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Observation of a Single-Spin Azimuthal Asymmetry in Semi-Inclusive Pion Electro-Production

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Single-spin asymmetries for semi-inclusive pion production in deep-inelastic scattering have been measured for the first time. A significant target-spin asymmetry of the distribution in the azimuthal angle ϕ of the pion relative to the lepton scattering plane was observed for π^+ electro-production on a longitudinally polarized hydrogen target. The corresponding analyzing power in the $\sin\phi$ moment of the cross section is $0.022 \pm 0.005 \pm 0.003$. This result can be interpreted as the effect of terms in the cross section involving chiral-odd spin distribution functions in combination with a time-reversal-odd fragmentation function that is sensitive to the transverse polarization of the fragmenting quark.

13.87.Fh; 14.20.Dh; 14.65.Bt; 24.85.+p

Polarized deep-inelastic lepton scattering has been the primary experimental basis for our present understanding of the spin structure of the nucleon. Inclusive and semi-inclusive measurements with both beam and target polarized have been used to provide precise information on quark helicity-distribution functions. These quantities represent the distribution of quark spin in a longitudinally polarized nucleon, in a suitably Lorentz-boosted kinematic frame. Additional spin-distribution functions have been identified, but remain unmeasured. One of these is called transversity and corresponds to the distribution of transverse quark spin in a nucleon polarized transverse to its (infinite) momentum [1]. This and related distribution functions are predicted to be measurable via single-spin asymmetries, where only the beam *or* target are polarized, in certain lepton and hadron scattering experiments [2–6].

In simple models based on hadrons consisting of non-interacting collinear partons (quarks and gluons), single-spin asymmetries are expected to vanish. This follows from the conservation of parity, total angular momentum and helicity of the individual partons. Correspondingly, in the language of perturbative QCD, single-spin asymmetries vanish at the "twist-2" level, i.e. when multi-parton correlations and parton transverse momenta internal to hadrons are ignored. However, single-spin asymmetries have been observed in a few hadron-hadron scattering experiments [7]. In these measurements, a scattered hadron was detected with a momentum transverse to the beam direction in the range $P_\perp \simeq$ 1-2 GeV, which is not much larger than either the scale parameter of QCD ($\Lambda_{QCD} \sim 0.2$ GeV) or typical parton transverse momenta of a few hundred MeV. Therefore these asymmetries may arise from non-collinear parton configurations or from multi-parton correlations ("higher twist" effects), which are suppressed at large $P_\perp$ where perturbative QCD becomes effective.

Transversity and related spin-distribution functions are as yet unmeasured because their unusual chiral-odd structure implies that they are not directly observable in inclusive lepton-nucleon scattering experiments [1]. However, it has been suggested that the needed sensitivity can be provided by semi-inclusive production of pions with modest $P_\perp$ [2]. An observable single-spin dependence is predicted to appear in the dependence of the cross section on the angle between the spin axis of a *transversely* polarized target and the plane defined by the virtual photon momentum and the momentum of the pion (known as the Collins angle). Here the pion is produced from the struck quark in soft processes described by a fragmentation function having a chiral-odd structure like that of the spin-distribution functions of interest. This Collins fragmentation function describes how the probability for producing a pion depends on its direction with respect to the direction of transverse polarization of the struck quark. It has also a time-reversal odd structure resulting from the final-state interactions in the fragmentation process, rather than from any fundamental violation of time-reversal invariance [8]. Such T-odd fragmentation (and distribution) functions can thus be considered as effective parameterizations of specific complex processes. There is preliminary evidence from $Z^0 \to$ 2-jet decay [9] that the Collins fragmentation function has a substantial magnitude – of order 10% of the well-known chiral-even spin-independent one. If this can be confirmed, it could provide experimental sensitivity to the transverse polarization of scattered quarks in future experiments designed to make the first measurements of transversity.

In the case of semi-inclusive pion production in lepton scattering from a *longitudinally* polarized nucleon, chiral-odd quark spin-distribution functions closely related to transversity can be manifest. In such exper-

iments, the Collins angle becomes the azimuthal angle ϕ of the pion around the virtual photon direction, with respect to the lepton scattering plane. Recent theoretical studies [3,4] have shown how each chiral-odd spin-distribution function coupled with the Collins fragmentation function gives rise to a specific single-spin dependent moment of the pion yield distribution in ϕ.

