Proc. 24th International Spin Symposium (SPIN2021)
JPS Conf. Proc. **37**, 020115 (2022)
https://doi.org/10.7566/JPSCP.37.020115

Beam-Spin Induced Polarization of Λ and $\bar{\Lambda}$ Hyperons in Semi-Inclusive Deep-Inelastic Scattering

Denis Veretennikov [On behalf of the HERMES Collaboration]

[1]*Department of Physics, University of the Basque Country UPV/EHU, 48080 Bilbao, Spain*

E-mail: denis.veretennikov@desy.de

(Received March 1, 2022)

The beam-spin induced polarization of Λ and $\bar{\Lambda}$ hyperons produced in deep-inelastic scattering of longitudinally polarized positrons from unpolarized nucleons is being investigated by the HERMES experiment at a positron beam energy of 27.6 GeV. The spin-transfer coefficients D_{LX} and D_{LZ}, i.e., transverse and along the hyperon momentum direction, are studied as function of the relevant kinematic variables. A novel extraction method, which does not rely on accurate detector-response simulations, is employed and presented here for the first time exploiting the regular reversal of the beam helicity at the HERMES experiment.

KEYWORDS: Λ hyperon, polarisation, spin-transfer, HERMES

1. Introduction

In the naive Constituent Quark Model, the spin of the Λ hyperon is entirely carried by the s quark, i.e., $\Delta q_s^\Lambda = 1$, while the ud pair is in a spinless (singlet) state, i.e., $\Delta q_u^\Lambda = \Delta q_d^\Lambda = 0$. Here, $\Delta q_f^\Lambda \equiv q_f^{\Lambda+} - q_f^{\Lambda-}$, where $q_f^{\Lambda+}$ and $q_f^{\Lambda-}$ are the probabilities to find a quark with the spin parallel or anti-parallel to the spin direction of a longitudinally polarized hyperon, respectively, q_f^Λ ($f = u, d, s$) are the number densities for quarks plus antiquarks of flavor f in the Λ hyperon, while $q_f^\Lambda \equiv q_f^{\Lambda+} + q_f^{\Lambda-}$ are the polarization-averaged number densities.

Alternatively, one can use SU(3)-flavor symmetry in conjunction with the experimental results on the proton as well as axial charges from hyperon β decay to estimate the first moments of the helicity-dependent quark distributions in the Λ hyperon. Using such assumptions, Burkardt and Jaffe found $\Delta q_u^\Lambda = \Delta q_d^\Lambda = -0.23 \pm 0.06$ and $\Delta q_s^\Lambda = 0.58 \pm 0.07$ [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 semi-inclusive deep-inelastic scattering data on the nucleon [4], the values $\Delta q_u^\Lambda = \Delta q_d^\Lambda = -0.09 \pm 0.06$ and $\Delta q_s^\Lambda = 0.47 \pm 0.07$ are obtained instead, favoring a much smaller polarization of the u and d quarks and anti-quarks. A lattice-QCD calculation [3] also finds small light-quark polarization, $\Delta q_u^\Lambda = \Delta q_d^\Lambda = -0.02 \pm 0.04$, but larger $\Delta q_s^\Lambda = 0.68 \pm 0.04$.

Experimental information on the hyperon spin structure might be obtained by measuring the spin transfer to the hyperon produced in the process of polarized quark fragmentation. In the case of $\Lambda(\bar{\Lambda})$, the hyperon polarization (spin transfer) can be measured via the weak decay channel $\Lambda \to p + \pi^-$ ($\bar{\Lambda} \to \bar{p} + \pi^+$) through the angular distribution of the final-state particles. It is important that, as compared to other hyperons, the yield of the Λ hyperons is typically high enough to obtain satisfactory statistical precision of the polarization measurements. In the LEP experiments OPAL and ALEPH [5, 6], Λ hyperons were predominantly produced via $Z^0 \to s\bar{s}$ decay and as a result both strange quarks were strongly polarized.

2. Definition of the beam spin transfer

The Λ polarization is defined as $P^{\Lambda} = \frac{\sigma^{\uparrow}-\sigma^{\downarrow}}{\sigma}$, where $\sigma^{\uparrow(\downarrow)}$ is the Λ production cross section with spin projection along (opposite to) the Λ polarization direction, i.e., $\sigma = \sigma^{\uparrow} + \sigma^{\downarrow}$ is the unpolarized cross section for Λ production. As follows from Eqs. (100)–(102) in [1] for the case of unpolarized targets and the current-fragmentation region (fragmentation of the struck quark), the three components of the Λ polarization in the Λ rest frame can be presented as functions of PDFs and FFs by

