MEASUREMENT OF LONGITUDINAL SPIN TRANSFER TO THE Λ-HYPERON AT HERMES

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The spin transfer to the Λ-hyperon from a longitudinally polarized positron beam has been measured at the HERMES experiment in the semi-inclusive reaction $\vec{e} + p(d) \rightarrow e' + \vec{\Lambda} + X$ in deep inelastic scattering regime with negative four-momentum transfer squared of the exchanged virtual photon $Q^2 > 1$ GeV^2. The data were accumulated in the years 1996-2000 using the 27.5 GeV polarized HERA positron beam and an unpolarized internal gas target in a storage cell. The longitudinal spin transfer coefficient $D^{\Lambda}_{LL'}$ is found to be $0.11 \pm 0.10(stat) \pm 0.03(syst)$ at the average fractional Λ energy $\langle z \rangle = 0.45$.

1. INTRODUCTION

Longitudinal spin transfer from a polarized positron to a Λ hyperon produced in the deep-inelastic scattering process is sensitive to two unknowns: the spin structure of the lightest hyperon, and the spin-dependent dynamics of the fragmentation process in deep-inelastic scattering. Given the non-trivial spin structure of the proton [1], it is of interest to consider the spin structure of other baryons.

In the naive Constituent Quark Model the spin of the Λ hyperon is entirely carried by the s quark: $\Delta q^{\Lambda}_s = 1$, while the ud pair is in a spinless (singlet) state, i.e., $\Delta q^{\Lambda}_u = \Delta q^{\Lambda}_d = 0$. Here $\Delta q^{\Lambda}_f \equiv q^{\Lambda+}_f - q^{\Lambda-}_f$, where $q^{\Lambda+}_f$ and $q^{\Lambda-}_f$ are the probabilities to find a quark with the spin parallel and anti-parallel to the the hyperon spin direction, respectively, and q^{Λ}_f ($f = u, d, s$) is the number density for quarks plus antiquarks of flavor f in the Λ hyperon, while the unpolarized number density is $q^{\Lambda}_f \equiv q^{\Lambda+}_f + q^{\Lambda-}_f$. Alternatively, one can use SU(3)-flavor symmetry in conjunction with the experimental results on the proton to estimate the first moments of the helicity-dependent quark distributions in the Λ hyperon. Using such assumptions Burkardt and Jaffe found $\Delta q^{\Lambda}_u = \Delta q^{\Lambda}_d = -0.23 \pm 0.06$ and $\Delta q^{\Lambda}_s = 0.58 \pm 0.07$ [2]. According to this estimate, the spins of the u and d quarks and antiquarks are directed predominantly opposite to the spin of the Λ hyperon resulting in a weak but non-zero net polarization. If such an SU(3)-flavor rotation (see Eq. 3 of Ref. [3], for example) is applied to the recent semi-inclusive data on the nucleon [4], the values $\Delta q^{\Lambda}_u = \Delta q^{\Lambda}_d = -0.09 \pm 0.06$ and $\Delta q^{\Lambda}_s = 0.47 \pm 0.07$ are obtained instead, favoring a much smaller polarization of the u and d quarks and antiquarks. A lattice-QCD calculation [3] also finds small light-quark polarizations, $\Delta q^{\Lambda}_u = \Delta q^{\Lambda}_d = -0.02 \pm 0.04$ and $\Delta q^{\Lambda}_s = 0.68 \pm 0.04$. Finally, other authors [5–7] have employed phenomenological models to explore the dependence of $\Delta q^{\Lambda}_f(x)$ on the Bjorken scaling variable x. These models predict a large positive polarization of the u and d quarks in the kinematic region $x > 0.3$.

Longitudinal spin transfer to Λ hyperons has previously been explored by the LEP experiments OPAL and ALEPH at an energy corresponding to the Z^0 pole [8,9]. In these experiments the Λ hyperons are predominantly produced via the decay $Z^0 \rightarrow s\bar{s}$, in which the primary strange quarks from the decay are strongly (and negatively) polarized at the level of −91%. The OPAL and ALEPH data show a Λ polarization of about −30% at $z > 0.3$.

