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Experiments to Measure the Gluon Helicity Distribution in Protons

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Abstract

Several experiments are described that could obtain information about the gluon helicity distribution in protons. These experiments include inclusive direct-γ, direct-γ + jet, jet, and jet + jet production with colliding beams of longitudinally-polarized protons. Some rates and kinematics are also discussed.

1 Introduction

Measurements of asymmetries in deep inelastic lepton scattering with longitudinally-polarized electron or muon beams and proton targets have been performed at SLAC [1] and CERN [2,3]. The experimental results have been interpreted to mean that the quarks and antiquarks in the proton may carry little net helicity [2,4]. Many theoretical papers have been written to attempt to understand this result.

The proton spin consists of contributions from valence and sea quarks, sea antiquarks, gluons, and orbital angular momentum of the partons. Most contributions can be measured, but it is not known how to directly and cleanly obtain a measurement of the orbital angular momentum distribution. As a result, a direct determination of the net helicity carried by the gluons in the proton is crucial for understanding the spin structure of the proton. Experiments described here will measure the helicity carried by the gluons. In addition, other experiments will provide a consistency check of these results, or equivalently, a test of QCD with spin. Finally, these same type of experiments will yield the spin-average gluon distribution in nuclei.

2 Some Background Information

Important information on the spin-average gluon distribution in the proton, G(x), has been obtained from measurements of high-energy inclusive direct-γ and direct-γ + jet production, where x is the fraction of the proton's longitudinal momentum carried by gluons. In these reactions, care must be taken to insure that the detected γs do not originate from π°, η°,... decays, but rather are "directly produced." After many successful experiments, the techniques for measurement of inclusive direct-γ and inclusive jet production are well established.

One reason for the importance of these reactions in determining G(x) is the dominance of a single parton-level subprocess, namely the Compton subprocess or $g + q \rightarrow \gamma + q$. Berger et al. [5] estimate that in the RHIC energy range (~ 200 GeV), bremsstrahlung backgrounds contribute 20-30% of the total inclusive direct γ + jet cross sections; this background can be considerably reduced by requiring the γ to be isolated in angle from accompanying particles in the event. Of the remaining contributions, the Compton subprocess accounts for over 80%, with the annihilation subprocess $q + \bar{q} \rightarrow \gamma + g$ giving the rest. Both of these subprocesses have a γ and a jet, from either the outgoing quark or gluon, in the final state. Thus G(x) can be determined from: 1) measurements

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of inclusive direct-γ + jet cross sections, 2) values of q(x) and $\bar{q}(x)$ obtained from deep inelastic lepton and neutrino scattering, and 3) subprocess cross sections calculated from perturbative QCD. Such a program has been carried out at the ISR [6] and is in progress at CDF.

The probability of finding a negative-helicity gluon in a positive-helicity proton will be denoted $G^{\pm}(x)$, and similarly for other helicities and for u, d, $\bar{u}$, etc. quarks. Spin average and helicity structure functions for the gluon will be denoted by $G(x) = [G^{+}_{+}(x) + G^{-}_{+}(x)]/2$ and $\Delta G(x) = [G^{+}_{+}(x) - G^{-}_{+}(x)]/2$, respectively, and similarly for the quark structure functions. The proton or parton cross sections will be defined as $\sigma = [\sigma(++) + \sigma(--) + \sigma(+-) + \sigma(-+)]/4$ and $\Delta\sigma = [\sigma(++) + \sigma(--) - \sigma(+-) - \sigma(-+)]/4$, parton asymmetries as $\hat{a}_{LL} = \Delta\sigma/\sigma$, and proton asymmetries as $A_{LL} = \Delta\sigma/\sigma$. In terms of these quantities, the spin average cross section for inclusive direct-γ + jet production will be:

$$\frac{d^4\sigma(pp \to \gamma + \mathrm{Jet} + X)}{d(p_T{}^2)d\phi\, dy_\gamma dy_{Jet}} \approx \sum_f \sum_{1\leftrightarrow 2} q_f(x_1)\cdot G(x_2)\cdot \frac{d\sigma}{d\hat{t}}(q_f g \to \gamma\, q). \quad (1)$$

