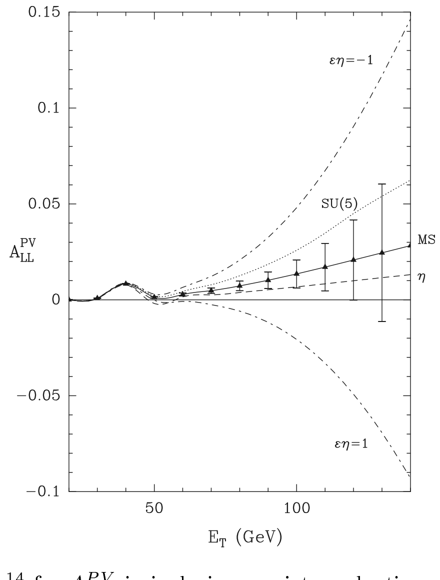

Figure 1: Prediction[14] for A_{LL}^{PV} in inclusive one-jet production at RHIC ($\Lambda_c = 1.6$ TeV)

where the X means that the measurement is via the inclusive $e^{\pm}$ channel with no "missing energy" detection. This is a textbook example of a process with virtually no background for which PVA is really **HUGE** at production [10], on the order of **UNITY**. Both PHENIX and STAR have respectable counting rates (see Table 1). In the standard model, the differential cross section for the reaction

$$pp \to W^{\pm} + \quad \text{anything} \tag{12}$$

is given in leading order by the quark-antiquark fusion reactions $u\bar{d} \to W^{+}$ and $\bar{u}d \to W^{-}$. The parity violating single-spin asymmetry for W^{+} production is given by [6]

$$A_L^{W^+}(y) = \frac{\Delta u(x_1, M_W^2)\bar{d}(x_2, M_W^2) - \Delta\bar{d}(x_1, M_W^2)u(x_2, M_W^2)}{u(x_1, M_W^2)\bar{d}(x_2, M_W^2) + \bar{d}(x_1, M_W^2)u(x_2, M_W^2)} \quad . \tag{13}$$

The sensitivity to unknown spin structure functions is generally much larger for the W^{-} than the W^{+}, which is easy to understand by simple arguments [6]. Near $y = 0$, the PVA's are given to a good approximation by

$$A_L^{W^+} = \frac{1}{2}\left(\frac{\Delta u}{u} - \frac{\Delta\bar{d}}{\bar{d}}\right) \quad \text{and} \quad A_L^{W^-} = \frac{1}{2}\left(\frac{\Delta d}{d} - \frac{\Delta\bar{u}}{\bar{u}}\right) \quad , \tag{14}$$

and $\Delta u/u$ is large and well measured [9]. For large positive rapidity, $x_1 \gg x_2$, so that $A_L^{W^+} \simeq \Delta u/u$, $A_L^{W^-} \simeq \Delta d/d$; similarly at large negative rapidity, $x_1 \ll x_2$, $A_L^{W^+} \simeq -\Delta\bar{d}/\bar{d}$, $A_L^{W^-} \simeq -\Delta\bar{u}/\bar{u}$.[c] (See Fig. 2.)

The expected sensitivities for spin-structure measurements in PHENIX using the latest Bourrely and Soffer polarized structure functions [11] are shown in Fig. 2. Table 1 gives an overall PHENIX/STAR comparison.

7 New Physics—Composite Models or Other Surprises

Composite models of quarks and leptons [12] generally violate parity, since the scale of compositeness $\Lambda_c \gg M_W$. Without the PVA handle, detectors at the Tevatron are limited to searching for substructure by deviations of jet production from QCD predictions at large values of p_T. It is difficult to prove that a small deviation is really due to something new. However a few % parity-violation effect would be **a clear indication of new physics**. The limit is presently [13] $\Lambda_c \cong 1.6$ TeV with which the latest estimate of sensitivity at RHIC [14] is shown on Fig. 1. The limits accessible at RHIC are comparable to Tevatron Run II, $\Lambda_c \sim 3$ TeV. Structure function uncertainties can be calibrated out using the PVA in $W \to$ Jet (inclusive) which is clearly visible on the plot.

[c] x_1 and x_2 can be distingushed in a single-spin asymmetry.

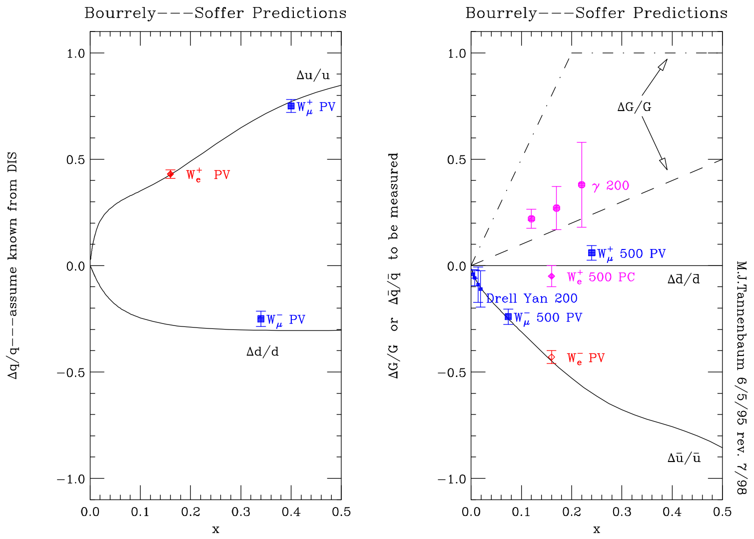

Figure 2: Expected sensitivities for spin-structure function measurements in PHENIX shown with Bourrely-Soffer distributions [11] for 800 pb^{-1} at $\sqrt{s} = 500$ GeV and 320 pb^{-1} at $\sqrt{s} = 200$ GeV

Table 1: RHIC Spin Collaboration:PHENIX/STAR Comparison

	PHENIX	**STAR**
$W^{\pm} \to l^{\pm} + X$ Parity Violation, $\Delta\bar{q}$	$e^{\pm}$: 15K W^+, 3K W^- $\mu^{\pm}$: 9K W^+, 10K W^-	$e^{\pm}$: 72K W^+, 21K W^-
$Z^0 \to l^+ l^-$ Transversity $h_1(x)$, $\bar{u}(x)$	e^+e^-: 120 Z^0 $\mu^+\mu^-$: 700 Z^0	e^+e^-: 4200 Z^0
Direct γ (ΔG)	Highly Segmented EMCAL Resolve π^0 $p_T \leq 25$ GeV/c	Shower Max Detector γ, $p_T < 20$ GeV/c
γ+Jet (ΔG)	Away-Jet 15% efficiency via leading particle.	γ+ Jet $\Delta G(x)$, $x < 0.2$
JETS (ΔG, PV) Di-Jets	π^0's as Leading Particles π^0 pairs	Full Jets $\lvert\eta\rvert \leq 0.5$ $\geq 10^6$ Di-jets
Drell-Yan ($\Delta\bar{q}$, $\Delta_T\bar{q}$)	$\mu^+\mu^-$: 30K pairs mass 9 to 12 GeV	e^+e^-: 37K pairs mass 9 to 12 GeV
$J/\psi \to l^+ + l^-$ (ΔG?) $\Upsilon \to \mu^+\mu^-$	200K e^+e^-; $\geq$ 1M $\mu^+\mu^-$ 25K events	Sizable rates for e^+e^- trigger only at high p_T

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