The polarization of final-state Λ hyperons can be measured via the weak decay channel $\Lambda^0 \rightarrow p\pi^-$ through the angular distribution of the final-state particles:

$$\frac{dN}{d\Omega_p} \propto 1 + \alpha \vec{P}_\Lambda \cdot \hat{k}_p. \quad (1)$$

Here $\frac{dN}{d\Omega_p}$ is the angular distribution of the protons, $\alpha = 0.642 \pm 0.013$ is the asymmetry parameter of the parity-violating weak decay, $\vec{P}_\Lambda$ is the polarization of the Λ^0, and $\hat{k}_p$ is the unit vector along the proton momentum in the rest frame of the Λ^0. Because of the parity-violating nature of this decay, the proton is preferentially emitted along the spin direction of its parent, thus offering access to spin degrees of freedom in the deep-inelastic scattering final state.

The component of the polarization transferred along the direction L' from the virtual photon to the produced Λ is given by

$$P^\Lambda_{L'} = P_b D(y) D^\Lambda_{LL'}, \quad (2)$$

where P_b is the longitudinal polarization of the beam, $y = \nu/E$ is the fractional energy carried by the photon in the target rest frame, $\nu = E - E'$ is the energy transfer of the virtual photon to the nucleon, $E(E')$ is the energy of the positron before (after) the scattering process and $D(y) \simeq [1-(1-y)^2]/[1+(1-y)^2]$ is the depolarization factor taking into account the loss of polarization of the virtual photon as compared to that of the incident positron, L is the primary quantization axis, directed along the virtual photon momentum. The spin transfer coefficient $D^\Lambda_{LL'}$ in Eq. 2 describes the probability that the polarization of the struck quark is transferred to the Λ hyperon along a secondary quantization axis L'. In this analysis, the quantization axis L' is chosen along the virtual photon direction L.

2. THE HERMES EXPERIMENT AND DATA ANALYSIS

The Λ electroproduction data were accumulated by the HERMES experiment at DESY. In this experiment, the 27.6 GeV longitudinally-polarized positron beam [10] of the HERA e-p collider passes through an open-ended tubular storage cell into which polarized or unpolarized target atoms in undiluted gaseous form are continuously injected. The HERMES detector is described in detail in Ref. [11].

The data presented here were recorded using positron beams during two two-year periods: 1996-1997 and 1999-2000. A variety of unpolarized target gases were used in the analysis. Most of the data were collected from hydrogen and deuterium, but ^{3}He, ^{4}He, ^{14}N, ^{20}Ne and ^{84}Kr targets were also included, and the data from all targets were combined. An average beam polarization of about 55% was typical during data taking.

The scattered positrons and the Λ decay products were detected by the HERMES spectrometer in the polar-angle range from 40 to 220 mrad. A positron trigger was formed from a coincidence between three scintillator hodoscope planes and a lead-glass calorimeter. The trigger required a minimum energy deposit in the calorimeter of 3.5 GeV for the data employed in this analysis.

The Λ hyperons were identified in the analysis through their $p\pi^-$ decay channel. Events were selected by requiring the presence of at least three reconstructed tracks: a positron track and two hadron candidates of opposite charge. If more than one positive or negative hadron was found in one event, all possible combinations of positive and negative hadrons were used. The requirements $Q^2 > 0.8$ GeV^2 and $W > 2$ GeV, where $-Q^2$ is the four-momentum transfer squared of the exchanged virtual photon and W is the invariant mass of the photon-nucleon system, were imposed on the positron kinematics to ensure that the events originated from the deep-inelastic scattering domain. In addition, the requirement $y = 1 - E'/E < 0.85$ was imposed to exclude the large contribution of radiative corrections.

