STUDYING THE SPIN STRUCTURE OF THE PROTON USING THE SOLENOIDAL TRACKER AT RHIC

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INTRODUCTION

The primary goal of RHIC is to produce nuclear matter under extremes of temperature and density sufficient to excite the QCD vacuum, resulting in the creation of a deconfined plasma of quarks and gluons. A second goal central to the RHIC scientific program is to advance the study of the spin structure of the proton significantly beyond what has been learned from deep inelastic scattering (DIS) measurements by studying spin asymmetries in strong processes involving the partonic constituents of polarized protons.

After decades of being regarded as an inessential complication to the strong interaction at high energy, spin has again become a topic of considerable experimental and theoretical interest. This is largely due to the observation from DIS that the net contribution to the proton spin from the quark constituents ($\sim 30\%$) is smaller than expected relative to the momentum carried in this sector. The RHIC accelerator will provide an unprecedented opportunity to fully explore the spin structure of the proton with high precision studies focussed on measuring the spin-dependent parton distributions (valence quark, sea quark, gluon) of the proton. It is designed to operate both with high luminosity (10^{31}-10^{32} cm^{-2} sec^{-1}) and high polarization ($\sim$70%). In addition, the energy range at RHIC ($\sqrt{s} = 200 - 500$ GeV) is sufficiently high that spin effects in polarized proton interactions should be calculable once the spin structure of the proton is sufficiently understood. The experimental results will therefore provide a rigorous test of QCD.

A further focus of the RHIC spin physics program will be to search for physics beyond the standard model. The increased sensitivity afforded by using polarized protons to study parity violation in inclusive jet production at high p_t makes this exploration[1, 2] competetive with respect to ongoing searches using unpolarized beams (see for example Figure 1).

Figure 1. Prediction[1, 2] for the effect of quark substructure on inclusive jet cross section with and without parity violation capability.

GENERAL CONSIDERATIONS

To obtain an intuitive feeling for how the spin structure of the proton may be probed using longitudinally polarized protons, it is useful to consider the situation in DIS when a polarized virtual photon collides longitudinally with a polarized proton. Assuming orbital angular momentum does not play a role, at the quark level in order to preserve a net spin of 1/2 for the proton, incoherent absorbtion of the virtual photon can only take place when the quark and photon spins are oppositely directed. The analagous situation in strong interactions involves the exchange of a gluon. Conceptually therefore, the degree to which the constituent parton spins are aligned or anti-aligned with the net spin of a longitudinally polarized proton can be determined from the asymmetry in the parton-level cross sections for probes of differing (positive and negative) helicity.

The scattering of two polarized protons is in essence the collision of two beams of polarized partons. Assuming the interaction cross section may be "factorized" into a hard scattering component and terms representing the parton distribution functions, the resulting asymmetry A_{LL} observed in the laboratory for a final state resulting from the collision of two longitudinally polarized protons can be related conceptually at the parton-level to a product:

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{\Delta a}{a}\frac{\Delta b}{b}\hat{a}_{LL(ab\to cd)} \tag{1}$$

where A_{LL} is the measured asymmetry in the laboratory, $\frac{\Delta a}{a} = \frac{a^+ - a^-}{a^+ + a^-}$ is the percentage difference of "a" type partons in one proton having spins aligned and anti-aligned in the direction of that proton's spin, $\frac{\Delta b}{b}$ is the same percentage of "b" type partons in the other proton, and $\hat{a}_{LL}$ is a calculable parton-level asymmetry for the subprocess describing the interaction between partons a and b (e.g., $ab \to cd$). For quarks, $\frac{\Delta a}{a} = \frac{\Delta q}{q} = \frac{q^+ - q^-}{q^+ + q^-}$ (e.g., $q = u, d$), and for gluons, $\frac{\Delta b}{b} = \frac{\Delta G}{G} = \frac{G^+ - G^-}{G^+ + G^-}$. Therefore (noting explicitly the dependence of the parton distribution functions on the fraction x of the

Figure 2. The spin asymmetry predicted[3] for various parton-level subprocesses as a function of the scattering angle in the parton cm system.

proton's momentum carried by the partons in the infinite momentum frame), to study the process $qg \rightarrow \gamma q$, for example, the asymmetry of interest would be

$$A_{LL} = \frac{\Delta q(x)}{q(x)} \frac{\Delta G(x)}{G(x)} \hat{a}_{LL(qg \rightarrow \gamma q)}, \tag{2}$$

measured in the valence region where $\frac{\Delta q(x)}{q(x)}$ is largely known from deep inelastic scattering.