The first sum corresponds to the flavors of quarks and antiquarks, the second sum to interchanging x_1 and x_2, the values of y_γ and y_{Jet} are the γ and jet rapidities, and the parton level cross sections $d\sigma/d\hat{t}$ are functions of x_1 and x_2. In a similar way, the helicity cross section is

$$\frac{d^4\Delta\sigma(pp \to \gamma + \mathrm{Jet} + X)}{d(p_T{}^2)d\phi\, dy_\gamma dy_{Jet}} \approx \sum_f \sum_{1\leftrightarrow 2} \Delta q_f(x_1)\cdot \Delta G(x_2)\cdot \frac{d\Delta\sigma}{d\hat{t}}(q_f g \to \gamma\, q). \quad (2)$$

In these expressions, the annihilation and Bremsstrahlung contributions are ignored for simplicity. Note that the inclusive direct-γ production cross sections, without detection of the jet, can be found by integrating over y_{Jet}.

From the previous equations and definitions,

$$A_{LL}(x_1,x_2)\cdot \sum_f \sum_{1\leftrightarrow 2} q_f(x_1)\cdot G(x_2)\frac{d\sigma}{d\hat{t}}(q_f g \to \gamma q).$$
$$\cong \sum_f \sum_{1\leftrightarrow 2} \Delta q_f(x_1)\cdot \Delta G(x_2)\cdot \frac{d\Delta\sigma}{d\hat{t}}(q_f g \to \gamma q). \quad (3)$$

Thus, in order to obtain good sensitivity to $\Delta G(x)$, the gluon helicity or spin distribution in the proton, three conditions should be met: 1) $\Delta q_f(x)$ (and therefore $q_f(x)$ as well) must be sizable for some flavor f, 2) $d\Delta\sigma/d\hat{t}$ must be large for the same f, and 3) cancellations from other flavors should not be large. It is known that $q(x) \gtrsim G(x) >> \bar{q}(x)$ for $x \gtrsim 0.2 - 0.3$ and that $\Delta u/u$ is large in this same x range [1-3]. Thus, a useful criterion for obtaining $\Delta G(x)$ would be to require $x_{quark} \gtrsim 0.2 - 0.3$.

3 Inclusive Direct-γ Production

In order to estimate rates and backgrounds, published experimental data on inclusive π° and direct-γ production were both fit [7] as functions of P_T for $\sqrt{s} \sim 20$-1800 GeV. The data were interpolated to the range of interest for RHIC experiments, namely $\sqrt{s} \sim 50$-500 GeV and $P_T \sim 10$-20 GeV/c. The requirement $P_T \gtrsim 10$ GeV/c was imposed to insure that perturbative calculations of $d\sigma/d\hat{t}$ and $\hat{a}_{LL}$ are valid. Total cross sections from the fits for $0 \leq \phi \leq 2\pi$ and $-1 \leq \eta_\gamma \leq +1 (\eta = -\ell n \tan \theta/2 =$

pseudorapidity) indicate 1) a very steep rise with increasing $\sqrt{s}$, 2) $\sigma_{\pi^\circ} \simeq 5 \cdot \sigma_\gamma$, demonstrating that effects of π°, η°, etc. backgrounds need to be carefully considered, and 3) a steep drop with P_T, so $d\sigma(P_T = 10\ GeV/c)/d\sigma(P_T = 20\ GeV/c) > 1000$.

The estimated statistical uncertainty δA_{LL} ($pp \rightarrow \gamma + X$) can be expressed as $\delta A_{LL} = Q_{Detector}/P_{Beam}^2/\sqrt{N_\gamma}$, where the number of inclusive direct-γ events is N_γ, the beam polarizations are P_{Beam}, and $Q_{Ideal} = 1$ when $|A_{LL}| << 1$. Table 1 contains the estimated value of δA_{LL} at three $\sqrt{s}$ values and two luminosities for a one month run with 100% operating efficiency, acceptance as described above, and an ideal detector with no background. One luminosity is taken from the RHIC Conceptual Design Report [8], while an enhanced high luminosity option is being considered as an upgrade.

