Measurement of the Spin Asymmetry in the Photoproduction of Pairs of High-p_T Hadrons at HERMES

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We present a measurement of the longitudinal spin asymmetry $A_{||}$ in photoproduction of pairs of hadrons with high transverse momentum p_T. Data were accumulated by the HERMES experiment using a 27.5 GeV polarized positron beam and a polarized hydrogen target internal to the HERA storage ring. For h^+h^- pairs with $p_T^{h_1} > 1.5$ GeV/c and $p_T^{h_2} > 1.0$ GeV/c, the measured asymmetry is $A_{||} = -0.28 \pm 0.12$ (stat.) $\pm$ 0.02 (syst.). This negative value is in contrast to the positive asymmetries typically measured in deep inelastic scattering from protons, and is interpreted to arise from a positive gluon polarization.

From polarized deep inelastic lepton-nucleon scattering (DIS) experiments, it has been inferred that the quark spins account for only a fraction of the nucleon spin. One possible explanation is a significant gluon polarization in the nucleon. In principle, the polarized gluon distribution $\Delta G(x_G)$ (x_G is the fraction of the nucleon momentum carried by the struck gluon) can be probed by a measurement of the scaling violation of the polarized structure functions. However, the presently available data on polarized inclusive deep inelastic scattering only poorly constrain $\Delta G(x_G)$, although there is some indication for the integral to be positive [1–3]. On the other hand, two theoretical calculations in the bag model obtain different predictions for the sign of the integral of $\Delta G(x_G)$ [4,5]. Several recent experimental proposals have concentrated on ways to measure $\Delta G(x_G)$ directly [6–8].

One way to measure $\Delta G(x_G)$ directly is via the photon gluon fusion process. Two useful experimental signatures of this process are charm production and production of jets with high transverse momentum p_T. In the former case, the large mass of the charm quark suppresses its production in the fragmentation process. A similar argument applies to the production of jets: the transverse momentum produced in the fragmentation process is small and two back-to-back jets with sufficiently high p_T thus reflect the high p_T of the quark and anti-quark produced in the photon gluon fusion process. Both charm production and high-p_T jet production in DIS have resulted in direct measurements of the unpolarized gluon structure function $G(x_G)$ [9–11].

At lower energy fixed target experiments, high-p_T hadrons must serve in place of jets [12]. Several phenomenological studies of the potential of high-p_T meson photoproduction as a probe of $\Delta G(x_G)$ have been performed [13,14].

In this Letter we present the first measurement of a spin asymmetry in photoproduction of pairs of high-p_T hadrons. The data were collected in 1996 and 1997 by the HERMES experiment at the HERA storage ring of the DESY laboratory. Polarized positrons of energy 27.5 GeV were scattered off a polarized internal hydrogen gas target. The beam polarization was continuously measured by Compton back scattering and had an average value of 0.55 ± 0.02 [15,16]. The average target polarization was 0.86 ± 0.04 [15,17]. In both cases the quoted uncertainty is predominantly systematic. The HERMES detector [18] is a forward spectrometer that identifies charged particles in the scattering angle range of 0.04 $< \theta <$ 0.22 rad. Particle identification (PID) is accomplished using an electromagnetic calorimeter, a scintillator hodoscope preceded by two radiation lengths of lead, a transition radiation detector, and a C_4F_{10}/N_2(70:30) gas threshold Čerenkov counter. A likelihood method, based on the empirical responses of each of the four PID detectors, is used to discriminate between positrons and hadrons. The luminosity is measured in a pair of $NaBi(WO_4)_2$ electromagnetic calorimeters that detect Bhabha-scattering from target electrons.

The longitudinal cross section asymmetry $A_{||}$ was determined using the formula:

$$A_{||} = \frac{N^{\uparrow\downarrow}L^{\uparrow\uparrow} - N^{\uparrow\uparrow}L^{\uparrow\downarrow}}{N^{\uparrow\downarrow}L_P^{\uparrow\uparrow} + N^{\uparrow\uparrow}L_P^{\uparrow\downarrow}} \,. \tag{1}$$

Here $N^{\uparrow\uparrow}(N^{\uparrow\downarrow})$ is the number of oppositely charged hadron pairs observed for target spin parallel (anti-parallel) to the beam spin orientation. The luminosities for each target spin state are $L^{\uparrow\uparrow(\uparrow\downarrow)}$ and $L_P^{\uparrow\uparrow(\uparrow\downarrow)}$, the latter being weighted by the product of the beam and target polarization values for each spin state.