From equation 1 it is evident that to measure a large asymmetry experimentally, it is desirable to study a parton-level process that is calculated to have a large parton-level asymmetry ($\hat{a}_{LL}$) or "analyzing power". Figure 2 shows the parton-level asymmetries expected for various parton-level subprocesses as a function of the scattering angle (θ^*) in the constituent cm system.[3] From the figure, the subprocess $qg \rightarrow \gamma q$ has a large asymmetry in general and this process is therefore well suited to study the gluon polarization in the proton.

A further consideration is that, in general, many parton-level processes contribute to a given final state. In the case of di-jet production, numerous parton-level processes contribute (e.g., $qq \rightarrow$jet-jet ($q = u, d$), $qg \rightarrow$ jet-jet etc.), the relative strength of each depending on the kinematic region which is explored. In the case of the photon-jet final state discussed above as a useful probe of the spin-dependent gluon distribution of the proton, two processes which contribute significantly are quark-gluon scattering and $q\bar{q}$ annihilation. Since RHIC is a proton collider (as opposed to a $p\bar{p}$ collider) the contribution from $q\bar{q}$ annihilation in this energy range is relatively small ($\sim 10\%$). Consequently, the interpretation of asymmetries observed in gamma-jet final state production is relatively straightforward. The fact that the process $qg \rightarrow \gamma q$ has both a large asymmetry and leads to a final state which is relatively easy to interpret makes it a preferred process for studying the gluon contribution to the proton spin.

A number of important questions concerning the fundamental structure of the

Figure 3. For jet + direct photon coincidences in STAR; the acceptance and yield as a function of x for events in which at least one of the final state products has $x > 0.2$. The results indicate there are ≈ 6500 direct $\gamma+$ jet events per month in the kinematic region of interest for studying $\Delta G(x)$.

proton will be addressed by studying parity conserving and parity violating spin asymmetries in polarized pp interactions in STAR. One topic of particular interest is the effective polarization of gluons in the proton. In general, the spin of the proton may contain contributions not only from quarks, but also from gluons, and perhaps orbital angular momentum of the constituent partons as well. Once the degree of gluon polarization has been established using hadronic probes, it may also be possible to assess the significance of any possible contribution from orbital angular momentum. A further focus will be to search for physics beyond the standard model using parity violation in inclusive high p_t jet production as a probe. Some examples of measurements which are possible with the STAR detector are discussed below.

SPIN PHYSICS MEASUREMENTS WITH STAR

In STAR, measurement of the gluon polarization will be addressed with beams of longitudinally polarized protons using a number of hard QCD probes; inclusive direct photon production, di-jet production, and jet + direct photon coincidences. For measuring $\Delta G(x)$, the jet + jet and jet + direct photon final states are superior, since the kinematic information available on the initial state partons (quarks, gluons) is complete modulo the k_t of the partons. Figure 3 gives an estimate of the acceptance and yield of jet + direct photon coincidences in STAR in one month of running at the RHIC design luminosity at $\sqrt{s} = 200$ GeV. It is noted that for a jet p_t range of $10 < p_t < 20$ GeV/c, at this $\sqrt{s}$, the gluon distribution may be probed down to x Bjorken of approximately 0.02. (If the range for the measurement of jets is extended to lower p_t, the lower limit of the accessible x range is lowered as well). The results also show that for jet + direct photon events in which one of the final state products has $x_{BJ} = x_b \geq 0.2$, which statistically is most likely to correspond to a quark in the valence region in which the polarization transfer from the proton is rather well known from DIS, the yield of "gluon-like" events in which the other final state product has $x_{BJ} = x_a < 0.1$ is approximately 6500 per month. By measuring the parity conserving

Table 1. [a]

		$\max(x_1,x_2)$ ≤ 0.2	0.2-0.3	0.3-0.4	> 0.4
	0.00-0.05		0.012	0.009	0.007
	0.05-0.10	0.006	0.006	0.010	0.012
$\min(x_1,x_2)$	0.10-0.15	0.007	0.010	0.020	0.030
	0.15-0.20	0.021	0.019	0.038	0.060
	> 0.20		0.035	0.049	0.073

[a]The estimated statistical uncertainty δA_{LL} in the two-spin, parity conserving asymmetry of Eq. 2 in jet + direct photon events. Various ranges of the "quark" ($\max(x_1,x_2)$) and "gluon" ($\min(x_1,x_2)$) kinematics are indicated.

