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Spin Physics with the PHENIX Detector System

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The PHENIX experiment at RHIC has extended its scope to cover spin physics using polarized proton beams. The major goals of the spin physics at RHIC are elucidation of the spin structure of the nucleon and precision tests of the symmetries. Sensitivities of the spin physics measurements with the PHENIX detector system are reviewed.

1. PHENIX and RHIC Spin Physics

The Relativistic Heavy Ion Collider (RHIC) is under construction at Brookhaven National Laboratory. In addition to its primary purpose, the search for quark-gluon plasma, a proposal to explore spin physics at RHIC [2] has been approved. The major goals of the spin physics program at RHIC are:

- elucidation of the spin structure of the nucleon, and
- precision tests of symmetries.

RHIC offers a unique opportunity for those studies because of its capability of accelerating polarized proton beams up to $\sqrt{s}$= 500 GeV at the luminosity of $2\times10^{32}\text{cm}^{-2}\text{sec}^{-1}$ or more with large polarizations of ∼70%. Obviously we will reach the high-energy frontier for polarized proton-proton collisions at RHIC.

The PHENIX detector is one of the two large detectors at RHIC [1]. Its basic design concept is to detect photons, leptons, and hadrons with high momentum resolution and strong particle identification. It consists of two spectrometers covering the central rapidity region (Central Arms), which include an electromagnetic (EM) calorimeter with fine segmentation ($\Delta\eta \sim \Delta\phi \sim 0.01$), and two endcap muon spectrometers (Muon Arms). Since hadron reactions with photonic or leptonic final states such as prompt photon production and lepton production from weak boson decays play major roles in spin physics program, PHENIX is very well suited to spin physics at RHIC.

The studies are done by measuring the spin asymmetries in the cross sections for various reactions. By use of the spin rotators located upstream and downstream of PHENIX experimental hall, any combination of beam polarizations is possible. Thus we can measure the *helicity* dependent cross sections $\sigma(++)$, $\sigma(--)$, $\sigma(+-)$, and $\sigma(-+)$ separately, where + and − represent positive and negative helicity states of the beam particles as

*For the complete list of authors, please refer to Ref. [1]. Visit `http://www.rhic.bnl.gov/phenix` for the most current PHENIX information.

well as *transversity* dependent cross sections, $\sigma(\uparrow\uparrow)$, $\sigma(\downarrow\downarrow)$, $\sigma(\uparrow\downarrow)$, $\sigma(\downarrow\uparrow)$, where $\uparrow$ and $\downarrow$ represent transverse polarization of the beam particles. Among these asymmetries, we will discuss only two asymmetries in this presentation, a double longitudinal-spin asymmetry, $\mathcal{A}_{LL}$, and a single longitudinal-spin asymmetry, $\mathcal{A}_L$;

$$\mathcal{A}_{LL} = \frac{\sigma(++) + \sigma(--) - \sigma(+-) - \sigma(-+)}{\sigma(++) + \sigma(--) + \sigma(+-) + \sigma(-+)}, \quad \text{and} \quad \mathcal{A}_L = \frac{\sigma(-) - \sigma(+)}{\sigma(-) + \sigma(+)}. \tag{1}$$

The quantity $\mathcal{A}_{LL}$ is often used to extract helicity dependent structure functions; $\mathcal{A}_L$ extracts parity violation effects in the reaction. In the following section, the sensitivity of our measurements is calculated assuming integrated luminosity of 320 pb^{-1} and 800 pb^{-1} for $\sqrt{s} = 200$ GeV and 500 GeV, respectively, which corresponds to 10 weeks of running with 70% machine efficiency.

