Search for a two-photon exchange contribution to inclusive deep-inelastic scattering

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Abstract. The transverse-target single-spin asymmetry for inclusive deep-inelastic scattering with effectively unpolarized electron and positron beams off a transversely polarized hydrogen target was measured, with the goal of searching for a two-photon exchange signal in the kinematic range $0.007 < x_B < 0.9$ and $0.25 \text{ GeV}^2 < Q^2 < 20 \text{ GeV}^2$. In two separate regions $Q^2 > 1 \text{ GeV}^2$ and $Q^2 < 1 \text{ GeV}^2$, and for both electron and positron beams, the asymmetries are found to be consistent with zero within statistical and systematic uncertainties, which are of order $10^{-3}$ for the asymmetries integrated over $x_B$.

1. Introduction

Electromagnetic reactions like, e.g., elastic charged-lepton nucleon scattering, exclusive processes or deep-inelastic charged-lepton nucleon scattering usually are analyzed in the approximation of one-photon exchange. Recently, however, it was shown that two-photon exchange contributions could potentially have a substantial impact on the extraction of the proton electric and magnetic form factors, $G_E$ and $G_M$, using the Rosenbluth separation technique and therefore could explain the observed discrepancy in the measurements of $G_E/G_M$ at large momentum transfers between the Rosenbluth method and the polarization transfer method (for details see e.g., Refs. [1, 2] and references therein). Furthermore it has been shown that two-photon exchange leads to sizeable effects in parity violating $e^- p$ scattering [3], and that it produces transverse-beam single spin asymmetries of order $10^{-5} - 10^{-6}$ in $e^+ p \rightarrow e^{'} + p'$ [4, 5, 6].

To date, all evidence of non-zero two-photon exchange effects comes from elastic lepton-nucleon scattering, $l + N \rightarrow l^{'} + N'$, while in inelastic scattering no clear signature of two-photon exchange effects has yet been observed. Here, one possible signature is the beam-charge asymmetry in the unpolarized cross section which is sensitive to the real part of the two-photon exchange amplitude. Such an asymmetry arises from the interference of the one-photon and the two-photon exchange amplitudes. The interference term is proportional to $e_l \alpha^3$, where $e_l$ is the beam charge and $\alpha$ is the electromagnetic coupling constant. Early measurements of the inelastic cross-section ratio $R = \sigma_{l^{+}p}/\sigma_{l^{-}p}$ with $e^+/e^-$ beams [7, 8, 9, 10, 11] and $\mu^+ / \mu^-$ beams [12, 13] showed no effect within their accuracy of a few percent.

Another possible signature is the transverse-target single-spin asymmetry (SSA) in inelastic scattering of an unpolarized (U) lepton beam from a transversely (T) polarized target, i.e., an asymmetry in the azimuthal angular distribution of the scattered lepton about the beam direction. In the one-photon exchange approximation such a SSA is forbidden by the combination...
of time reversal invariance, parity conservation, and the hermiticity of the electromagnetic current operator, as stated in the Christ-Lee theorem [14]. A non-zero SSA can therefore be interpreted as an indication of two-photon exchange [15]. It is sensitive to the imaginary part of the two-photon exchange amplitude.

The spin-dependent part of the cross section can be written as

$$\sigma_{UT} \propto e_1^\alpha \frac{M}{Q} \varepsilon_{\mu\nu\rho\sigma} S^\mu p^\nu k^\rho k'^\sigma C_T. \quad (1)$$

Here, $M$ is the nucleon mass, $-Q^2$ is the squared four-momentum transfer, $p$, $k$ and $k'$ are the four-moments of the target, the incident and the scattered lepton, respectively, while $\varepsilon_{\mu\nu\rho\sigma}$ is the Levi-Civita tensor. The term $\varepsilon_{\mu\nu\rho\sigma} S^\mu p^\nu k^\rho k'^\sigma$ is proportional to $\vec{S} \cdot (\vec{k} \times \vec{k}')$, consequently the largest asymmetry is obtained when the spin vector $\vec{S}$ is perpendicular to the lepton scattering plane defined by the three-momenta $\vec{k}$ and $\vec{k'}$. Finally, $C_T$ is a higher-twist term arising from quark-quark and quark-gluon-quark correlations that cannot be completely evaluated at present.