Two spatial vertices were reconstructed for each event by determining the intersection (i.e., point of closest approach) of pairs of reconstructed tracks. The primary (production) vertex was determined from the intersection of the beamline and the scattered beam lepton, while the secondary (decay) vertex was determined from the intersection of the proton and pion tracks. In both cases, the distance of closest approach was required to be less than 1.5 cm. For tracks fulfilling these requirements the invariant mass of the hadron pair was evaluated, under the assumption that the high-momentum leading hadron is the proton while the low-momentum hadron is the pion. In order to suppress the background from hadrons emitted from the the primary vertex, a vertex separation requirement of $z_2 - z_1 > 10$ cm has been applied, where z_1 and z_2 represent the coordinates of the primary and secondary vertex positions along the beam direction. In addition to that a RICH (or Čerenkov) based particle identification has been used for the leading particle. The spectrum with and without these background suppression constraints is displayed in Fig. 1.

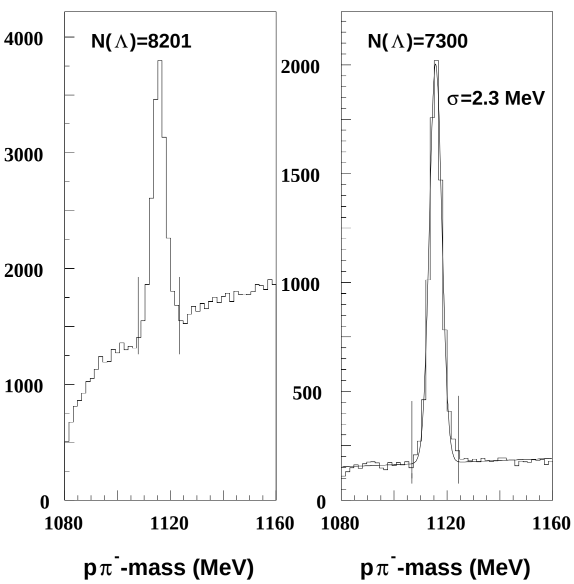

Figure 1. The yield of semi-inclusively produced Λ hyperons in deep-inelastic scattering. The left (right) panel shows the invariant-mass spectrum before (after) the application of background suppression cuts. The vertical lines show the boundaries at $\pm 3.3\,\sigma$.

Without background suppression, 8,200 Λ events were extracted from all unpolarized data, while the final data sample, with all requirements imposed, contained 7,300 Λ events.

The HERMES spectrometer has a limited acceptance for the reconstruction of Λ hyperons. In order to cancel the effect of the acceptance on the result, the spin transfer to the Λ has been determined by combining the two data sets measured with opposite beam polarizations into one helicity-balanced data sample, in which the luminosity-weighted average beam polarization for the selected data is $\overline{P_b} \equiv \frac{1}{L}\int P_b\, dL = 0$. Here $L = \int dL$ is the integrated luminosity.

A detailed derivation based on the method of maximum likelihood leads to the relation [12]:

$$D^{\Lambda}_{LL'} = \frac{1}{\alpha \overline{P_b^2}} \cdot \frac{\sum_{i=1}^{N_\Lambda} P_{b,i}\, D(y_i) \cos\Theta^i_{pL'}}{\sum_{i=1}^{N_\Lambda} D^2(y_i) \cos^2\Theta^i_{pL'}}. \qquad (3)$$

Here $\Theta_{pL'}$ is the angle between the proton momentum in the Λ rest frame and the Λ spin quantization axis L', where L' is chosen along the virtual photon direction L.

3. RESULTS

In the forward-production region ($x_F > 0$, where x_F is the fractional longitudinal momentum of the Λ hyperon) at $\langle x_F \rangle = 0.31$, and at the average fractional Λ energy $\langle z \rangle = 0.45$, the spin-transfer coefficient $D^{\Lambda}_{LL'} = 0.11 \pm 0.10\ \text{(stat)} \pm 0.03\ \text{(syst)}$ was obtained.