$\sqrt{s}$	100 GeV	200 GeV	500 GeV
Time (ΔT)	2.59×10^6 sec	2.59×10^6 sec	2.59×10^6 sec
σ_γ	250 pb	1080 pb	8000 pb
σ_{π°	1000 pb	5200 pb	60000 pb
Design Luminosity	$2.8 \times 10^{30}/cm^2/sec$	$5.6 \times 10^{30}/cm^2/sec$	$1.4 \times 10^{31}/cm^2/sec$
N_γ	1.81×10^3	1.57×10^4	2.90×10^5
δA_{LL}	± 0.048	± 0.016	± 0.0038
High Luminosity	$4.0 \times 10^{31}/cm^2/sec$	$8.0 \times 10^{31}/cm^2/sec$	$2.0 \times 10^{32}/cm^2/sec$
N_γ	2.59×10^4	2.24×10^5	4.25×10^6
δA_{LL}	± 0.013	± 0.0043	± 0.0010

Table 1. Estimates of N_γ and δA_{LL} for an ideal detector at three values of $\sqrt{s}$ and two luminosities with $P_{Beam} = 0.7$.

Theoretical estimates of $A_{LL}(pp \rightarrow \gamma + x)$ for various assumptions of $\Delta G(x)$ and a variety of $\sqrt{s}$ have been performed [9-13]. Near $P_T = 10$ GeV/c, the values of A_{LL} for "large" and "small" $\Delta G(x)$ typically differ by 0.05 [12]. Large $\Delta G(x)$ corresponds to $|\langle\Delta G\rangle| \sim 2\text{-}3\ \hbar$ and small $\Delta G(x)$ to $|\langle\Delta G\rangle| \lesssim \hbar/2$, where $\langle\Delta G\rangle = \int \Delta G(x)\, dx$. In order to distinguish these two cases, $\delta A_{LL} \lessapprox \pm 0.01$ is required. Table 1 indicates that this can be achieved with an ideal detector in a one month run with design luminosity at $\sqrt{s} \gtrsim 200$ GeV, or with high luminosity for $\sqrt{s} = 100\text{-}500$ GeV.

Preliminary designs for the two large RHIC detectors were evaluated for suitability for inclusive direct-γ measurements. The PHENIX design has a finely-segmented lead glass and/or crystal detector with acceptance $-0.35 \leq \eta \leq +0.35$ and $\Delta\phi = \pi$. Evaluation of the effects of π° and η° decay backgrounds gave $Q_{PHENIX} \simeq 1.1$. The STAR design includes as an upgrade a lead-scintillator sampling electromagnetic calorimeter (EMC) with 1 cm-wide scintillator strips or wire chamber detector near shower maximum. The full acceptance of the planned barrel EMC is $-1 \leq \eta \leq +1$ and $\Delta\phi = 2\pi$. Evaluation of backgrounds gave $Q_{STAR} = 1.6$. A comparison at $\sqrt{s} = 200$ GeV, the design luminosity, and a one month run ($\int \mathcal{L}dt = 14.5\ pb^{-1}$) gave $(\delta A_{LL})_{IDEAL} \equiv \pm 0.016$ from Table 1, $(\delta A_{LL})_{PHENIX} \equiv \pm 0.043$, and $(\delta A_{LL})_{STAR} \equiv \pm 0.026$. These results suggest that both detectors could achieve the desired statistical accuracy $\delta A_{LL} \lesssim \pm 0.01$ for inclusive direct-γ production in a reasonable run time of about a year at the design luminosity. Further details are given in Ref. [7].

4 Inclusive Direct-γ + Jet Production

More detailed information on $\Delta G(x)$ will be available if both the direct-γ and the jet are detected. The PHENIX detector is not expected to have adequate acceptance for jet detection, so only the STAR detector with EMC upgrade will be available for these measurements. The jet energy in STAR will be obtained from the electromagnetic and hadron energy deposited in the EMC and from charged particle tracking information using the time projection chamber and perhaps the silicon vertex tracker in STAR. Neutrons and K_L^0's will have poor detection efficiency. Simulations of the STAR detector indicate that jets can be adequately detected. Note that a similar procedure was used successfully by the AMY detector at TRISTAN.

The momentum fractions x_1 and x_2 of the incoming partons can be estimated using P_T measured by the direct-γ, and the directions η_γ and η_{Jet}. Assuming massless partons and negligible intrinsic P_T for these partons in the proton, then momentum and energy conservation give:

$$x_1 \cong \frac{2P_T}{\sqrt{s}}\left(\frac{e^{\eta_\gamma}+e^{\eta_{Jet}}}{2}\right), \quad x_2 \cong \frac{2P_T}{\sqrt{s}}\left(\frac{e^{-\eta_\gamma}+e^{-\eta_{Jet}}}{2}\right). \tag{4}$$

A detailed evaluation of acceptances using the above two equations indicates the need for at least one endcap electromagnetic calorimeter for STAR with $1 \leq \eta \leq 2$ and $\Delta\phi = 2\pi$. If $x_a \equiv \min(x_1, x_2)$ and $x_b \equiv \max(x_1, x_2)$, then there is no acceptance in the barrel EMC alone for $\sqrt{s} \geq 200$ GeV when $P_T = 10$ GeV/c and $x_b \geq 0.2$. At lower energies, both the cross section and luminosity decrease rapidly.