As $\sigma_{UT}$ is proportional to $\alpha M/Q$, it is expected to be small and to increase with decreasing $Q^2$. Asymmetries of order $10^{-4}$ have been predicted for JLAB kinematics [16], but asymmetries as large as $10^{-2}$ are also not excluded due to the uncertainties in the calculation of $C_T$ [15].

Early measurements [17, 18, 19] that were confined to the region of nucleon resonances and were declared as ‘Search for T violation’ resulted in asymmetries being compatible with zero within the few percent level of the experimental uncertainties.

The HERMES experiment has performed a first precise measurement of the transverse target SSA in inclusive deep-inelastic scattering (DIS) of both unpolarized electrons and positrons off a transversely polarized hydrogen target [20]. The results are presented in this contribution.

2. Experiment

The data were collected with the HERMES spectrometer [21] at the HERA e-p accelerator facility. The 27.6 GeV lepton (electron or positron) beam was scattered off a nuclear-polarized gaseous hydrogen target internal to the lepton ring. The direction of the target-spin vector was transverse to the beam direction. It was reversed in both “upward” (↑) and “downward” (↓) directions at 1-3 minute time intervals to minimize systematic effects. Both the nuclear polarization $P$ and the atomic fraction inside the target cell were continuously measured [22].

The beam was longitudinally polarized, but a helicity-balanced data sample was used to obtain an effectively unpolarized beam. Only the scattered leptons were considered for this analysis. Leptons were distinguished from hadrons by using a dual-radiator ring-imaging Cherenkov (RICH) detector, a transition-radiation detector, a scintillator pre-shower counter, and an electromagnetic calorimeter. Hadrons were suppressed by very stringent particle identification requirements to a level of less than $10^{-4}$ to exclude any contamination from a possible transverse hadron SSA in the lepton signal. Events were selected in the kinematic region $0.007 < x_B < 0.9$, $0.25 \text{ GeV}^2 < Q^2 < 20 \text{ GeV}^2$, $0.1 < y < 0.85$, and $W^2 > 4 \text{ GeV}^2$. Here, $x_B = Q^2/2M_yE$ is the Bjorken scaling variable, $y$ is the fraction of the beam energy $E$ carried by the virtual photon in the laboratory frame and $W$ is the invariant mass of the photon-nucleon system. The total statistics collected with a positron (electron) beam amount to about 2.9 million (4.8 million) events in this kinematic region.

The differential yield for a given target spin direction can be expressed as

$$\frac{d^4N^{(1)}}{dx_B dQ^2 d\phi_s} = d^3\sigma_{UU} \left[ L^{(1)} + (-)L_P^{(1)} A_{UT}^{\sin \phi_s}(x_B, Q^2) \sin \phi_s \right] \Omega(x_B, Q^2, \phi_s). \quad (2)$$

Here, $\phi_s$ is the azimuthal angle about the beam direction between the lepton scattering plane and the “upwards” target spin direction, and $\sigma_{UU}$ denotes the unpolarized cross section. Also,
\( L^{(1)} \) is the total luminosity in the \( \uparrow (\downarrow) \) polarization state, \( L_{p}^{(1)} \) is the luminosity weighted by the magnitude \( P \) of the target polarization, and \( \Omega \) is the detector acceptance efficiency. The average beam polarization was about 0.76 (0.71) for the data taking periods with a positron (electron) beam. The \( \sin \phi_{s} \) azimuthal dependence follows directly from the form \( \vec{S} \cdot (\vec{k} \times \vec{k'}) \) of the spin-dependent part of the cross section in Eq. (1).