Events were selected that contained at least one positively charged hadron h^+ and at least one negatively charged hadron h^-. The observation of the scattered positron was not required, in order to include the very low Q^2 region which dominates the cross section. Here Q^2 is the negative square of the 4-momentum of the virtual photon. The highest momentum hadrons of each charge were required to have a momentum above 4.5 GeV/c and a transverse momentum p_T above 0.5 GeV/c. Here p_T is defined as the momentum transverse to the positron beam direction and is approximately equal to the momentum transverse to the photon direction when $Q^2 \approx 0$. To suppress contributions from vector meson resonances from the data sample, a minimum value of the invariant mass of the two hadrons (assuming both hadrons to be pions) $M(2\pi) > 1.0$ GeV/c^2 was imposed. Additionally, both hadrons were required to originate from the target region and to have a common vertex. A detailed account of the analysis may be found in [19].

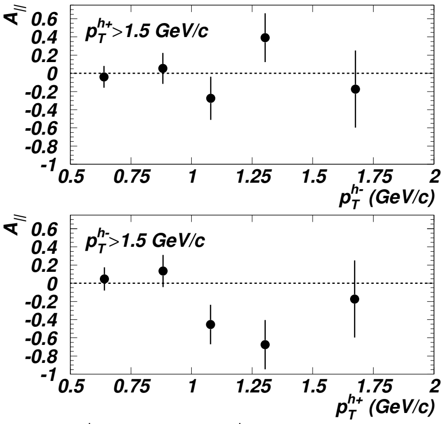

FIG. 1. $A_{||}(p_T^{h^+}, p_T^{h^-})$ for $p_T^{h^+} > 1.5$ GeV/c (top) and for $p_T^{h^-} > 1.5$ GeV/c (bottom). Note that the rightmost data point is identical in both plots.

Fig. 1 presents the measured $A_{||}$ for the highest values of transverse momenta accessible at HERMES; in the top (bottom) panel the positive (negative) hadron was required to have a p_T greater than 1.5 GeV/c and the asymmetry $A_{||}$ is then plotted as a function of the p_T of the hadron of opposite charge. The data suggest a more negative asymmetry when the transverse momentum of the negative hadron is higher than that of the positive hadron. Ignoring this charge asymmetry and averaging over the five bins satisfying the requirement $p_T^{h_1} > 1.5$ GeV/c and $p_T^{h_2} > 1.0$ GeV/c, a negative asymmetry $A_{||} = -0.28 \pm 0.12$ (stat.) ± 0.02 (syst.) is observed. (The symbol h_1 signifies the hadron with the higher p_T.) When the requirement $p_T^{h_1} > 1.5$ GeV/c is not enforced, the asymmetry is consistent with zero. The observed negative asymmetry is in contrast to the positive asymmetries typically measured in deep inelastic scattering from protons.

A possible background to the observed asymmetry arises from coincident detection of a negative hadron and the scattered positron, the latter being misidentified as a positive hadron. From studies of other processes, the probability for positron/hadron misidentification has been determined to be less than 0.2%. By comparing yields of h^+h^- pairs to those of e^+h^- pairs detected in the final state, the background arising from this misidentification has been estimated to be less than 0.1%, for the kinematics selected by this analysis. Other sources of background include high-p_T particles from charm decays. Contributions from both open charm and J/ψ decays have been found to be negligible using the AROMA [20] Monte Carlo generator.

The systematic uncertainty arising from the measurement of the beam and target polarizations is about 6% of $A_{||}$, much smaller than the statistical error and independent of p_T. Resolution effects and alignment uncertainties were found to be negligible. Electroweak radiative corrections are expected to be very small compared to the statistical uncertainty.

The measured asymmetry was interpreted assuming that several different processes could contribute to the two-hadron cross section: lowest order deep inelastic scattering (containing no hard QCD vertex), interaction via the hadronic structure of the photon – described by the vector meson dominance model (VMD) and by non-resonant hadronic "anomalous" photon structure, and the two first order QCD processes (termed "direct") which describe the interaction of a pointlike photon. These are photon gluon fusion (PGF) and the QCD Compton effect (QCDC).

The contribution from lowest order DIS is suppressed by the requirement of high p_T, and was confirmed to be negligible by a simulation based on the LEPTO Monte Carlo generator [21]. Contributions from VMD were assumed to have a negligible spin asymmetry, and were thus treated as a dilution of the other asymmetries. Finally, we neglect possible contributions from anomalous photon structure, where the photon fluctuates into a non-resonant $q\bar{q}$ pair which interacts via hard processes with the partons inside the nucleon. This is supported by a model [22] that explains the excess of forward hadrons with high p_T observed in γp reactions at $70-90$ GeV, relative to those from πp and Kp scattering [23]. At this energy, the model prediction at high p_T is dominated by direct processes involving hard coupling of the photon to the partons in the proton. At the lower energy of the present experiment, a negligible contribution from anomalous photon structure is predicted by the model.