Assuming the presence of both the barrel and endcap EMC's in STAR, the rate of "good" inclusive direct-γ + jet events (n_a/month) was estimated with the ISAJET computer program. Good events satisfy the condition $x_b \geq 0.2$, so that x_b has a high probability of corresponding to x_{quark}. The results are shown in Fig. 1 for the design luminosity, only one endcap, and 100% operating efficiency. The conclusions are: 1) the fraction of good events n_a/N_{Tot} drops with increasing $\sqrt{s}$ (see Eq. 4), where N_{Tot} direct-γ + jet events occur with $P_T \geq 10$ GeV/c, 2) the rate of good events n_a/month is roughly constant for $\sqrt{s} \sim 150$-500 GeV, and peaks in the RHIC energy range, and 3) the mean x for the good events $\langle x_a \rangle$ drops with increasing $\sqrt{s}$ and covers the range of interesting x_{gluon}. Crude estimates indicate that the statistical uncertainty on $\Delta G(x)/G(x)$ will be roughly $\pm$ 0.05 - 0.20 for x bins of width 0.05 and $x_{gluon} = 0 - 0.25$. This assumes a run period of one year at design luminosity and 100% operating efficiency. Clearly the high luminosity upgrade would be very beneficial for these measurements. Note that A_{LL} ($pp \rightarrow \gamma + X$) data, which are an integral over the pp $\rightarrow \gamma$ + Jet + X results, will provide a consistency check on the derived $\Delta G(x)$.

5 Inclusive Jet and Jet + Jet Production

Inclusive jet and jet + jet production cross sections are orders of magnitude larger than direct-γ cross sections at the same P_T. Many more parton level subprocesses contribute as well. The values of $d\sigma/d\hat{t}$ and $\hat{a}_{LL}$ for these subprocesses are known from perturbative QCD. In principle, A_{LL} (pp $\rightarrow$ Jet + X) and A_{LL} (pp $\rightarrow$ Jet + Jet + X) can be calculated using these values from QCD, q(x) and $\Delta q(x)$ from neutrino and deep inelastic lepton scattering, and G(x) and $\Delta G(x)$ from inclusive direct-γ + Jet production. These calculations can be compared to measurements as a test of QCD with spin. Alternately, the inclusive jet production data could be used to improve the determination of $\Delta G(x)$.

Simulations of the STAR EMC and tracking detector performance for jet detection indicate that the jet P_T and E_T can be crudely measured, although there will be a sizable low-energy tail caused by loss of neutrons and K_L^0's. These simulations also suggest reasonable jet triggering efficiency for $P_T \gtrsim$ 15-20 GeV/c using the energy deposited in the EMC. Finally, theoretical estimates of A_{LL} (pp → Jet + X) for large and small ΔG(x) [12] give similar differences to those observed for A_{LL} (pp → γ + X). Much additional work is needed to specify rates and predict statistical uncertainties for inclusive jet and jet + jet production.