The asymmetry was calculated as

\[
A_{UT}(x_{B}, Q^{2}, \phi_{s}) = \frac{N_{\uparrow}/L_{p}^{\uparrow} - N_{\downarrow}/L_{p}^{\downarrow}}{N_{\uparrow}/L^{\uparrow} + N_{\downarrow}/L^{\downarrow}} \simeq A_{UT}^{\sin \phi_{s}} \sin \phi_{s}, \tag{3}
\]

where \( N^{(1)} \) are the number of events measured in bins of \( x_{B}, Q^{2}, \) and \( \phi_{s} \). Due to the rapid reversal of the target-spin direction, the acceptance function \( \Omega \) cancels in each \( (x_{B}, Q^{2}, \phi_{s}) \) kinematic bin, if the bin size or the asymmetry is small. Experimentally, the \( A_{UT}^{\sin \phi_{s}} \) amplitudes were extracted for the two regions in \( Q^{2} \) performing a maximum-likelihood fit to the asymmetry binned in \( x_{B} \), and unbinned in \( \phi_{s} \). For a detector with full \( 2\pi \)-coverage in \( \phi_{s} \), the \( \sin \phi_{s} \) amplitude and the left-right asymmetry \( A_{N} \) are related by \( A_{N} = 2A_{UT}^{\sin \phi_{s}}/\pi \).

3. Results

Results for the measured \( A_{UT}^{\sin \phi_{s}} \) amplitudes are shown as a function of \( x_{B} \) in Fig. 1, separately for electrons (top panel) and positrons (center panel). Data with \( Q^{2} > 1 \) GeV\(^2\) (closed symbols) and with \( Q^{2} < 1 \) GeV\(^2\) (open symbols) are shown separately. The error bars indicate the statistical uncertainties of the measurement. Systematic uncertainties are shown as bands. They include contributions due to corrections for misalignment of the detector, beam position and slope at the interaction point and bending of the beam and the scattered lepton in the transverse holding field of the target magnet. They were determined from a high-statistics Monte Carlo sample obtained from a simulation containing a full description of the detector, where an artificial spin-dependent \( \sin \phi_{s} \) azimuthal asymmetry was implemented. For each measured point the systematic uncertainty was obtained as the maximum value of either the statistical uncertainty of the Monte Carlo sample or the difference between the input asymmetry and the extracted one. Input asymmetry amplitudes of zero or as small as \( 10^{-3} \) were reproduced within the statistical Monte Carlo uncertainty of less then \( 3 \times 10^{-4} \). The results are not corrected for smearing, radiative effects and elastic background events. An overall 9.3\% (6.6\%) scale uncertainty stems from the uncertainty of the target polarization. Due to the kinematics of the experiment the quantities \( x_{B} \) and \( < Q^{2} > \) are strongly correlated as shown in the bottom panel of the figure. The collected statistics does not allow to study the \( Q^{2} \) dependence of the amplitude for fixed values of \( x_{B} \). Also shown in this panel is the fraction of elastic events in the data sample estimated from a Monte Carlo simulation.

The asymmetries integrated over \( x_{B} \) are shown on the left panel of the figure and are given in the Table separately for the two \( Q^{2} \) regions along with their statistical and systematic uncertainties. All asymmetry amplitudes are consistent with zero within their uncertainties, which in the DIS region (\( Q^{2} > 1 \) GeV\(^2\)) are of order \( 10^{-3} \). No hint of a sign change between electron and positron asymmetries is observed within uncertainties. Consequently no evidence of a two-photon exchange contribution has been observed in this measurement which sets the so far most precise limit for this effect in inclusive deep-inelastic scattering.

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Figure 1. The $A_{UT}^{\sin \phi_S}$ amplitudes as a function of $x_B$ measured with an electron beam (top) and a positron beam (center). The open (closed) circles identify the data with $Q^2 < 1$ GeV$^2$ ($Q^2 > 1$ GeV$^2$). The asymmetries integrated over $x_B$ are shown on the left. Bottom panel: average $Q^2$ (squares) and fraction of elastic background events (triangles) as a function of $x_B$.