This value is in a good agreement with the NOMAD result [14] $-P^{\nu}_{\Lambda} = 0.09 \pm 0.06\ \text{(stat)} \pm 0.03\ \text{(syst)}$ measured for $x_F > 0$ ($\langle x_F \rangle = 0.21$), where $-P^{\nu}_{\Lambda} = D^{\Lambda}_{LL'}$ [15].

The dependence of $D^{\Lambda}_{LL'}$ on z with the requirement $x_F > 0$ imposed is presented in Fig. 2. Superimposed on the data are the phenomenological model calculations of Ref. [5] (pQCD and quark-diquark models) which predict a pronounced rise of the spin transfer at high values of z. The pQCD prediction is disfavoured by the data. Also shown is the model of Ref. [13] (SU(3)-flavor rotation of proton values) which predicts a more gradual increase.

The HERMES data [15] as a function of x_F are presented in Fig. 3 together with data obtained by the NOMAD experiment [14] at CERN with a 43 GeV ν_μ-beam and the Fermilab E665

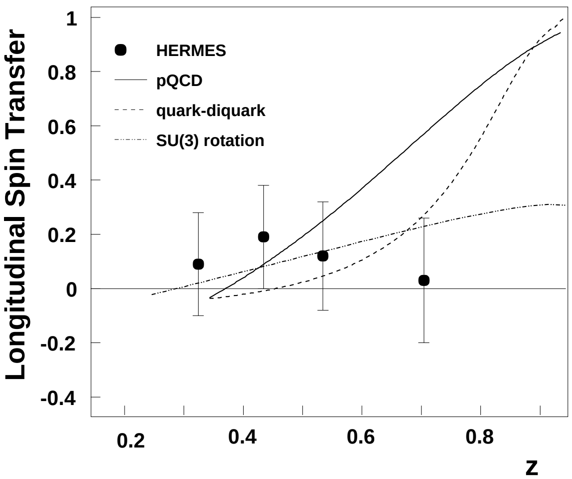

Figure 2. Dependence of the longitudinal spin-transfer coefficient $D^{\Lambda}_{LL'}$ on z, for $x_F > 0$. The curves represent the phenomenological model calculations of Refs. [5,13]. Error bars are statistical only.

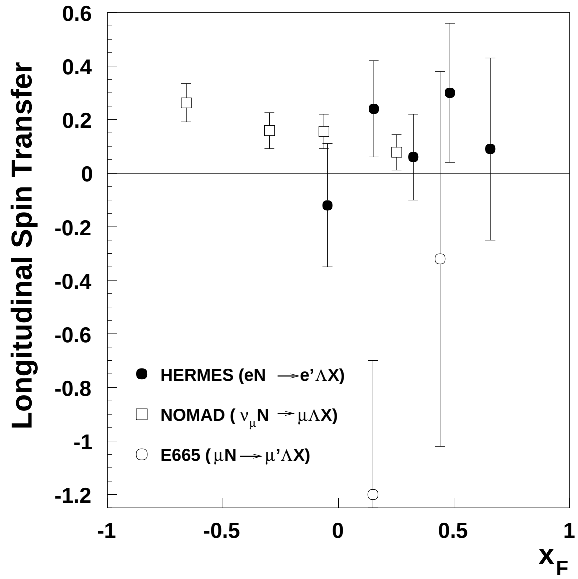

Figure 3. Dependence of the longitudinal spin-transfer coefficient $D^{\Lambda}_{LL'}$ on x_F. The HERMES measurements [15] are represented by the solid circles, while the open symbols represent data from NOMAD [14] (squares) and E665 [16] (circles). Error bars are statistical only.

experiment [16] obtained with a 470 GeV polarized muon beam. As it can be see from Fig. 3 the NOMAD and HERMES results are compatible in the kinematic region of overlap $-0.1 < x_F < 0.3$.

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