2. Spin Structure of the Nucleon

The results of polarized muon scattering off a polarized proton target reported by the EMC collaboration have stimulated both experimental and theoretical works to elucidate the spin structure of the proton. The fraction of the proton spin carried by quarks, $\Delta\Sigma$=0.12±0.09±0.14, was amazingly small comparing to the canonical expectation 0.60±0.12 [3]. Post-EMC experiments, which have provided data with much better statistics including deuterium and ^{3}He targets, have confirmed the EMC results. A recent global analysis gives $\Delta\Sigma \approx 0.3$, and thus still shows a significant deficit.

PHENIX will measure the gluon polarization $\Delta G(x)$ and anti-quark polarization $\Delta\bar{q}_i(x)$ with flavor i identified not only to search for the origin of the deficit but also to check the validity of assumptions in the analysis to obtain $\Delta\Sigma$, e.g. SU(3)$_{\text{flavor}}$. These measurements will be described in the following subsections.

2.1. Gluon polarization

One of the most reliable channels to measure the gluon polarization is high p_T prompt photon production. The production is dominated by the gluon Compton process, followed in significance by the annihilation process. By neglecting the contribution from annihilation channel, (which is justified in several predictions [4]), the asymmetry $\mathcal{A}_{LL}$ can be written at the leading order (LO) as a function of photon p_T,

$$\mathcal{A}_{LL}(p_T) \approx \frac{\Delta G(x_T)}{G(x_T)} A_1^p(x_T) a_{LL}^{\theta^*=\frac{\pi}{2}}(gq \to \gamma q), \; A_1^p(x_T) = \frac{g_1^p(x_T)}{f_1^p(x_T)} = \frac{\Sigma_i e_i^2 \Delta q_i(x_T)}{\Sigma_i e_i^2 q_i(x_T)}. \tag{2}$$

Here $x_T = 2p_T/\sqrt{s}$, θ^* stands for the scattering angle of partons in their CMS, and a_{LL} represents the double longitudinal spin asymmetry for the parton cross sections. It should be noted that the PHENIX acceptance ($|\eta| \leq 0.35$) strongly selects the samples in symmetric quark-gluon scattering at $\theta^* \sim \frac{\pi}{2}$ and this selection allows great simplification of the expression in Eq. (2) [4]. Since $a_{LL}(gq \to \gamma q)$ is calculated in QCD and $A_1^p(x)$ has been measured in lepton scattering experiments, $\Delta G(x)$ can be extracted from the measured $\mathcal{A}_{LL}$.

To overcome experimental difficulties due to the huge background from hadron decays, PHENIX's finely segmented EM calorimeter plays a crucial role in avoiding the fake prompt photon signal that results from the merging of two photons from a high-p_T π^0.

Since the PHENIX calorimeter is as fine as $\Delta\eta \sim \Delta\phi \sim 0.01$, the prompt photon can be identified up to 30 GeV/c or more without serious background.

The yield for the assumed integrated luminosities has been calculated using PYTHIA for the PHENIX acceptance and listed in Table 1 for both $\sqrt{s}$ =200 GeV and 500 GeV. In addition, the sensitivity of the measurement of $\Delta G(x)$ has been evaluated using a_{LL} and the measured $A_1^p(x)$. The listed errors are statistical only. We have identified the origin of the systematic errors and have begun studies to minimize them. In addition, studies of $\Delta G(x)$ measurements with other channels such as π^0, open charm/beauty, and heavy quarkonium production are in progress.

Table 1
Sensitivity summary for the measurements of gluon polarization via prompt γ production.

	$\sqrt{s} = 200$ GeV			$\sqrt{s} = 500$ GeV		
photon p_T	yield	errors on		yield	errors on	
(GeV/c)		$\mathcal{A}_{LL}$	$\Delta G/G$		$\mathcal{A}_{LL}$	$\Delta G/G$
10—15	1.0×10^5	0.006	0.05	9.0×10^5	0.002	0.05
15—20	1.3×10^4	0.017	0.09	1.8×10^5	0.005	0.06
20—25	2.7×10^3	0.038	0.17	5.3×10^4	0.009	0.08
25—30	5.9×10^2	0.080	0.31	1.9×10^4	0.015	0.12

2.2. Anti-quark polarization

The polarized-DIS experiments are sensitive to neither differences between anti-quarks and quarks nor their flavors, since the photon couples to the square of their electric charge. Therefore the measurement of anti-quark polarization and the flavor decomposition will improve the knowledge on the spin of the nucleon significantly.

