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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.

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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 measuring the scaling violation of the polarized structure functions. However, the presently available data on polarized inclusive DIS only poorly constrain $\Delta G(x_G)$, although there is some indication that the integral is positive [1–3]. On the other hand, two bag-model calculations obtain different signs for the integral of $\Delta G(x_G)$ [4,5]. Recent experimental proposals have concentrated on ways to measure $\Delta G(x_G)$ directly [6–8].

One way to do so is via the photon gluon fusion (PGF) process. Two 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 reflect the high p_T of the quark and antiquark produced in the PGF process. Both signatures 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]. Phenomenological studies have shown the potential of photoproduction of high-p_T mesons as a probe of $\Delta G(x_G)$ [13,14].

We present here the first measurement of a spin asymmetry in photoproduction of pairs of high-p_T hadrons. The data were collected by the HERMES experiment at the HERA storage ring of the DESY laboratory. Polarized 27.5 GeV positrons were scattered off a polarized internal hydrogen gas target. The beam polarization was continuously measured by Compton backscattering 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 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

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

$N^{\uparrow\uparrow}(N^{\uparrow\downarrow})$ is the number of oppositely charged hadron pairs observed for target spin parallel (antiparallel) 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 polarizations 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 e^+ was not required in the trigger, so as to include the very low Q^2 region which dominates the measured cross section (Q^2 is the negative square of the virtual-photon 4-momentum). The highest momentum hadrons of each charge were required to have a momentum $p > 4.5$ GeV$/c$ and a transverse momentum $p_T > 0.5$ GeV$/c$. Here p_T is the momentum transverse to the positron beam direction and is about equal to the momentum transverse to the photon direction when $Q^2 \approx 0$. To suppress contributions from vector meson resonances to the data sample, a minimum value of the two-hadron invariant mass (assuming both hadrons to be pions) $M(2\pi) > 1.0$ GeV$/c^2$

was imposed. Also, the hadrons were required to have a common vertex in the target region. In this event sample, the average charge multiplicity of reconstructed events is 2.2, limited by the forward acceptance of the detector. By using a simulation, the mean charged hadron multiplicity was estimated to be 5.5. A detailed account of the analysis may be found in [19].

Figure 1 shows $A_{||}$ for the highest p_T accessible at HERMES; in the top (bottom) panel the positive (negative) hadron was required to have a $p_T > 1.5$ GeV$/c$ and $A_{||}$ is then plotted as a function of the p_T of the hadron of opposite charge. About 600 events were available for this analysis. The data suggest a more negative asymmetry when the transverse momentum of the h^- is higher than that of the h^+. Ignoring this charge asymmetry and averaging over the five bins where $p_T^{h_1} > 1.5$ GeV$/c$ and $p_T^{h_2} > 1.0$ GeV$/c$, a negative asymmetry $A_{||} = -0.28 \pm 0.12(\text{stat}) \pm 0.02(\text{syst})$ is observed (h_1 signifies the hadron with the higher p_T). When $p_T^{h_1} > 1.5$ GeV$/c$ is not required, $A_{||}$ is consistent with zero. The observed negative $A_{||}$ is in contrast to the positive asymmetries typically measured in DIS from protons.

A possible background to the observed $A_{||}$ arises from coincident detection of an h^- and the scattered e^+, the latter being misidentified as an h^+. From studies of other processes, the probability for e^+/h^+ misidentification has been determined to be <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 was estimated to be <0.1%, for the kinematics selected by this analysis. Other sources of background include high-p_T particles from charm decays. Contributions from open charm and $\mathbf{J}/\psi$ decays were found to be negligible using the AROMA [20] event 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

