Search for a Two-Photon Exchange Contribution to Inclusive Deep-Inelastic Scattering

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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 $0.25\ \mathrm{GeV}^2 < Q^2 < 20\ \mathrm{GeV}^2$. In two separate regions $Q^2 > 1\ \mathrm{GeV}^2$ and $Q^2 < 1\ \mathrm{GeV}^2$, 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.

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In recent years, the contribution of two-photon exchange to the cross section for electron-nucleon scattering has received considerable attention. In elastic ep scattering, two-photon exchange effects are believed to be the best candidate to explain the discrepancy in the measurement of the ratio G_E/G_M of the electric and magnetic form factors of the proton obtained at large four-momentum transfer between the Rosenbluth method and the polarization transfer method [1]. It has been shown that the interference between the one-photon and two-photon exchange amplitudes can affect the Rosenbluth extraction of the nucleon form factors at the level of a few percent. This is enough to explain most of the discrepancy between the results of the two methods [2, 3], although none of the recent calculations can fully resolve the discrepancy at all momentum transfers [4]. Two-photon exchange effects have also been shown to affect the measurement of parity violation in elastic scattering of longitudinally polarized electrons off unpolarized protons, with corrections of several percent to the parity-violating asymmetry [5].

In order to investigate contributions from two-photon exchange, it is necessary to find experimental observables that allow their isolation. Beam-charge and transverse single-spin asymmetries (SSAs) are two suitable candidates. In both elastic and inclusive inelastic lepton-nucleon scattering, these asymmetries arise from the interference of one-photon and two-photon exchange amplitudes. Specifically, beam-charge asymmetries in the unpolarized cross section arise from the real part of the two-photon exchange amplitude [6], while inclusive transverse SSAs are sensitive to the imaginary part [7].

To date, all evidence of non-zero two-photon exchange effects in lepton-nucleon interactions comes from elastic scattering, $l + N \to l' + N'$. Measurements of the cross-section ratio $R = \sigma_{e^+p}/\sigma_{e^-p}$ are compiled in Ref. [6]. Though the individual measurements are consistent with R being unity, a recent reanalysis [8] demonstrates that a deviation of about 5% at low values of four-momentum transfer and virtual-photon polarization is not excluded. Three experiments have measured a non-zero transverse-beam SSA of order $10^{-5} - 10^{-6}$ in elastic scattering of transversely polarized electrons off unpolarized protons [9, 10, 11].

In inelastic scattering no clear signature of two-photon exchange effects has yet been observed. Measurements of the cross-section ratio R with e^+/e^- and μ^+/μ^- beams [12, 13, 14, 15, 16, 17, 18] show no effect within their accuracy of a few percent. The transverse-target SSA has been measured at the Cambridge Electron Accelerator [19, 20] and at SLAC [21]. The data are confined to the region of nucleon resonances, and show an asymmetry which is compatible with zero within the few-percent level of the experimental uncertainties.

In inclusive deep-inelastic scattering (DIS), $l + p \to l' + X$, and 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 [22]. A non-zero SSA can therefore be interpreted as an indication of two-photon exchange.

Ref. [7] presents a theoretical treatment of the transverse SSA arising from the interference of one-photon and two-photon exchange amplitudes in DIS. For an unpolarized beam (U) and a transversely (T) polarized nucleon target, the spin-dependent part of the cross section is given by

$$\sigma_{UT} \propto e_l \alpha_{em} \, \frac{M}{Q} \, \varepsilon_{\mu\nu\rho\sigma} \, S^\mu p^\nu k^\rho k'^\sigma \, C_T. \qquad (1)$$

Here, e_l is the charge of the incident lepton, M is the nucleon mass, $-Q^2$ is the squared four-momentum transfer, p, k and k' are the four-momenta 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.

As σ_{UT} is proportional to the electromagnetic coupling constant α_{em}, it is expected to be small. Furthermore, due to the factor M/Q in Eq. (1), σ_{UT} is expected to increase with decreasing Q^2. A calculation based on certain model assumptions [23] for a JLAB experiment [24] yields expectations for the asymmetry of order 10^{-4} at the kinematics of that experiment. The authors in Ref. [7], on the other hand, do not exclude asymmetries as large as 10^{-2} and point out that the term C_T in Eq. (1) cannot be completely evaluated at present. Due to the factor e_l in Eq. (1), the asymmetry is expected to have a different sign for opposite beam charges. The capability of the HERA accelerator to supply both electron and positron beams thus provides an additional means to isolate a possible effect from two-photon exchange.

