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Semi-inclusive pion production in polarized deep-inelastic scattering is a powerful tool for investigating the spin structure of the nucleon and providing information about the spin-dependent parton distribution and fragmentation functions. The recent observation of a significant azimuthal asymmetry for semi-inclusive \( \pi^+ \) production in deep-inelastic scattering (DIS) of unpolarized protons off longitudinally polarized protons [1] has revealed effects of quark distribution and fragmentation functions that describe the transverse polarization of quarks. In particular, the occurrence of single-spin asymmetries, where only the target is polarized, offers access to the fundamental but still unmeasured chiral-odd transversity distribution functions [2,3] through the so-called Collins effect [4–7]. This effect involves a chiral-odd fragmentation function, the Collins function, that describes the fragmentation of a transversely polarized quark into an unpolarized hadron and is discussed in recent experimental [1,8] and theoretical publications [9–19] on this subject.

Single-spin asymmetries in pion production have already been measured in proton-proton scattering experiments [20], where the \( \pi^0 \) asymmetry is found to be similar to the \( \pi^+ \) one, but with opposite sign as compared with the \( \pi^- \) one. This isospin dependence could be understood [21] in terms of the difference between the unpolarized cross sections for \( \pi^+ \) and \( \pi^- \) production. However, these asymmetries from proton-proton scattering may also arise from initial-state interactions, which are negligible for semi-inclusive lepton-nucleon scattering processes. In the latter case any single-spin asymmetry can originate only from a spin dependence in the fragmentation of a polarized quark. In fact such a dependence is assumed in [15,16,22] where a sizable \( \pi^0 \) single-spin asymmetry is predicted for lepton-nucleon scattering.

This paper reports the first observation of a single-spin azimuthal asymmetry in semi-inclusive neutral pion electroproduction. The relevant kinematic variables of this process in the target rest frame are the spacelike squared four-momentum \( Q^2 \) of the exchanged virtual photon with energy \( \nu \), the pion fractional energy \( z = E_\pi/\nu \), the pion transverse momentum \( P_\perp \), and the azimuthal angle \( \phi \) of the pion around the virtual-photon axis. Here \( E_\pi \) is the pion energy, \( P_\perp \) is defined with respect to the virtual-photon direction and \( \phi \) is defined relative to the lepton scattering plane. The fractional energy transferred to the proton is given by \( y = \nu/E \) and the Bjorken scaling variable is defined as \( x = Q^2/(2M\nu) \), where \( E \) is the lepton beam energy and \( M \) is the proton mass.

The data were collected in 1996 and 1997 using a longitudinally polarized hydrogen gas target in the 27.57 GeV HERA positron storage ring at DESY. The average target polarization was 0.86 with a fractional uncertainty of 5%. The scattered positron and the decay photons from the \( \pi^0 \) were detected by the HERMES spectrometer [23]. Positrons were distinguished from hadrons with an average efficiency of 99% at a hadron contamination of less than 1% using the information from an electromagnetic calorimeter, a transition radiation detector, a preshower scintillator detector, and a threshold Cherenkov detector. The kinematic requirements imposed on the scattered positrons were \( Q^2 > 1 \) (GeV/c)\(^2 \), 0.023<\( x < 0.4 \), 0.2<\( y < 0.85 \), and an invariant mass squared of the initial photon-nucleon system \( W^2 > 4 \) (GeV/c)\(^2 \).

Neutral pion identification was provided by the detection of the two photon clusters originating from the \( \pi^0 \) decay in the electromagnetic calorimeter [24], each with a minimum energy deposition of 1.0 GeV and without a corresponding charged track. The reconstructed photon-pair invariant mass \( m_{\gamma\gamma} \) shows a clear \( \pi^0 \) mass peak with a mass resolution of about 0.012 GeV/c\(^2 \). Neutral pions were selected within the invariant mass range of 0.10<\( m_{\gamma\gamma} < 0.17 \) GeV/c\(^2 \) where background contributions from uncorrelated photons typically amount to 20%. An upper limit of \( z < 0.7 \) was used in order to minimize acceptance effects and to suppress possible contributions of exclusive processes. The requirement \( P_\perp > 0.05 \) GeV/c ensures an accurate measurement of the azimuthal angle \( \phi \).