The parity violating asymmetry $\mathcal{A}_L$ for W production is presented at LO as

$$\mathcal{A}_L(W^+) = \frac{\Delta u(x_1)\bar{d}(x_2) - \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)} \tag{3}$$

For W^- production, the u and d should be exchanged in this expression. The asymmetry is just the linear combination of the quark and anti-quark polarizations. Furthermore, the flavor in the reaction is almost fixed. Thus flavor decomposition is possible. The asymmetry converges to $\frac{\Delta u(x)}{u(x)}$ at the limit of $x_1 \gg x_2$ and to $\frac{\Delta\bar{d}(x)}{\bar{d}(x)}$ at the limit of $x_2 \gg x_1$.

$W^\pm$ production can be identified by the detection of muon with $p_T \geq$20 GeV/c. With the assumed $\int \mathcal{L}dt$=800 pb^{-1}, we expect about 5000 events for each of W^+ and W^-. Furthermore the x-range can be selected using the muon momentum as shown in Figure 1(a).

Using the muon sample which is divided into several energy bins (and thus x-bins), we have estimated the sensitivities of our measurements (with statistical errors only). The results are plotted on two model predictions for polarized structure functions [5] in Figure 1(b). Error bars indicate the expected statistical errors. Our measurement will be quite sensitive to both quark and anti-quark helicity distributions, although further studies are needed to minimize the background contributions.

3. Symmetry tests

The nature of parity non-conservation itself can be directly probed using the polarized beams at RHIC, with $\mathcal{A}_L$ the measure of violation. Taxil and Virey studied various possibility to find new physics at RHIC through the measurements of $\mathcal{A}_L$ using polarized proton beams [6]. While their predictions are only for single-jet production, which is not detectable with PHENIX, we expect that such asymmetries, however, should persist with inclusive or leading particle production. Sensitivity studies for PHENIX are underway.

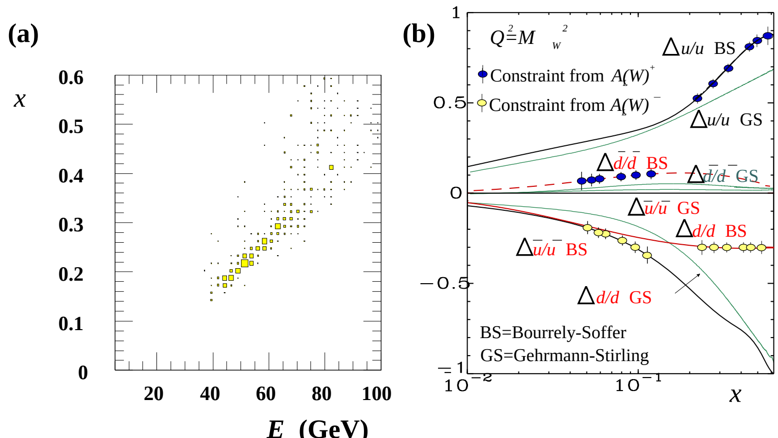

Figure 1. (a) Correlation between x and muon energy E^μ and (b) models on polarized parton distributions and projected statistical error.

4. Summary

The PHENIX physics scope has been extended to include the spin physics program. It will provide measurements of $\Delta G(x)$ and $\Delta\bar{q}_i(x)$ that greatly reduce the uncertainties in the knowledge of the spin structure of the nucleon. Precision tests of symmetries in the standard model is foreseen. The first collision of the polarized proton beams is expected to start in the year of 2000.

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