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Proposal for direct measurement of polarized gluon distributions

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We propose a special experiment for direct measurement of polarized gluon distributions in the collision of real high energy photons with polarized nuclear target. Polarised photon beam is obtained through Compton backscattering of laser photons off electrons from a ring-type accelerator (LEP, TRISTAN, HERA). In our opinion, realization of this experiment will play a principal role in solving the so-called "spin crisis".

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Recent experiments on the measurement of polarized structure functions in lepton-nucleon scattering [1, 2] have shown that spin content of hadrons are far from the naive quark-parton estimations. This surprising result has led to a burst of theoretical works, see for example [3–7]. Both experimental and theoretical investigations strongly indicate that the direct measurement of polarized gluon distribution should play a key role in understanding of nucleon spin structure. Existing proposals for $\Delta G = G_+ - G_-$ measurement, G_+ and G_- denote the distributions of gluons with spins aligned parallel and antiparallel to the proton spin, deal with polarized proton-proton or proton-nuclear collisions [8, 9]. Note that these experiments will be able to measure the product of gluon-gluon [8] or quark-gluon [9] distributions. Alternative proposals capable of probing ΔG through investigation of heavy quark pair production in polarized lepton-nucleon collisions involve product of quasi-real photon and gluon distributions [4, 10]. Here we propose an experiment to measure ΔG alone.

The scheme of the proposed experiment is pictured in Fig. 1. Circularly polarized laser beam with photon energy $w_0 \simeq 1\text{eV}$ and helicity $\lambda_0=1$ or -1 are scattered off the electrons from a ring-type accelerator like LEP, TRISTAN or HERA. Through the process of Compton backscattering one obtains high energy photon beam which closely follows the trajectory of electrons in the conversion region. After a certain distance the photon beam comes to a wall with a slit which selects photons with highest energy and consequently with polarization close to 1 (see text below). Selected photons will strike on the polarized nuclear target, i.e. butanol [11]. Main requirements for the detector are efficient particle identification and high angular and energy resolutions.

Cross sections and kinematics for Compton backscattering of laser photons off high energy electrons have been widely discussed [12–14]. Although there are a proposals for obtaining longitudinally polarized electrons in a ring-type accelerators, at

this stage we restrict ourselves to nonpolarized electrons. For our purpose we need differential Compton cross section and scattered photon helicity. Corresponding expressions are the following

$$\frac{1}{\sigma_c} \frac{d\sigma_c}{d\omega} \equiv f(\omega) = \frac{1}{E_b \sigma_c} \frac{2\pi\alpha^2}{\kappa m_e^2} \left\{ \frac{1}{1-y} + 1 - y - 4r(1-r) \right\}, \quad (1)$$

where

$$\sigma_c = \frac{\pi\alpha^2}{\kappa m_e^2} \left\{ \left(2 - \frac{8}{\kappa} - \frac{16}{\kappa^2} \right) \ln(\kappa + 1) + 1 + \frac{16}{\kappa} - \frac{1}{(\kappa + 1)^2} \right\}$$

and

$$\lambda_\gamma(\omega) = \frac{\lambda_0(1-2r)(1-y+\frac{1}{(1-y)})}{1-y+\frac{1}{(1-y)}-4r(1-r)}. \quad (2)$$

In Eq(1) and Eq(2)

$$\kappa = \frac{4E_b\omega_0}{m_e^2}, \quad y = \frac{\omega}{E_b}, \quad r = \frac{y}{\kappa(1-y)}, \quad (3)$$

where E_b , ω_0 and ω are energies of initial electron, laser photon and backscattered photon, respectively. Note also that maximal energy of backscattered photons $\omega_{max} = \kappa E_b / (\kappa + 1)$. In Fig. 2 energy distributions of backscattered photons are shown for $\kappa \simeq 1$ and $\kappa \simeq 3$ which correspond to $\omega_0 = 1.17$ eV (Nd:YAG laser) and $\omega_0 = 3.3$ eV (Nitrogen laser) with $E_b = 55$ GeV of LEP. Fig. 3 shows energy dependence of backscattered photon helicities for the same parameters. The photon scattering angle is a unique function of the photon energy

$$\theta_\gamma(\omega) \simeq \frac{m_e}{E_b} \sqrt{\frac{E_b \kappa}{\omega} - (\kappa + 1)}. \quad (4)$$