Table 2. [a]

Boson	STAR(Barrel)	STAR(Barrel+Endcaps)
$W^+ + W^-$	83,000	110,000
W^+	61,000	80,000
W^-	22,000	30,000
Z^0	3,840	7,200

[a]The $W^{+/-}, Z^0$ yield in the STAR acceptance for an integrated luminosity of 800 pb^{-1} (100 days at 50% efficiency) at a pp center of mass energy of 500 GeV.

two-spin asymmetry

$$A_{LL} = (1/P^2)(N^{++} - N^{+-})/(N^{++} + N^{+-}) \tag{3}$$

for "gluon-like" events (where P is the polarization), it will be possible in a relatively short period of running (100 days with 50% efficiency yields an integrated luminosity of 320 pb^{-1} at the design luminosity for $\sqrt{s} = 200$ GeV) to make a significant measurement of both ΔG and $\Delta G(x)$. Table 1 shows the statistical uncertainty, δA_{LL}, in the jet + direct photon asymmetry for various combinations of the quark and gluon kinematics assuming an integrated luminosity of 320 pb^{-1}. Accounting for statistical errors only, this corresponds roughly to an uncertainty in the measurement of $\Delta G/G$ of a few percent.

As noted in Table 2, it will also be possible to measure a significant yield of $W^{+/-}$ bosons using longitudinally polarized protons. The yield of $W^{+/-}$ is sensitive to the polarization of the valence quark and sea anti-quark distributions, and may be used to provide an independent measurement of both distributions. An example is shown in Figure 4, in which the two spin parity violating asymmetry

$$A_{LL}^{PV} = \sigma^{--} - \sigma^{++}/\sigma^{--} + \sigma^{++} \tag{4}$$

as a function of rapidity is noted to be strikingly different depending on whether the $\bar{u}$ and $\bar{d}$ distributions of the proton are polarized or unpolarized[4]. Although the W yield can not be determined directly as a function of rapidity in STAR, an integral measurement across the STAR acceptance will provide a very sensitive measurement of the degree to which the sea anti-quark distributions in the proton are polarized. The background and trigger rates for the measurement of W production in STAR have been simulated, and the results indicate this study is feasible.

The feasibility is also being studied of using the STAR detector with one beam transversely polarized, to address an entirely new aspect of the spin structure of the proton. The idea being explored is a recent suggestion[5] that it may be possible to study the transversity distribution of quarks in the proton by studying final state interactions between pairs of leading mesons (e.g. $\pi\pi$) produced in jets. Ostensibly,

Figure 4. The parity violating asymmetry A_{LL}^{PV} versus y for $W^{+/-}$ production at center of mass energy of 500 GeV. The solid lines correspond to non-zero sea quark polarization whereas dashed lines correspond to $\Delta\bar{u} = \Delta\bar{d} = 0$. The estimated uncertainity δA_{LL}^{PV} for an integral measurement in STAR for a running period corresponding to 800 Pb^{-1} (100 days at 50% efficiency is $\approx$ 1%.

this study is intended to provide information on a new, as yet unmeasured, fundamental structure function of the proton, which will indicate the degree to which the quark spins are either aligned or anti-aligned with the spin of a proton which is polarized transverse to its direction of motion. In the non-relativistic limit, the results using longitudinally polarized protons should be recovered. The transversity distribution can not be probed using DIS measurements, and information from hadronic interactions is essential. The difference between the results for transversely and longitudinally polarized ultra-relativistic protons, will provide unique information on parton dynamics within the proton.

SEARCHING FOR PHYSICS BEYOND THE STANDARD MODEL

Another very interesting aspect of the STAR physics program is the ability to address the question of physics beyond the standard model by searching for parity violation in high p_t jet production. This measurement would be accomplished in pp interactions at $\sqrt{s} = 500$ GeV, using longitudinally polarized protons. Specifically, by examining the two-spin parity violating asymmetry

$$A_{LL}^{pv} = \sigma^{--} - \sigma^{++}/\sigma^{--} + \sigma^{++} \tag{5}$$

as a function of p_t, it will be possible in one year of RHIC running to perform a sensitive test of the hypothesis that quarks may be composite objects up to a compositeness scale of $\Lambda \approx 3$ TeV. This is significantly higher than the limit presently afforded ($\Lambda \approx$ 1.4 TeV) by unpolarized pp interactions at Fermilab (CDF) which is determined by comparing the cross section for inclusive high p_t jet production to the predictions of QCD in leading order.