In this paper a first precise measurement of the transverse-target SSA in inclusive DIS of unpolarized electrons and positrons off a transversely polarized hydrogen target is presented.

The data were collected with the HERMES spectrometer [25] during the period 2002-2005. The 27.6 GeV

positron or electron beam was scattered off the transversely polarized gaseous hydrogen target internal to the HERA storage ring at DESY. The open-ended target cell was fed by an atomic-beam source [26] based on Stern-Gerlach separation combined with radio-frequency transitions of hydrogen hyperfine states. The direction of the target spin vector was reversed at 1-3 minute time intervals to minimize systematic effects, while both the nuclear polarization and the atomic fraction of the target gas inside the storage cell were continuously measured [27]. Data were collected with the target polarized transversely to the beam direction, in both "upward" and "downward" directions in the laboratory frame. 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 in this analysis. Leptons were distinguished from hadrons by using a transition-radiation detector, a scintillator pre-shower counter, a dual-radiator ring-imaging Cherenkov detector, and an electromagnetic calorimeter. In order to exclude any contamination from a transverse hadron SSA in the lepton signal, hadrons were suppressed by very stringent particle identification requirements such that their contamination in the lepton sample is smaller than 2×10^{-4}. This resulted in a lepton identification efficiency greater than 94%. Events were selected in the kinematic region $0.007 < x_B < 0.9, 0.1 < y < 0.85$, $0.25\ \mathrm{GeV}^2 < Q^2 < 20\ \mathrm{GeV}^2$, and $W^2 > 4\ \mathrm{GeV}^2$. Here, x_B is the Bjorken scaling variable, y is the fractional beam energy carried by the virtual photon in the laboratory frame, and W is the invariant mass of the photon-nucleon system.

The differential yield for a given target spin direction ($\uparrow$ upwards or $\downarrow$ downwards) can be expressed as

$$\begin{aligned}\frac{\mathrm{d}^3N^{\uparrow(\downarrow)}}{\mathrm{d}x_B\ \mathrm{d}Q^2\ \mathrm{d}\phi_S} &= \\ &\left[L^{\uparrow(\downarrow)}\ \mathrm{d}^3\sigma_{UU} + (-)L_P^{\uparrow(\downarrow)}\ \mathrm{d}^3\sigma_{UT}\right]\ \Omega(x_B, Q^2, \phi_S) \\ &= \mathrm{d}^3\sigma_{UU}\left[L^{\uparrow(\downarrow)} + (-)\right. \\ &\left. L_P^{\uparrow(\downarrow)}\ A_{UT}^{\sin\phi_S}(x_B, Q^2)\sin\phi_S\right]\ \Omega(x_B, Q^2, \phi_S). \qquad (2)\end{aligned}$$

Here, ϕ_S is the azimuthal angle about the beam direction between the lepton scattering plane and the "upwards" target spin direction, σ_{UU} is the unpolarized cross section. Also, $L^{\uparrow(\downarrow)}$ is the total luminosity in the $\uparrow$ ($\downarrow$) polarization state, $L_P^{\uparrow(\downarrow)} = \int L^{\uparrow(\downarrow)}(t)\ P(t)\ \mathrm{d}t$ is the integrated luminosity weighted by the magnitude P of the target polarization, and Ω is the detector acceptance efficiency. 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; $A_{UT}^{\sin\phi_S}$ refers to its amplitude.

year	beam	$\langle P^{\uparrow}\rangle$	$\langle P^{\downarrow}\rangle$	Events
2002	e^+	0.783±0.041	0.783±0.041	0.9 M
2004	e^+	0.745±0.054	0.742±0.054	2.0 M
2005	e^-	0.705±0.065	0.705±0.065	4.8 M

TABLE I: Average target polarizations and total number of inclusive events for the three data sets used in this analysis.