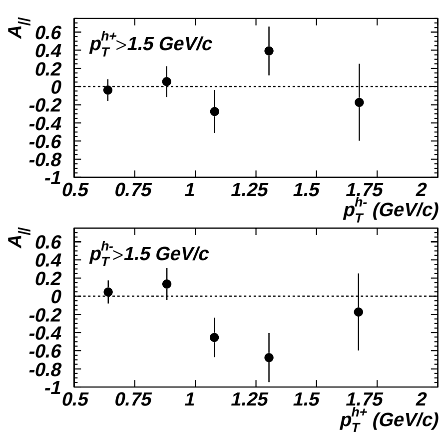

FIG. 1. $A_{||}(p_T^{h^+}, p_T^{h^-})$ for $p_T^{h^+} > 1.5$ GeV$/c$ (top) and for $p_T^{h^-} > 1.5$ GeV$/c$ (bottom). The error bars represent the statistical uncertainty. Note that the rightmost data point is identical in both plots.

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 by assuming that several different processes could contribute to the two-hadron cross section: lowest order DIS (containing no hard QCD vertex); interaction via the hadronic structure of the photon—described by the vector meson dominance model (VMD) and by nonresonant hadronic "anomalous" photon structure; and the two first-order "direct" QCD processes which involve a pointlike photon, 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 generator [21]. Contributions from VMD were assumed to have a negligible spin asymmetry, and were treated as a dilution of the other asymmetries. Finally, we neglect possible contributions from anomalous photon structure, where the photon fluctuates into a nonresonant $q\bar{q}$ 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 HERMES, a negligible contribution from anomalous photon structure is predicted.

Under the above assumptions, only A_{PGF} and A_{QCDC} contribute significantly to the measured asymmetry,

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

where f_i is the unpolarized fraction of events from subprocess i ($f_{\text{PGF}} + f_{\text{QCDC}} + f_{\text{VMD}} = 1$), 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 $\hat{a}_{\text{PGF}} = \hat{a}(\gamma g \rightarrow q\bar{q})$ and $\hat{a}_{\text{QCDC}} = \hat{a}(\gamma q \rightarrow qg)$ are calculable in leading order (LO) QCD [13]. For real photons and massless quarks, $\hat{a}_{\text{PGF}} = -1$, while $\langle \hat{a}_{\text{QCDC}} \rangle$ is $\approx +0.5$ (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 $\Delta d/d$, known from inclusive and semi-inclusive polarized DIS measurements [24,25]. The measured asymmetry can then be expressed as

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

where the kinematic dependences have been suppressed for brevity. Equation (3) can be solved for $\Delta G/G$ after appropriate averaging over the selected kinematics.

The PYTHIA generator [26] was used to provide a model for the data. The minimum transverse momentum of the outgoing partons ($\hat{p}_T^{\min}$) was set to 0.5 GeV/c, following Ref. [22]. 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].

The normalized yield for the production of two high-p_T hadrons is compared to the simulation in Fig. 2. Here, the Weizäcker-Williams approximation was used to relate the photoproduction cross section simulated by PYTHIA to the measured electroproduction cross section. Also 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 may be due to contributions from higher-order QCD processes and/or hard interactions of the photon hadronic structure. We note that the agreement becomes 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 $A_{||}$ 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 PGF. The consequent sensitivity of the measured $A_{||}$ to the polarized gluon distribution is shown in Fig. 3, where $A_{||}$ at high transverse momenta (i.e., the average of the two panels of Fig. 1) is compared with simulations for different distributions of $\Delta G/G$.

To relate the data to $\langle \Delta G/G \rangle$, where the angle brackets indicate averaging over the kinematics of the measurement, the necessary quantities were determined by the simulation: $\langle D \hat{a}_{\mathrm{QCDC}} \frac{\Delta q}{q} \rangle = 0.15$, $\langle D \rangle = 0.93$, $\langle x_G \rangle = 0.17$, $\langle Q^2 \rangle = 0.06$ (GeV/c)^2, and $\langle p_T^2 \rangle = 2.1$ (GeV/c)^2. The distribution $\Delta G(x_G)$ is probed principally in the range $0.06 < x_G < 0.28$. 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 in Fig. 3, $\langle \Delta G/G \rangle$ was extracted using Eq. (3). As these four measurements probed essentially the same range of x_G, the results for $\langle \Delta G/G \rangle$ were averaged. Using the above assumptions and model parameters, $\langle \Delta G/G \rangle$ was determined in LO QCD to be 0.41 ± 0.18(stat) $\pm$ 0.03(syst); the systematic uncertainty represents the experimental contribution only.