Under the assumptions described above, only two of the five possible spin asymmetries A_i contribute significantly to the measured asymmetry:

$$A_{||} \approx (A_{\mathrm{PGF}} f_{\mathrm{PGF}} + A_{\mathrm{QCDC}} f_{\mathrm{QCDC}}) D \qquad (2)$$

where f_i is the unpolarized fraction of events from subprocess i ($f_{\mathrm{PGF}} + f_{\mathrm{QCDC}} + f_{\mathrm{VMD}} = 1$), and D is the virtual photon depolarization factor. In the small region of phase space selected by the present analysis, the A_i's may be approximated by the products of the hard subprocess asymmetries and the quark and gluon polarizations. The subprocess asymmetries $\hat{a}_{\mathrm{PGF}} = \hat{a}(\gamma g \to q\bar{q})$ and $\hat{a}_{\mathrm{QCDC}} = \hat{a}(\gamma q \to qg)$ are directly calculable in leading order (LO) QCD [13]. For real photons and massless quarks, $\hat{a}_{\mathrm{PGF}} = -1$, while $\langle \hat{a}_{\mathrm{QCDC}} \rangle$ is about $+0.5$ (averaged over the kinematics selected by this analysis) and is independent of the quark flavor. The effective quark polarization $\Delta q/q$ is computed as a suitably weighted combination of $\Delta u/u$ and $\Delta d/d$, which are known from inclusive and semi-inclusive polarized DIS measurements [24,25]. The measured asymmetry can therefore be expressed as follows:

$$A_{||} \approx \left(\hat{a}_{\mathrm{PGF}} \frac{\Delta G}{G} f_{\mathrm{PGF}} + \hat{a}_{\mathrm{QCDC}} \frac{\Delta q}{q} f_{\mathrm{QCDC}} \right) D, \qquad (3)$$

where the kinematic dependences have been suppressed for brevity. This equation can be solved for $\Delta G/G$ after appropriate averaging over the selected kinematics.

The PYTHIA Monte Carlo generator [26] was used to provide a model for the data. An important parameter in the simulation of the direct processes, the minimum transverse momentum of the outgoing partons ($\hat{p}_T^{\min}$), was chosen following Ref. [22] to be 0.5 GeV/c. The kinematic region used in the interpretation of the measurement ($p_T^{h_1} > 1.5$ GeV/c and $p_T^{h_2} > 0.8$ GeV/c) was chosen so that the final results depend only weakly on the choice of $\hat{p}_T^{\min}$. The Lund fragmentation parameters used in the simulation have been adjusted to fit the HERMES semi-inclusive hadron multiplicity data [27].

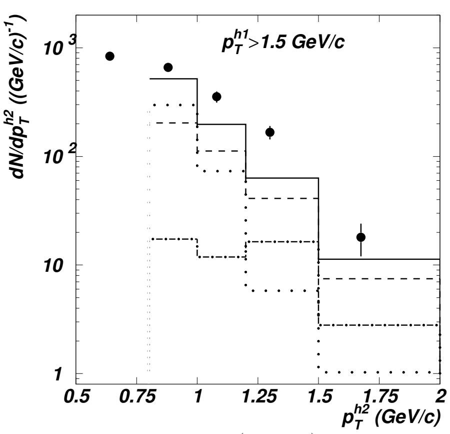

FIG. 2. Comparison of data (circles) and Monte Carlo simulation (full histogram) for $dN/dp_T^{h_2}$ for $p_T^{h_1} > 1.5$ GeV/c. The dashed, dashed-dotted and dotted lines represent the contributions from the PGF, VMD and QCDC processes, respectively; the solid line represents their sum.

The normalized yield for the production of two high-p_T hadrons is compared to the Monte Carlo simulation in Fig. 2. Here, the Weizsäcker-Williams approximation has been used to relate the photoproduction cross section simulated by PYTHIA to the measured electroproduction cross section. Also shown in Fig. 2 are the contributions from the three subprocesses included in the simulation. The simulated yield has a p_T-dependence similar to that of the data, but is significantly smaller in magnitude. Good agreement is found for the distributions in other kinematic variables, such as the azimuthal angle between the two hadrons and $\Delta p_T = |\vec{p}_T^{h^-}| - |\vec{p}_T^{h^+}|$. As the simulation of the direct QCD processes is restricted to leading order, the observed difference in normalization might be due to contributions from higher-order QCD processes and/or contributions from hard interactions of the hadronic structure of the photon. We also note that the agreement becomes much better if the default Lund fragmentation parameters are used. However, the final result for $\Delta G/G$ is found to depend only weakly on the choice of fragmentation parameters.

In the same region of phase space where a negative asymmetry is observed ($p_T^{h_1} > 1.5$ GeV/c and $p_T^{h_2} > 1.0$ GeV/c), the simulated cross section is dominated by photon gluon fusion. The consequent sensitivity of the measured asymmetry to the polarized gluon distribution is demonstrated in Fig. 3, where $A_{||}$ at high transverse momenta (i.e. the average of the two panels of Fig. 1) is compared with Monte Carlo predictions for different distributions of $\Delta G/G$.