$$\begin{aligned}
P_Z^{\Lambda}(x,y,z) &= P_b\lambda_e D_Z(y)\,\frac{\sum_q e_q^2 x f_1^q(x)\,G_1^q(z)}{\sum_q e_q^2 x f_1^q(x)\,D_1^q(z)},\\
P_Y^{\Lambda}(x,y,z) &= D_Y(y)\,\frac{M_N}{Q}\frac{\sum_q e_q^2 x f_1^q(x)\,D_{1T}^{\perp(1)q}(z)}{\sum_q e_q^2 x f_1^q(x)\,D_1^q(z)},\\
P_X^{\Lambda}(x,y,z) &= -P_b\lambda_e D_X(y)\left\{\frac{M_N}{Q}\frac{\sum_q e_q^2 x e^q(x) H_1^q(z)}{\sum_q e_q^2 x f_1^q(x)\,D_1^q(z)} + \frac{M_{\Lambda}}{Q}\frac{\sum_q e_q^2 x f_1^q(x)\,\tilde{G}_T^q(z)/z}{\sum_q e_q^2 x f_1^q(x)\,D_1^q(z)}\right\},
\end{aligned} \tag{1}$$

where P_b is the longitudinal beam polarization, M_N is the proton mass, M_{Λ} is the Λ mass, λ_e is the beam helicity state, $D_X(y)$, $D_Y(y)$, and $D_Z(y)$ are kinematic factors defined elsewhere (cf. Ref. [1]), and P_Z^{Λ}, P_Y^{Λ}, as well as P_X^{Λ} are the components of the Λ polarization in the coordinate system with the unit vectors $\vec{e}_X$, $\vec{e}_Y$, and $\vec{e}_Z$ defined in Fig. 1.

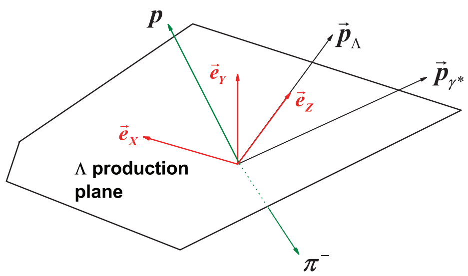

Fig. 1. Sketched view of coordinate systems in Λ rest frame.

As follows from Eq. (1), the P_X^{Λ} and P_Z^{Λ} components depend on the beam polarization P_b. The component P_Y^{Λ} is not related neither to the beam nor to the target polarization [1]. "Spontaneous polarization" has been an intriguing and much discussed effect in hadron physics. Besides numerous measurements of it in Λ hadroproduction, it has been the topic of investigations also in electroproduction (e.g., in Refs. [7, 8]), as well as e^+e^- annihilation [9], though the description of all those in terms of the fragmentation function $D_{1T}^{\perp(1)q}$ is still under debate.

Here, the focus will be on the beam-spin induced polarization components. Using Eq. (1), the Λ polarization vector can be defined as

$$\vec{P^{\Lambda}} = P_Y^{\Lambda}\vec{e}_Y + P_b D_X(y) D_{LX}\vec{e}_X + P_b D_Z(y) D_{LZ}\vec{e}_Z. \tag{2}$$

The values $D_{LZ}(x,z)$ and $D_{LX}(x,z)$ in Eq. (2) are the so-called spin-transfer coefficients. In the current fragmentation region, according to Eq. (1), they can be written as

$$D_{LZ}(x,z) = \frac{\sum_q e_q^2 x f_1^q(x)\,G_1^q(z)}{\sum_q e_q^2 x f_1^q(x)\,D_1^q(z)},$$

$$D_{LX}(x,z) = -\frac{M_N}{Q}\frac{\sum_q e_q^2 x e^q(x) H_1^q(z)}{\sum_q e_q^2 x f_1^q(x) D_1^q(z)} - \frac{M_\Lambda}{Q}\frac{\sum_q e_q^2 x f_1^q(x) \tilde{G}_T^q(z)/z}{\sum_q e_q^2 x f_1^q(x) D_1^q(z)}. \tag{3}$$

In the one-photon-exchange approximation, one may interpret the spin-transfer phenomenon as follows: the spin is transferred from the longitudinally polarized lepton to the virtual photon, then from the virtual photon to the struck quark. The longitudinal (along Z axis) polarization of the quark $P_b D_Z(y)$ and the transverse (along X axis) polarization of the quark $P_b D_X(y)$ are then transferred to the Λ. Fractions of the longitudinal and transverse quark polarization transferred to the Λ are the spin-transfer coefficients D_{LZ} and D_{LX}. As one can see from Eq. (3), these coefficients are sensitive to the spin-dependent fragmentation functions.

3. The HERMES experiment and data selection

The data were accumulated by the HERMES experiment at DESY. In this experiment, the 27.6 GeV longitudinally polarized lepton 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 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 lepton 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 larger contributions from radiative corrections and to remain in a region of quasi full trigger efficiency.

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 beam-line and the scattered beam lepton, while the secondary, decay, vertex was determined from the intersection of the proton and pion tracks. For the production vertex, the distance of closest approach was required to be less than 1.5 cm. For the decay vertex, vertex probabilities from fitting detached vertices were employed in the selection. In order to suppress backgrounds from hadrons emitted from the primary vertex, a vertex-separation requirement for minimum flight distance of the hyperon of 11 cm has been applied. The invariant mass of the hadron pair was evaluated for track combinations fulfilling all these requirements, under the assumption that the high-momentum leading hadron is the proton while the low-momentum hadron is the pion. In addition to that, a ring-imaging Cherenkov response has been used for rejecting leading pions. The resulting invariant-mass distributions for the Λ and $\bar{\Lambda}$ selections are shown in Fig. 2.