The asymmetry was calculated as

$$A_{UT}(x_B, Q^2, \phi_S) = \frac{\dfrac{N^{\uparrow}}{L_P^{\uparrow}} - \dfrac{N^{\downarrow}}{L_P^{\downarrow}}}{\dfrac{N^{\uparrow}}{L^{\uparrow}} + \dfrac{N^{\downarrow}}{L^{\downarrow}}}\ , \qquad (3)$$

where $N^{\uparrow(\downarrow)}$ are the number of events measured in bins of x_B, Q^2, and ϕ_S. With the use of Eq. (2), it can be approximated, for small differences of the two average target polarizations $\langle P^{\uparrow(\downarrow)}\rangle = L_P^{\uparrow(\downarrow)}/L^{\uparrow(\downarrow)}$, as

$$A_{UT}(x_B, Q^2, \phi_S) \simeq A_{UT}^{\sin\phi_S}\sin\phi_S + \frac{1}{2}\frac{\langle P^{\downarrow}\rangle - \langle P^{\uparrow}\rangle}{\langle P^{\uparrow}\rangle\langle P^{\downarrow}\rangle}. \quad (4)$$

As shown in Table I, $\langle P^{\uparrow}\rangle$ and $\langle P^{\downarrow}\rangle$ are the same to a good approximation for all data-taking periods.

The advantage of using the fully-differential asymmetry $A_{UT}(x_B, Q^2, \phi_S)$ in Eq. (3) instead of the more common left-right asymmetry $A_N(x_B, Q^2)$ is that the acceptance function Ω cancels in each (x_B, Q^2, ϕ_S) kinematic bin, if the bin size or the asymmetry is small. Assuming the ϕ_S dependence of σ_{UT} in Eq. (1) and Eq. (2), it can be easily shown that the $\sin\phi_S$ amplitude $A_{UT}^{\sin\phi_S}$ and the left-right normal asymmetry A_N are related by

$$\begin{aligned}A_N &= \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \\ &\frac{\int_0^{\pi} d\phi_S\ \mathrm{d}^3\sigma_{UU}\ A_{UT}^{\sin\phi_S}\ \sin\phi_S}{\int_0^{\pi} d\phi_S\ \mathrm{d}^3\sigma_{UU}} = \frac{2}{\pi}\ A_{UT}^{\sin\phi_S}, \qquad (5)\end{aligned}$$

where σ_L (σ_R) refers to the integrated cross section within the angular range $0 \le \phi_S < \pi$ ($\pi \le \phi_S < 2\pi$).

For this analysis the Q^2 range was divided into a "DIS region" with $Q^2 > 1\ \mathrm{GeV}^2$ and a "low-Q^2 region" with $Q^2 < 1\ \mathrm{GeV}^2$. To test for a possible enhancement of the transverse-target SSA due to the factor M/Q appearing in Eq. (1) the data at low Q^2 are also presented, though, strictly speaking, Eq. (1) may not be applicable to this range.

The $A_{UT}^{\sin\phi_S}$ amplitudes were extracted with a binned χ^2 fit of the functional form $p_1\sin\phi_S + p_2$ to the measured asymmetry. Leaving p_2 as a free parameter or fixing it to the values given by Eq. (4) and Table I had no impact on the extracted $\sin\phi_S$ amplitude $p_1 \equiv A_{UT}^{\sin\phi_S}$.

The final results for the measured $\sin\phi_S$ amplitudes $A_{UT}^{\sin\phi_S}$ are shown in Fig. 1 as a function of x_B separately