In our proposal we use this dependence for monochromatization of backscattered photons. In order to reach 1% monochromatization ($0.99\omega_{max} \leq \omega_\gamma \leq \omega_{max}$) one should select photons with $\theta_\gamma \leq 1.3 \times 10^{-6}$ rad for $\kappa = 1$ and $\theta_\gamma \leq 1.8 \times 10^{-6}$ rad

for $\kappa = 3$. Taking the distance between the conversion region and absorbing wall as 100 meter, these angles correspond to diameter of the selecting slit $d=260\mu\text{m}$ and $d=360\mu\text{m}$, respectively. As can be seen from Fig. 3 the helicity of the photons reaching to the target is nearly equal to one for the case considered.

It is obvious that the frequency of laser pulses must coincide with frequency of reaching electron bunches to the conversion region. Taking into account the circumference of LEP ring 26.66 km and the number of electron bunches in the ring is equal to four, one obtains $f=44980\text{ s}^{-1}$. Conversion coefficient is defined as

$$k = \frac{N_\gamma}{N_e} = \frac{A}{A_0}, \quad (5)$$

where N_e is the number of particles in electron bunch, N_γ is the number of converted photons, A_0 is laser pulse energy such that each electron in a bunch is subject to collision with a laser photon, and A is the pulse energy needed.

The number of converted photons N_γ is defined by the requirement to obtain one event in each collision with the polarized target

$$\beta N_\gamma T_n \sigma_{\gamma p} = 1, \quad (6)$$

where β is a fraction of the photons passing through the slit, T_n is the density of nucleons in the target and $\sigma_{\gamma p}$ is the total cross section of gamma-proton collision. Since we have chosen $0.99\omega_{max} \leq \omega \leq \omega_{max}$, then $\beta \simeq 0.012$ for $\kappa = 1$ and $\beta \simeq 0.015$ for $\kappa = 3$ (see Fig. 2). For butanol target $T_n = 4 \times 10^{25}\text{ cm}^{-2}$ and $\sigma_{\gamma p} \simeq 100\mu\text{b}$ for energy under consideration, therefore one gets $N_\gamma \simeq 2 \times 10^4$. Because $N_e = 4 \times 10^{11}$ for LEP one has $k = 5 \times 10^{-8}$.

The condition for each electron to be scattered once from laser bunch is given by

$$\frac{n_0}{S_{laser}} \sigma_c = 1, \quad (7)$$

where n_0 is a number of photons in a laser pulse, S_{laser} is the transverse area of the laser bunch in conversion region and $\sigma_c = 10^{-25} cm^2$ is total Compton cross section. It is obvious that $S_{laser} \geq S_e$, since all electrons should pass through the laser bunch. For LEP $S_e = 2 \times 10^{-4} cm^2$ and obtaining n_0 from Eq(7), one can easily get

$$A_0 = n_0 \omega_0 = \begin{cases} 160 J & \text{for } \omega_0 = 1.17 eV , \\ 450 J & \text{for } \omega_0 = 3.3 eV . \end{cases} \quad (8)$$

Let us remind that the needed laser pulse repetition rate is about $4.5 \times 10^4 Hz$. The laser pulses both with this repetition rate and energy of 160 J will possibly be available in the future. Fortunately, in our case the required pulse energy is much less than above value, namely

$$A = k A_0 \simeq 10^{-5} J \quad \text{for } \omega_0 \simeq 1.17 eV. \quad (9)$$

In order to increase conversion efficiency the length of the laser and electron bunches must overlap in the interaction region. Since the typical value of an electron bunch length is of the order of 1 cm, the duration time of a laser pulse should not be longer than 30 ps. The lasers with such parameters are widely used in industry [15].

Now, let us estimate the time for using up an electron bunch. In each collision 2×10^4 electrons have been scattered and the rest keep cycling in the ring. The LEP bunch contains 4×10^{11} electrons, so it can be repeatedly used 10^7 times. Since the collision frequency is $10^4 Hz$, the bunch lasts $10^3 s$ before used up. This is comparable with filling time of LEP.