Table 1. The integrated transverse single-spin asymmetry amplitude $A_{UT}^{\sin \phi_S}$ with its statistical and systematic uncertainties and the average values for $x_B$ and $Q^2$ measured separately for electron and positron beams in the two $Q^2$ ranges $Q^2 < 1$ GeV$^2$ (upper rows) and $Q^2 > 1$ GeV$^2$ (lower rows).
References

[1] Blunden P G, Melnitchouk W and Tjon J 2005 Phys. Rev. C 72 034612
[2] Arrington J, 2009 AIP Conf. Proc. C 1160 13-8
[3] Tjon J, Blunden P G and Melnitchouk W and 2009 Phys. Rev. C 79 055201
[4] Wells S P et al. (SAMPLE Collab.) 2001 Phys. Rev. Lett. 63 064001
[5] Maas F E et al. (A4 Collab.) 2005 Phys. Rev. C 94 082001
[6] Armstrong D S et al. (G0 Collab.) 2001 Phys. Rev. Lett. 99 092301
[7] Jostlein H, Kim I J, Königsmann K, Melissinos A C, Muhlemann P, Aslanides E and Limon P 1974 Phys. Lett. B 52 485-8
[8] Hartwig S, Heimlich F H, Huber G, Rössle E, Köblering M, Moritz J, Schmidt K H, Wegener D, Zeller D and Bleckwenn J 1976 Lett. Nuovo Cim. 15 429-34
[9] Fancher D L, Caldwell D O, Cumalat J P, Eisner A M, McPharlin T P, Morrison R J, Murphy F V and Yellin S J 1976 Phys. Rev. Lett. 37 1323-6
[10] Rochester L S, Atwood W B, Bloom E D, Cottrell R L A, Coward D H, DeStaebler H, Mestayer M, Prescott C Y, Stein S, Taylor R E and Trines D 1976 Phys. Rev. Lett. 36 1284-7, Erratum ibid. 37 233
[11] Hartwig S, Heimlich F H, Huber G, Rössle E, Köblering M, Moritz J, Schmidt K H, Wegener D, Zeller D, David P and Mommsen H 1976 Phys. Lett. B 79 297-300
[12] Aubert J J et al. (EMC) 1986 Nucl. Phys. B 272 158-92
[13] Argento A et al. (BCDMS Collab.) 1984 Phys. Lett. B 140 142-4
[14] Christ N and Lee T D 1966 Phys. Rev. 143 1310-21
[15] Metz A, Schlegel M and Goebbe K 2006 Phys. Lett. B 643 319-24
[16] Afanasev A, Strikman M and Weiss C 2008 Phys. Rev. D 77 014028
[17] Chen J R, Sanderson J, Appel J A, Gladding G, Goitein M, Hanson K, Imrie D C, Kirk T, Madaras R, Pound R V, Price L, Wilson R and Zajde C 1968 Phys. Rev. Lett 21 1279-82
[18] Appel J A, Chen J R, Sanderson J, Gladding G, Goitein M, Hanson K, Imrie D C, Kirk T, Madaras R, Pound R V, Price L, Wilson R and Zajde C 1970 Phys. Rev. D 1 1285-303
[19] Rock S, Borghini M, Chamberlain O, Fuzesy R Z, Morehouse C C, Powell T, Shapiro G, Weisberg H, Cottrell R L, Litt J, Mo L W and Taylor R E 1970 Phys. Rev. Lett 24 748-52
[20] Airapetian A et al. (HERMES Collab.) 2010 Phys. Lett. B 682 351-4
[21] Ackerstaff K et al. (HERMES Collab.) 1998 Nucl. Instr. Meth. A 417 230-65
[22] Airapetian A et al. (HERMES Collab.) 2005 Nucl. Instr. Meth. A 540 68-101