This 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 simulation.

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 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 have therefore been neglected in the model presented here. If such processes were important but had no significant

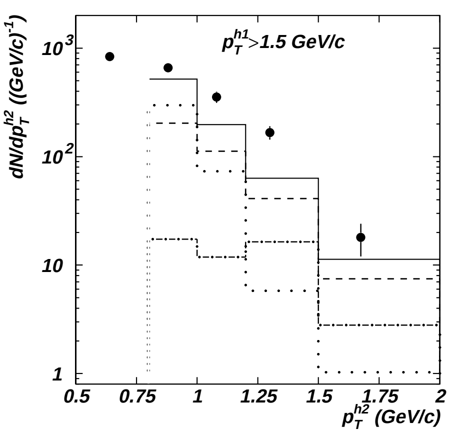

FIG. 2. Comparison of data (circles) and Monte Carlo simulation (full histogram) for $dN/dp_T^{h_2}$ for $p_T^{h_1} > 1.5$ GeV/c. The dashed, dashed-dotted, and dotted lines represent the contributions from the PGF, VMD, and QCDC processes, respectively; the solid line represents their sum.

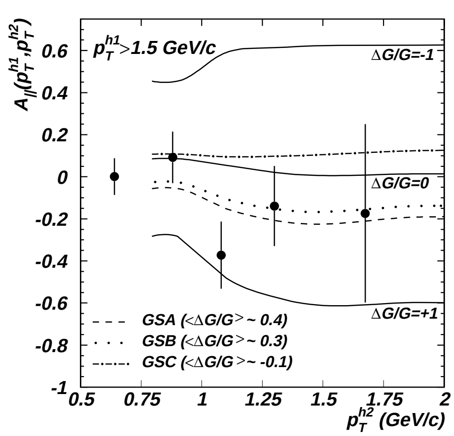

FIG. 3. $A_{||}$ for high-p_T hadron production measured at HERMES compared with Monte Carlo predictions for $\Delta G/G = \pm 1$ (lower/upper solid curves), $\Delta G/G = 0$ (middle solid curve), and the phenomenological LO QCD fits of Ref. [28] (dashed, dotted, and dotted-dashed curves).

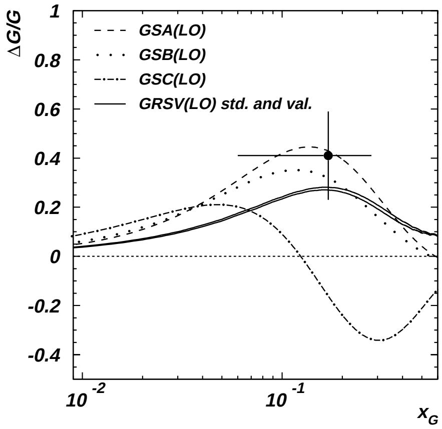

FIG. 4. The extracted value of $\Delta G/G$ compared with phenomenological QCD fits to a subset of the world's data on $g_1^{p,n}(x, Q^2)$. The curves are from Refs. [28,29], evaluated at a scale of 2 $(\mathrm{GeV}/c)^2$. The indicated error on $\Delta G/G$ represents statistical and experimental systematic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

spin asymmetry, the value of $\langle \Delta G/G \rangle$ would increase, but still differ from zero by 2.3σ. To alter our principal conclusion that $\langle \Delta G/G \rangle$ is >0 at $\langle x_G \rangle = 0.17$, a significant contribution from a neglected process with a large negative spin asymmetry would be needed.

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