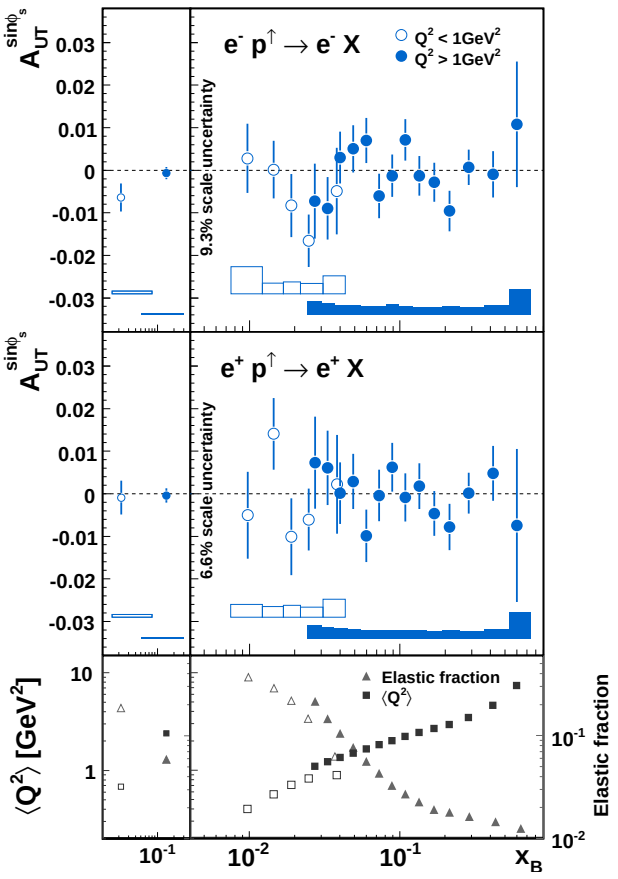

FIG. 1: The x_B dependence of the $\sin\phi_S$ amplitudes $A_{UT}^{\sin\phi_S}$ measured with an electron beam (top) and a positron beam (center). The open (closed) circles identify the data with $Q^2 < 1$ GeV^2 ($Q^2 > 1$ GeV^2). The error bars show the statistical uncertainties, while the error boxes show the systematic uncertainties. The asymmetries integrated over x_B are shown on the left. Bottom panel: average Q^2 vs. x_B from data (squares), and the fraction of elastic background events to the total event sample from a Monte Carlo simulation (triangles).

for electrons and positrons. In both cases the asymmetries are consistent with zero within their uncertainties. Due to the kinematics of the experiment, the quantities x_B and $\langle Q^2 \rangle$ are strongly correlated, as shown in the bottom panel of Fig. 1.

The resulting amplitudes were not corrected for kinematic migration of inelastic events due to detector smearing and higher order QED effects or contamination by the radiative tail from elastic scattering. The latter correction requires knowledge of the presently unknown elastic two-photon asymmetry. Instead, the contribution of the elastic radiative tail to the total event sample was estimated from a Monte Carlo simulation based on the LEPTO generator [28] together with the RADGEN [29] determination of QED radiative effects and with a GEANT [30] based simulation of the detector. The elastic fraction is shown in the lower panel of Fig. 1. It reaches values as high as about 35% in the lowest x_B bin, where y is large ($\langle y \rangle \simeq 0.80$) and hence radiative corrections are largest [31]. The elastic fraction rapidly decreases towards high x_B, becoming less than 3% for $x_B > 0.1$.

The systematic uncertainties, shown in the fourth column of Table II and as error boxes in Fig. 1, 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 azimuthal asymmetry was implemented. Input asymmetries being zero or as small as 10^{-3} were well reproduced within the statistical uncertainty of the Monte Carlo sample, which was about five times smaller than the statistical uncertainty of the data. 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. Systematic uncertainties from other sources like particle identification or trigger efficiencies were found to be negligible.

The transverse single-spin asymmetry amplitudes $A_{UT}^{\sin\phi_S}$ for electron and positron beams integrated over x_B are given separately for the "low-Q^2 region" and the "DIS region" in Table II along with their statistical and systematic uncertainties. All asymmetry amplitudes are consistent with zero within their uncertainties, which in the DIS region are of order 10^{-3}. The only exception is the low-Q^2 electron sample, where the asymmetry is 1.9 standard deviations different from zero. No hint of a sign change between electron and positron asymmetries is observed within uncertainties.

In conclusion, single-spin asymmetries were measured in inclusive deep-inelastic scattering at HERMES with unpolarized electron and positron beams and a transversely polarized hydrogen target with the goal of searching for a signal of two-photon exchange. No signal was found within the uncertainties, which are of order 10^{-3}.

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beam	$A_{UT}^{\sin\phi_S}$ $\times 10^{-3}$	$\delta A_{UT}^{\sin\phi_S}$(stat.) $\times 10^{-3}$	$\delta A_{UT}^{\sin\phi_S}$(syst.) $\times 10^{-3}$	$\langle x_B \rangle$	$\langle Q^2 \rangle$ [GeV^2]
e^+	-0.61	3.97	0.63	0.02	0.68
e^-	-6.55	3.40	0.63		
e^+	-0.60	1.70	0.29	0.14	2.40
e^-	-0.85	1.50	0.29		

TABLE II: 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). The systematic uncertainties contain the effects of detector misalignment and beam position and slope at the target, as estimated by a Monte Carlo simulation, but not the scale uncertainties from the target polarization which amounts to 9.3% (6.6%) for the electron (positron) sample. Also, the results are not corrected for smearing, radiative effects and elastic background events.

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