The kinematics of the process are illustrated in Fig. 1. The relevant variables are the 4-momentum transfer squared $-Q^2 = q^2 = (k - k')^2$, the energy transfer $\nu = E - E'$, the virtual photon fractional energy $y = \nu/E$, the invariant mass of the photon-proton system $W = \sqrt{2M\nu + M^2 - Q^2}$, the Bjorken variable $x = Q^2/2M\nu$, and the pion fractional energy $z = E_\pi/\nu$. Here k and k' are the 4-momenta and E and E' the laboratory energies of the incoming and outgoing leptons, respectively. E_π is the pion laboratory energy and M the proton mass. The transverse momentum ($P_\perp$) of the pion is defined with respect to the virtual photon direction in the initial photon-proton center-of-mass frame.

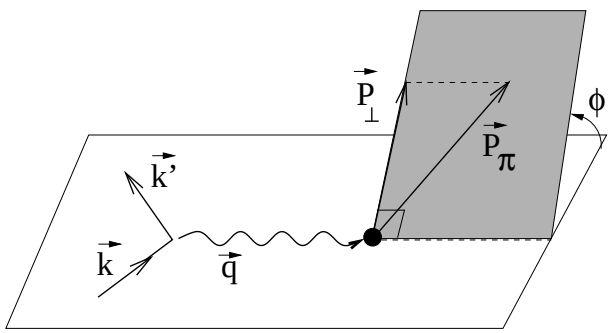

FIG. 1. Kinematic planes for pion production in semi-inclusive deep-inelastic scattering.

This Letter reports the first observation of a single-spin azimuthal asymmetry for semi-inclusive pion production in deep-inelastic scattering. The data were recorded during the 1996 and 1997 running periods of the HERMES experiment using both unpolarized and longitudinally nuclear-polarized hydrogen internal gas targets [10] in the 27.6 GeV HERA polarized positron storage ring at DESY. Longitudinal beam polarization is obtained by using spin rotators [11] located upstream and downstream of the HERMES experiment. The scattered positrons and associated pions are detected by the HERMES spectrometer [12] in the polar angle range 0.04 rad $< \theta <$ 0.22 rad. Positron and hadron identification is based on information from four detectors: a threshold gas Čerenkov counter, a transition-radiation detector, a preshower scintillator detector and a lead-glass electromagnetic calorimeter. The particle identification provides an average positron identification efficiency of 99% with a hadron contamination that is less than 1%.

The kinematic requirements on the scattered positron used in this analysis are $1\,\mathrm{GeV}^2 < Q^2 < 15\,\mathrm{GeV}^2$, $W > 2$ GeV, $0.023 < x < 0.4$ and $y < 0.85$. Pions were identified in the energy range 4.5 GeV $< E_\pi <$ 13.5 GeV. Acceptance effects were minimized and exclusive production was suppressed by imposing the requirement $0.2 < z < 0.7$. The limit $P_\perp > 50$ MeV was applied to the pions to allow an accurate measurement of the angle ϕ.

Measurements were performed with all combinations of beam and target helicities, giving the possibility of measuring single- and double-spin terms in the cross section. The average hydrogen target polarization in the 1996 and 1997 HERMES running periods was 0.86 with a fractional uncertainty of 5%. The average beam polarization for the analyzed data was 0.55 with a fractional uncertainty of 3.4%.

The various contributions to the ϕ dependent spin asymmetry are isolated by extracting moments of the cross section weighted by corresponding ϕ dependent functions. The analyzing powers for beam (target) longitudinal polarization are evaluated as

$$A^W_{LU(UL)} = \frac{\frac{L^\uparrow}{L^\uparrow_P}\sum_{i=1}^{N^\uparrow} W(\phi_i^\uparrow) \;-\; \frac{L^\downarrow}{L^\downarrow_P}\sum_{i=1}^{N^\downarrow} W(\phi_i^\downarrow)}{\frac{1}{2}[N^\uparrow \;+\; N^\downarrow]}, \quad (1)$$

where the $\uparrow$ / $\downarrow$ denotes positive/negative helicity of the beam (target). $N^{\uparrow/\downarrow}$ is the number of selected events involving a detected pion for each beam (target) spin state corresponding to the dead-time corrected luminosities $L^{\uparrow/\downarrow}$ and $L_P^{\uparrow/\downarrow}$, the latter being averaged with the magnitude of the beam (target) polarization. All of these quantities are effectively averaged over the two target (beam) helicity states to arrive at single-spin asymmetries. The weighting functions $W(\phi) = \sin\phi$ and $W(\phi) = \sin 2\phi$ are expected to provide sensitivity to the Collins fragmentation function discussed above, in combination with different spin distribution functions [3,4]. Analyzing powers were extracted by integrating over the spectrometer acceptance in the kinematic variables y and z. Corrections were applied for the effects of the spectrometer acceptance, based on a Monte Carlo simulation.