The proposed experiment will allow to measure directly both polarized quark and gluon distributions. Investigating the scattering of high energy polarized photons from quarks, one will get information about polarized u, d and s quark distributions. Searching for gamma-gluon fusion processes ($\gamma p \rightarrow j + j + X$, $s + \bar{s} + X$, $c + \bar{c} + X$) enables one to measure directly polarized gluon distributions. For illustration, let us

consider the process $\gamma p \rightarrow s + \bar{s} + X$ in detail. Neglecting s quark mass the differential cross section for the leading subprocess $\gamma g \rightarrow \bar{s}s$ is given by

$$\frac{d\hat{\sigma}}{d\hat{t}} = (1 + \lambda_g \xi_2) \frac{\pi \alpha \alpha_s}{9 \hat{s}^2} \left(\frac{\hat{u}}{\hat{t}} + \frac{\hat{t}}{\hat{u}} \right), \quad (10)$$

where λ_g and ξ_2 are gluon and photon helicities, respectively; $\hat{s} = xs$, $\hat{t}$ and $\hat{u}$ are Mandelstam variables of the subprocess, and x is the fraction of proton momentum carried by the gluon. For LEP $s \simeq 2E_\gamma m_p \simeq 51.7 \text{ GeV}^2$ for $\kappa = 1$ and $s \simeq 77.6 \text{ GeV}^2$ for $\kappa = 3$. In order to minimize the next order corrections, transverse momenta of quarks should be taken bigger than 1 GeV.

Dependence of nonpolarized total cross section for the process $\gamma p \rightarrow s\bar{s}X$ on p_T^{min} at $s = 51.7 \text{ GeV}^2$ is shown in Fig. 4 for three different gluon distribution parametrizations:

$$\begin{aligned} G &= \frac{3}{x} \{5(1-x)^4 - 4(1-x)^5 + (1-x)^6\} \\ \Delta G &= \frac{3}{x} \{5(1-x)^4 - 4(1-x)^5 - (1-x)^6\} \end{aligned} \quad \text{Brodsky-Schmidt [6]} \quad (11)$$

$$\begin{aligned} G &= \frac{2.62}{x} (1 + 3.5x)(1-x)^{5.9} \\ \Delta G &= \frac{2.901}{x} x^{0.35} (1 + 2.85x)(1-x)^{5.9} \end{aligned} \quad \text{Gupta [16]} \quad (12)$$

$$\begin{aligned} G &= \frac{1}{x} (1.75 + 15.575x)(1-x)^{6.03} \\ \Delta G &= 22x(1-x)^{10}G \end{aligned} \quad \text{Kunzst [5]} \quad (13)$$

Nonpolarized gluon distributions of the last two parametrizations are taken from Eichten et al., [17].

The integrated luminosity can be easily extracted from previous considerations and it is about 1 fb^{-1} per year. As can be seen from Fig. 4, this luminosity corresponds

to at least 10^6 events per year for $s\bar{s}$ production even if $p_T^{min} \geq 2.5$ GeV. In Fig. 5 asymmetry $A = (\sigma^{\uparrow\uparrow} - \sigma^{\uparrow\downarrow})/(\sigma^{\uparrow\uparrow} + \sigma^{\uparrow\downarrow})$ versus p_T^{min} is plotted for various polarized gluon distributions given above, assuming completely polarized free protons. Note that for butanol target the fraction of events originated from the free protons is $f \simeq 0.14$. Since the polarization of proton target is 0.8 [11], the predicted asymmetries should be reduced by this factor. Because the number of events are high enough even at large p_T values, the statistical error will be small and the distinction between different gluon distributions will be quite possible.

In conclusion, our proposal will provide a clean probe of gluon and quark polarization, particularly for $x \geq 0.1$. The similar consideration can easily be reproduced for HERA and TRISTAN by replacing corresponding parameters. Finally, the proposed experiment will give further opportunities for the investigation of polarization phenomena, such as elastic γp scattering, exclusive π photoproduction etc.

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FIGURES

FIG. 1. Schematic view of the proposed experiment.

FIG. 2. Energy distributions of backscattered photons

FIG. 3. Helicity of backscattered photons as a function of energy.

FIG. 4. Nonpolarized cross sections versus p_T^{min} . Curves a, b and c correspond to Brodsky-Schmidt, Eichten-Gupta and Kunzst parametrizations for gluon distributions, respectively.

FIG. 5. Asymmetries as a function of p_T^{min} . Curves a, b and c represent the same parametrizations as in Fig.4.

Fig. 1

Fig.2

Fig.3

Fig.4

Fig.5