The analyzing powers for unpolarized (U) beam and longitudinally (L) polarized target are evaluated as

\[
A_{UL}^W = \frac{\sum_{i=1}^{N^-} W(\phi_i^-) - \sum_{i=1}^{N^+} W(\phi_i^+)}{\frac{1}{2} [N^- + N^+]},
\]

using the weighting functions \( W(\phi) = \sin \phi \) and \( W(\phi) = \sin 2\phi \). Here, the superscripts → and ← denote opposite target helicity states. Each summation runs over the number \( N^\mp \) of pions selected for each target helicity state and is multiplied with the dead-time corrected luminosities \( L_{\mp}^- \) and \( L_{\pm}^+ \), the latter being weighted by the target polarization magnitude. The analyzing powers were determined by integrating over the spectrometer acceptance in the kinematic
The analyzing power in the azimuthal $\sin \phi$ moment of the $\pi^0$ production cross section, averaged over $z$, $x$, and $P_{\perp}$, with mean values of $0.48$, $0.09$, and $0.44$ GeV/c, respectively, is $0.19 \pm 0.007$ (stat) $\pm 0.003$ (syst). This result is consistent with the $\pi^+$ measurements for which an analyzing power of $0.022 \pm 0.005$ (stat) $\pm 0.003$ (syst) was reported [1]. The observed azimuthal asymmetry implies a substantial magnitude for the Collins fragmentation function $H_1^T$. The analyzing power in the $\sin 2\phi$ moment for the same process, calculated using Eq. (1), is consistent with zero within the statistical uncertainty: $0.006 \pm 0.007$ (stat) $\pm 0.003$ (syst). This is expected from predictions for the ratio of $A_{UL}^{\sin 2\phi}$ to $A_{UL}^{\sin \phi}$ [11], which are small in the valence region for the specific kinematic range of relatively low $Q^2$ and moderate $P_{\perp}$ accessible at HERMES.

In Fig. 1 the analyzing power $A_{UL}^{\sin \phi}$ is shown as a function of the pion fractional energy $z$, the Bjorken scaling variable $x$, and the pion transverse momentum $P_{\perp}$, after averaging over the other two kinematic variables. Also shown are results for charged pions [1] obtained in the same kinematic range. The $\pi^0$ and $\pi^+$ asymmetries exhibit a similar behavior in all kinematic variables. The $z$ dependence of the $\pi^0$ asymmetry is consistent with the monotonic increase of the $\pi^+$ asymmetry. The increase of $A_{UL}^{\sin \phi}$ with increasing $x$ suggests that single-spin asymmetries are associated with valence quark contributions. The dependence on $P_{\perp}$ can be related to the dominant kinematic role of the intrinsic transverse momentum of the quark, if $P_{\perp}$ remains below the typical hadronic mass of about 1 GeV/c$^2$ [1]. Also shown in Fig. 1 are the predictions of a model calculation [10,17] for the $\pi^0$ single-spin azimuthal asymmetry using isospin and charge conjugation invariance [15]. In the case of longitudinally polarized nucleons, two distribution functions enter the calculation. One, $h_{1L}^\perp$, is twist-2 and describes the quark transverse spin distribution in a longitudinally polarized nucleon, while $h_{1L}$ includes an interaction dependent twist-3 part. Both are related to the twist-2 distribution function $h_1$, called transversity, that describes the quark transverse spin distribution in a transversely polarized nucleon, by $h_1(x) = h_1(x) - (d/dx)h_{1L}^\perp(x)$ [6], where $h_{1L}^\perp$ is the $k_T$ moment of $h_{1L}^\perp$ over the intrinsic quark transverse momentum $k_T$.

Assuming a vanishing $h_{1L}^\perp$ [17], the number of unknown distribution functions can be reduced to one: $h_{1L} = h_1$. The range of predictions, shown in Fig. 1, is obtained by varying $h_1$ between the two assumptions $h_1 = g_1$ (non-relativistic limit) and $h_1 = (f_1 + g_1)/2$ (Soffer inequality), with the usual polarized and unpolarized distribution functions $g_1$ and $f_1$, respectively. In both cases a simple parameterization for the spin-dependent time-reversal-odd fragmentation function $H_1^T$ was adopted; see Eq. (14) in [17]. The predictions are consistent with the measured $\pi^0$ azimuthal asymmetries and describe the dependences on the kinematic variables. These new $\pi^0$ data provide additional information also for other phenomenological approaches [12–14,19].

In summary, a single-spin azimuthal asymmetry for $\pi^0$ production has been measured in semi-inclusive deep-inelastic lepton scattering off a longitudinally polarized pro-
ton target. The dependence of this asymmetry on the kinematic variables \(x\), \(z\), and \(P_\perp\) has been investigated. The results are similar to the previously measured azimuthal asymmetry for \(\pi^+\) electroproduction, while the \(\pi^-\) asymmetry was consistent with zero. This finding can be well described by a model calculation where the asymmetry is interpreted as the effect of the convolution of a chiral-odd distribution function and a time-odd fragmentation function. The observed single-spin azimuthal asymmetries for neutral and charged pion electroproduction are consistent with the described by a model calculation where the asymmetry is interpreted as the effect of the convolution of a chiral-odd distribution function and a time-odd fragmentation function. These results provide evidence in support of the existence of non-zero chiral-odd structures that describe the transverse polarization of quarks. New data are expected from future HERMES measurements on a transversely polarized target, which will give direct access to the transversity [26].

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