The question of the possibility of quark compositeness arises from the family structure of quarks and leptons within the standard model, the origin of which is

Figure 5. The two spin parity violating asymmetry of Eq. 5 (A_{LL}^{PV}) versus p_t at RHIC assuming a compositeness scale of $\Lambda \sim 2$ TeV. Calculations are shown for the structure functions of Ref. 11. The middle curve results from standard QCD-elctroweak interference terms. The top and bottom curves result if subconstituents of the proton interact by a new left handed ($\eta = -1$) or right handed ($\eta = +1$) contact interaction which interferes constructively ($\epsilon = -1$) or destructively ($\epsilon = +1$) with standard QCD-electroweak exchange graphs.

not presently understood. In particular, if the family structure arises due to subconstituents (e.g. preons) which interact by means of a new contact interaction, there is no reason a priori to assume that the new interaction conserves parity. It is of some interest therefore to search for parity violation in strong processes which conserve parity to indicate the possible existence of new physics beyond what is presently known from the standard model. To accomplish this, all known "conventional" sources of parity violation in high p_t hadronic processes must first be taken into account – in particular, the parity violation expected in this regime due to interference effects between standard QCD (gluon)-electroweak (W, Z) exchange graphs in e.g. high p_t quark-quark elastic scattering.

Recently, a comprehensive study of the degree of parity violation expected from "known" processes in high p_t jet production has been performed by a number of authors[6, 7, 8]. In Figure 5 the results from the work of Taxil and Virey[9] demonstrate the estimated sensitivity achievable in one year of RHIC running assuming a compositeness scale of $\Lambda = 2.0$ TeV. The middle curve of Figure 5 is the asymmetry that would be observed if all of the parity violation resulted from standard QCD-electroweak interference effects presently understood within the standard model. The top and bottom curves result from assuming quarks are indeed composite objects whose subconstituents interact by means of a new parity violating contact interaction which interferes either constructively or destructively with known QCD and electroweak exchange graphs. These plots were developed using a particular choice[10, 11] of the parton structure functions presently thought to best represent the partonic structure of the proton. There is some sensitivity to the choice of structure functions, but the basic conclusion is unchanged regardless

Table 3. [a]

$\epsilon \cdot \eta = -1$	$\epsilon \cdot \eta = +1$
BS: 3050	3010
GS: 2710	2670

[a]The estimated limit (in GeV) on the scale (Λ) for quark compositeness achieved in one RHIC year of polarized proton running at a *pp* center of mass energy of 500 GeV assuming a new right handed ($\eta = -1$) or left handed ($\eta = +1$) parity violating contact interaction which interferes constructively ($\epsilon = -1$) or destructively ($\epsilon = +1$) with known QCD and electroweak exchange graphs. The limits shown are for the structure functions of reference 10 (BS) and 11(GS).

Figure 6. The estimated statistical uncertainty in the determination in STAR of the asymmetry A_{LL}^{PV} of Eq. 5 taking known sources of parity violation within the standard model into account. The data assumes one year of RHIC polarized proton running at a *pp* center of mass energy of 500 GeV.

of which set is used. Figure 6 shows a realistic simulation within STAR, taking the acceptance and efficiency for jet detection into account, of the statistical uncertainty expected as a function of p_t in the measurement of A_{LL}^{PV} in one RHIC year of polarized proton running assuming all parity violation results from "conventional" sources within the context of the standard model. These results show that in one year of RHIC running, STAR will be able to provide significant new limits on the scale for possible quark substructure. An estimate from reference[9] of the limits which can be achieved in this study is shown in Table 3.

SUMMARY AND OUTLOOK

In conclusion, a number of important questions concerning the spin structure of the proton will be addressed by studying parity conserving and parity violating spin asymmetries in polarized *pp* interactions in STAR. Specifically these studies will focus on high precision measurements of the spin dependent parton distributions (valence quark, sea quark, gluon) of the proton. The study of parity violating asymmetries in high p_t jet production in STAR using polarized protons will also afford a sensitive test of the possibility of new physics beyond the standard model.

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