The values of $A_{UL}^{\sin\phi}$, $A_{UL}^{\sin 2\phi}$ and $A_{LU}^{\sin\phi}$ extracted from the data according to Eq. (1) and averaged over x and $P_\perp$ are given in Table I. For both π^+ and π^- the beam-related analyzing powers $A_{LU}^{\sin\phi}$ are consistent with zero. This is in agreement with the small contributions to $A_{LU}^{\sin\phi}$ predicted to arise from higher-twist and $O(\alpha_S^2)$ QCD effects [13,14]. The target-related term $A_{UL}^{\sin 2\phi}$ is also consistent with zero within errors, both for π^+ and π^-.

The other target-related analyzing power $A_{UL}^{\sin\phi}$ is consistent with zero for π^-, while it is significantly different from zero for π^+. The appearance of such an asymmetry suggests the influence of the Collins T-odd fragmentation function, in combination with one or more chiral-odd spin-distribution functions. The large difference between the π^+ and π^- asymmetries can be understood (in the QPM) only if there is a large difference between favored and disfavored chiral-odd fragmentation functions – *i.e.*

if there is a strong enhancement when the struck quark flavor is present in the hadron.

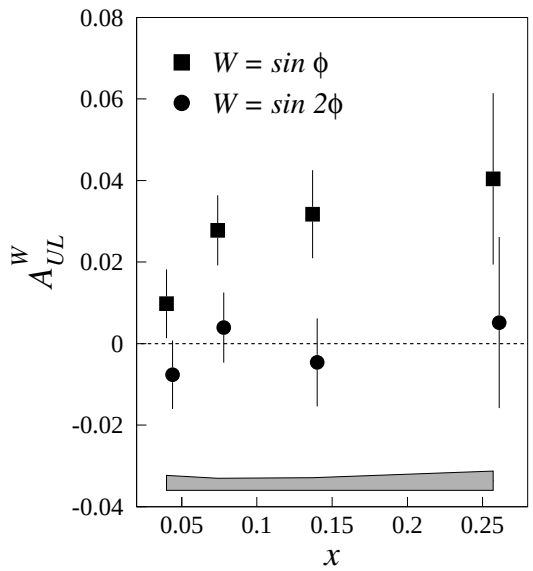

FIG. 2. Target-spin analyzing powers for π^+: $A_{UL}^{\sin\phi}$ (squares) and $A_{UL}^{\sin 2\phi}$ (circles) as a function of Bjorken x. Error bars show the statistical uncertainty and the band represents the systematic uncertainties for $A_{UL}^{\sin\phi}$. As shown in Table II, $\langle Q^2 \rangle$ varies with x.

In Table II the $A_{UL}^{\sin\phi}$ and $A_{UL}^{\sin 2\phi}$ analyzing powers are given for π^+ and π^- at the measured $\langle x \rangle$ and $\langle Q^2 \rangle$ values. In addition, in Fig. 2, the $A_{UL}^{\sin\phi}$ and $A_{UL}^{\sin 2\phi}$ values obtained for π^+ are shown as a function of x, after averaging over $P_\perp$. At higher energies, the analyzing power for the $\sin\phi$ moment that is sub-leading order in $1/Q$ is expected to be suppressed by the factor of $P_\perp/Q$ [3,4] with respect to the leading-order $\sin 2\phi$ moment. In the HERMES kinematics, which covers a range of relatively low Q^2 and moderate $P_\perp$, the ratio of $A_{UL}^{\sin 2\phi}$ to $A_{UL}^{\sin\phi}$ analyzing powers is predicted to be small in the valence region [15]. This is in agreement with a simple estimate of that ratio in the real photon limit [16]. The present data are consistent with these theoretical expectations, neglecting the contribution to the $\sin\phi$ moment from transversity itself arising from the small component of the target spin transverse to the virtual photon direction. Also, the apparent increase of $A_{UL}^{\sin\phi}$ with increasing x suggests that the sea contribution does not dominate the effect, in agreement with existing interpretations of single-spin asymmetries as being associated with valence quark contributions [17,18].

In Fig. 3, $A_{UL}^{\sin\phi}$ averaged over x is plotted for π^+ and π^- as a function of transverse momentum. The mean $\langle Q \rangle$ is about 1.55 GeV for all bins. There is an indication that $A_{UL}^{\sin\phi}$ for π^+ increases as $P_\perp$ increases up to ∼0.8 GeV. This behavior can be related to the dominant role of the intrinsic quark transverse momentum when $P_\perp$ remains below a typical hadronic mass (∼ 1 GeV). On this basis, the use of Gaussian transverse momentum parameterizations for distribution and fragmentation functions results in a behavior of $A_{UL}^{\sin\phi}$ that is proportional to $P_\perp$, at least for the moderate range of $P_\perp$ [3,4,19].