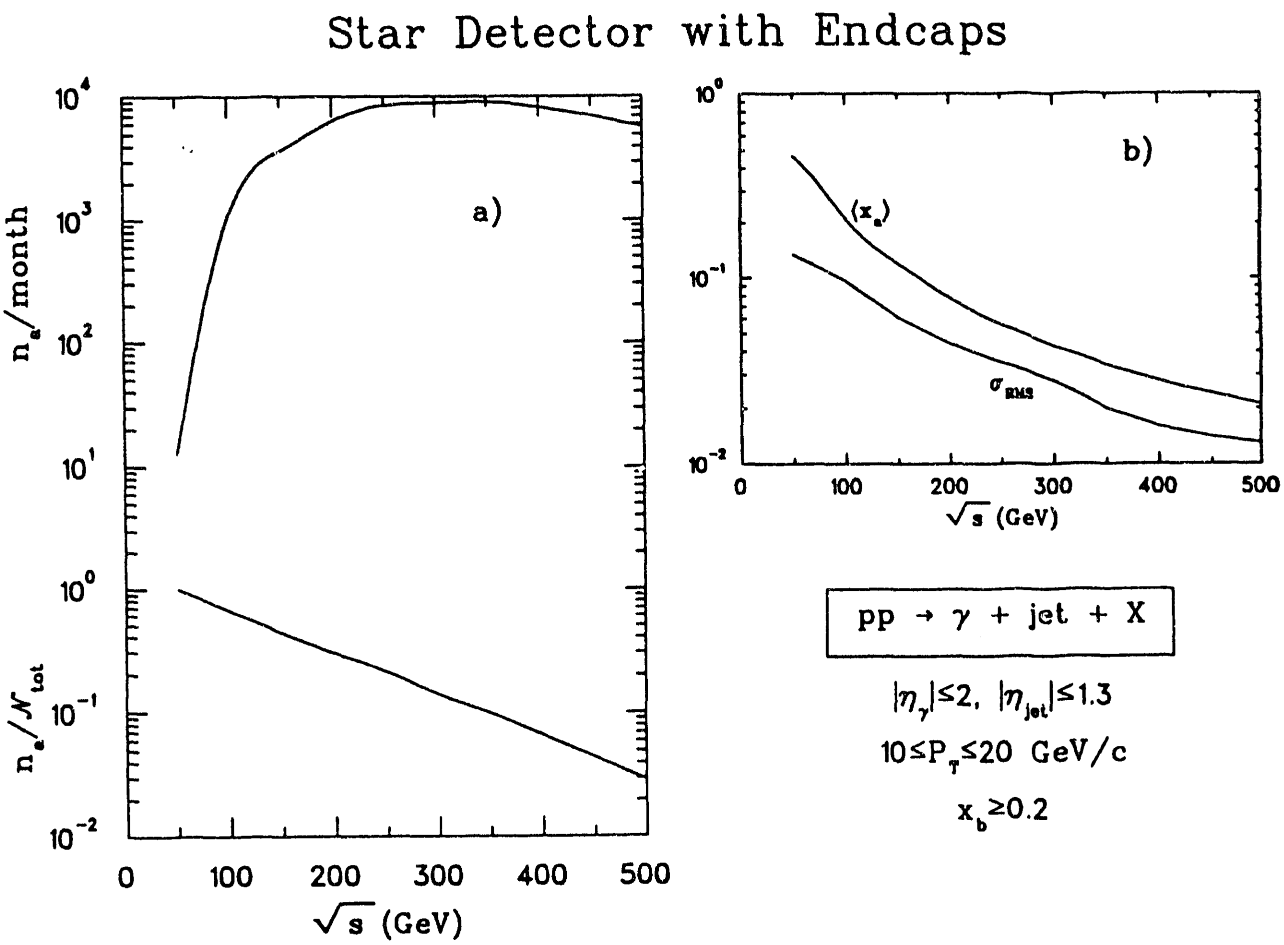

Fig. 1 a) The fraction of good events n_a/N_{Tot} and the rate of good events n_a/month as a function of $\sqrt{s}$. b) The mean x and width σ_{RMS} for the good events [7].

6 Conclusions

A) The integral of the gluon helicity or spin structure function ∫ΔG(x)dx, weighted by the x acceptance at a particular η_γ, can be measured at RHIC using inclusive direct-γ production with longitudinally polarized proton beams. Rate estimates indicate that reasonable statistical uncertainties on A_{LL} (pp → γ + X) could be obtained in times of approximately one year at the design luminosity for both the PHENIX and STAR detectors.

B) To measure $\Delta G(x)$ will require an endcap electromagnetic calorimeter for STAR. The RHIC energy range appears ideal for these measurements. High-luminosity running would be very beneficial to obtain sufficiently small statistical uncertainties.

C) Inclusive jet and jet + jet production will provide additional constraints on $\Delta G(x)$ or will permit a test of QCD with spin.

D) The STAR barrel and endcap electromagnetic calorimeters will allow measurements of G(x) in nuclei using p + A and A + A interactions. Eqs. 4 are still valid. The condition $\max(x_1, x_2) \gtrsim 0.2 - 0.3$, where x_1 and x_2 are the calculated momentum fractions per nucleon, will be needed as well so that x_{gluon} corresponds to $\min(x_1, x_2)$ with high probability.

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