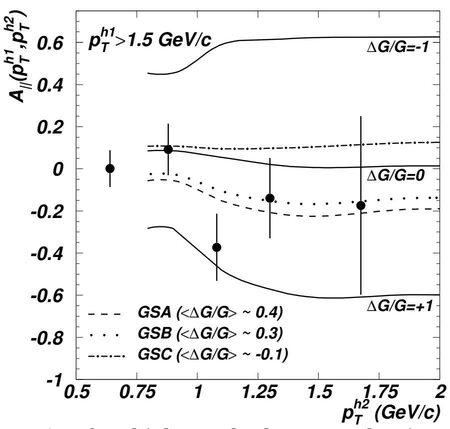

FIG. 3. $A_{||}$ for high-p_T hadron production measured at HERMES compared with Monte Carlo predictions for $\Delta G/G = \pm 1$ (lower/upper solid curves), $\Delta G/G = 0$ (middle solid curve), and the phenomenological LO QCD fits of Ref. [28] (dashed, dotted, and dot-dashed curves).

The Monte Carlo simulation was used to determine the quantities necessary to relate the data to $\langle \Delta G/G \rangle$, where the angle brackets indicate averaging over the kinematics of the measurement. These quantities have been determined from PYTHIA to be $\langle D \hat{a}_{\mathrm{QCDC}} \frac{\Delta q}{q} \rangle = 0.15$, $\langle D \rangle = 0.93$, $\langle x_G \rangle = 0.17$, $\langle Q^2 \rangle = 0.06$ (GeV/c)^2, and $\langle \hat{p}_T^2 \rangle = 2.1$ (GeV/c)^2. The distribution $\Delta G(x_G)$ is probed principally in the range $0.06 < x_G < 0.28$. Note that the hard scale of this process is not given by Q^2, but rather by $\hat{p}_T^2$, the square of the transverse momentum carried by each of the outgoing quarks.

For the four values of $A_{||}$ at $p_T^{h_2} > 0.8$ GeV/c presented in Fig. 3, $\langle \Delta G/G \rangle$ was extracted according to equation (3). Since these four measurements probed essentially the same range of x_G, the results for $\langle \Delta G/G \rangle$ were averaged. Using the assumptions and model parameters described above, a value for $\langle \Delta G/G \rangle$ was determined in LO QCD to be 0.41 ± 0.18 (stat.) ± 0.03 (syst.), where the systematic uncertainty represents the experimental contribution only.

The extracted value of $\langle \Delta G/G \rangle$ is compared in Fig. 4 with several phenomenological LO QCD fits of a subset of the world's data on $g_1(x,Q^2)$ [28,29]. The horizontal error bar represents the standard deviation of the x_G distribution for the cited kinematical constraints on the produced hadrons, as given by the Monte Carlo.

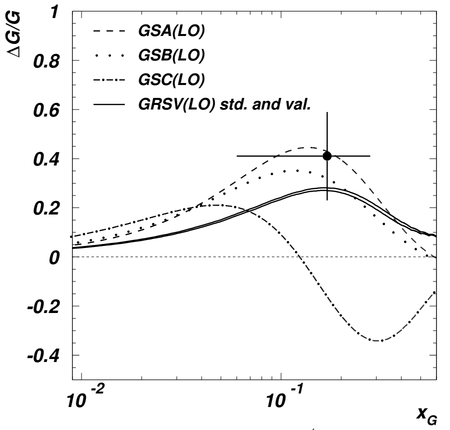

FIG. 4. The extracted value of $\Delta G/G$ compared with phenomenological QCD fits to a subset of the world's data on $g_1^{p,n}(x,Q^2)$. The curves are from Refs. [28,29], evaluated at a scale of 2 $(\mathrm{GeV/c})^2$. The indicated error on $\Delta G/G$ represents statistical and experimental systematic uncertainties only; no theoretical uncertainty is included.

In summary, a positive value for the gluon polarization has been extracted from a measurement of the spin asymmetry in the photoproduction of pairs of hadrons at high p_T. This interpretation of the observed negative asymmetry is based on a model which takes into account leading order QCD processes and VMD contributions to the cross section. At the kinematics of this measurement, no spin-dependent analyses of higher order QCD processes or contributions from anomalous photon structure are presently available; these processes have therefore been neglected in the model presented here. If such processes would be important but have no significant spin asymmetry, the extracted value of $\langle\Delta G/G\rangle$ would increase, but still differ from zero by 2.3σ. To alter the principal conclusion of this analysis, i.e., that $\langle\Delta G/G\rangle$ at $\langle x_G\rangle = 0.17$ is positive, a significant contribution from a neglected process with a large negative spin asymmetry would be needed.

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