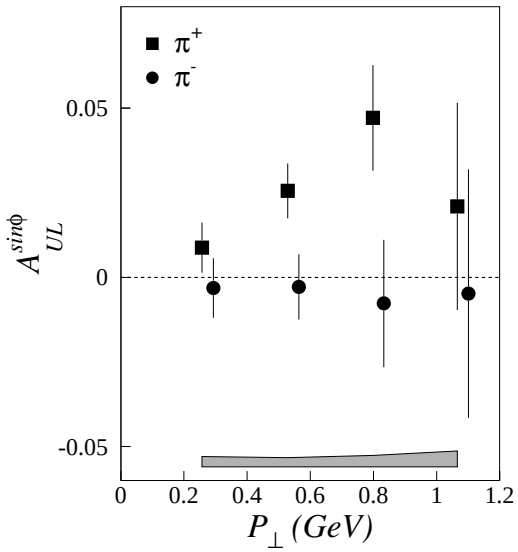

FIG. 3. Target-spin analyzing powers in the $\sin\phi$ moment as a function of transverse momentum, for π^+ (squares) and π^- (circles). Error bars show the statistical uncertainties and the band represents the systematic uncertainties.

The main contributions to the systematic uncertainties are those from the target and beam polarizations, from smearing due to detector resolution and from a false spin asymmetry induced by the spectrometer acceptance. Uncertainties in the acceptance corrections based on Monte Carlo calculations dominate the systematic uncertainties at small x and decrease with increasing x. At the average values of y of about 0.5, radiative effects are expected to be small and independent of the pion charge; these effects on the unpolarized cross section were evaluated and were indeed found to be negligible [20].

In summary, single-spin azimuthal asymmetries of pions produced in deep-inelastic scattering of polarized positrons from a longitudinally polarized hydrogen target have been measured. The analyzing power involving the $\sin\phi$ moment of the cross section is found to be significant for π^+-production with unpolarized (spin-averaged) positrons on a longitudinally polarized hydrogen target, while for π^- it is found to be consistent with zero. In addition, the analyzing powers involving the $\sin 2\phi$ moments of both π^+ and π^- are consistent with zero. The $\sin\phi$ target-related analyzing power for π^+, averaged over the full acceptance, is found to be $0.022 \pm 0.005 \pm 0.003$, and there are indications that this analyzing power increases with increasing x, and also with $P_\perp$ up to ∼0.8 GeV. The appearance of this single-spin asymmetry can be interpreted as an effect

of chiral-odd spin distribution functions coupled with a time-reversal-odd fragmentation function. This fragmentation function offers a means to measure transversity in future experiments using a *transversely* polarized target.

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	π^+	π^-
$A_{UL}^{\sin\phi}$	0.022±0.005±0.003	-0.002±0.006±0.004
$A_{UL}^{\sin 2\phi}$	-0.002±0.005±0.010	-0.005±0.006±0.005
$A_{LU}^{\sin\phi}$	-0.005±0.008±0.004	-0.007±0.010±0.004

TABLE I. Target- and beam-related analyzing powers, averaged over x and $P_\perp$, for the azimuthal $\sin\phi$ and $\sin 2\phi$ moments of the pion production cross section in deep-inelastic scattering.

	$\langle Q^2\rangle$	π^+		π^-	
$\langle x\rangle$	(GeV^2)	$A_{UL}^{\sin\phi}$	$A_{UL}^{\sin 2\phi}$	$A_{UL}^{\sin\phi}$	$A_{UL}^{\sin 2\phi}$
0.040	1.4	0.010±0.008±0.004	-0.008±0.008±0.011	-0.004±0.010±0.004	0.002±0.010±0.008
0.074	2.2	0.028±0.009±0.003	0.007±0.009±0.012	-0.004±0.010±0.003	-0.008±0.010±0.010
0.137	3.7	0.032±0.011±0.003	-0.005±0.011±0.009	0.012±0.013±0.003	-0.007±0.013±0.007
0.257	6.4	0.041±0.021±0.005	0.005±0.021±0.009	-0.025±0.028±0.005	-0.028±0.028±0.008

TABLE II. Target-related analyzing powers averaged over $P_\perp$, for the azimuthal $\sin\phi$ and $\sin 2\phi$ moment of the π^+ and π^- production cross section in deep-inelastic scattering as a function of x.