While the forward acceptance of the HERMES spectrometer favors Λ and especially $\bar{\Lambda}$ production in the current-fragmentation region, a sizable fraction stemming from the target remnants is present contributing predominantly to the lowest z bin. The extraction formalism presented below can still be applied for this contribution, and while any significant polarization in that kinematic region is of interest by itself (cf. Ref. [12]), the interpretation in terms of Eq. (1) does not hold.

4. Method of extraction of the spin-transfer coefficients

The polarization of a produced Λ ($\bar{\Lambda}$) hyperon can be measured by measuring the angular distribution of a weak $\Lambda \to p\pi^-$ ($\bar{\Lambda} \to \bar{p}\pi^+$) decay. This distribution of the decay proton is given by

$$\frac{dN}{d\Omega_p} = \frac{dN_0}{d\Omega_p}\left(1 + \alpha \vec{P}^\Lambda \hat{\vec{k}}_p\right). \tag{4}$$

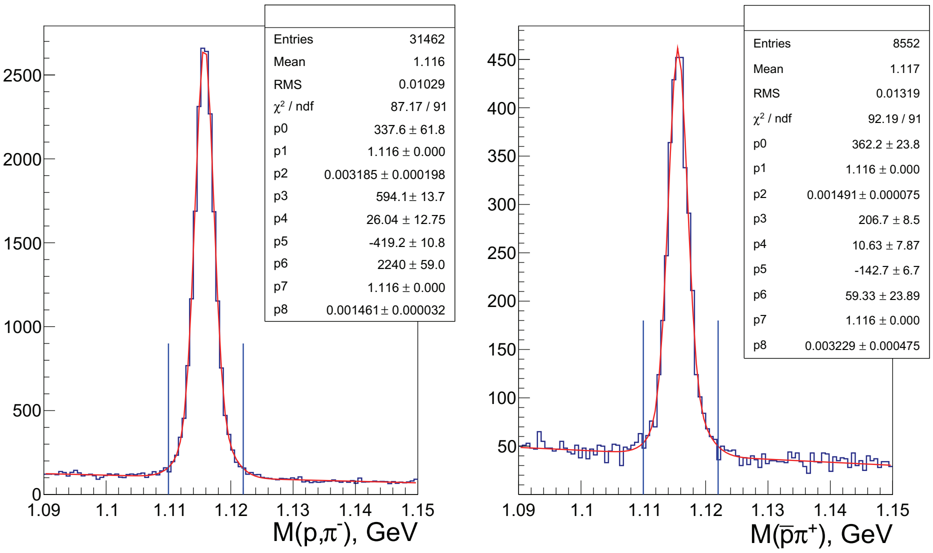

Fig. 2. Invariant-mass spectra for Λ (left) and $\bar{\Lambda}$ (right) candidates after application of all selection criteria.

Here, $\hat{\vec{k}}_p$ is the unit vector along the proton momentum in the Λ ($\bar{\Lambda}$) rest frame, $\alpha_\Lambda = 0.732 \pm 0.014$ ($\alpha_{\bar{\Lambda}} = -0.758 \pm 0.012$) is the weak-decay analyzing power parameter [13], and $\frac{dN_0}{d\Omega_p}$ represents the "unpolarized" distribution, i.e., distribution in case of unpolarized Λ hyperons, which in an actual experiment is in general not known. For the 4π case it is trivial, but for limited experimental acceptance it requires Monte Carlo simulated data including the effects of the detector, which often is a source of large systematic uncertainties. At HERMES, both beam-helicity states were available and could be exploited in a novel extraction formalism that does not rely on Monte Carlo simulations. The basic idea is that one can cancel $\frac{dN_0}{d\Omega_p}$ using data from both helicity states under the justifiable assumption that the acceptance remains the same for positive and negative beam-helicity states.

The extraction of the spin-transfer coefficients is based on the moment method [14, 15]. The one-dimensional case of this method, e.g., focusing only on the longitudinal spin transfer, was used in previous HERMES analyses and presented in, e.g., Refs. [16, 17]. Here, it is extended to the three-dimensional case and to data sets that are not helicity-balanced as was required before. As the Λ polarization perpendicular to the production plane is not correlated with the beam helicity, see Eq. (1), the polarization can be transferred only within the production plane. The nonzero components of the spin-transfer vector (X and Z) can then be found from a system of two equations:

$$\begin{aligned} A_{XX}D_{XX} + A_{XZ}D_{XZ} &= C_X\,, \\ A_{XZ}D_{XZ} + A_{ZZ}D_{ZZ} &= C_Z\,, \end{aligned} \tag{5}$$

with coefficients

$$\begin{aligned} A_{i,j} &= \left\langle \frac{D_k\,(y)\,D_i\,(y)\cos\theta_k\cos\theta_i}{1 + \alpha P_b \sum\limits_{j=X,Z} D_j\,(y)\,D_{Lj}\cos\theta_j} \right\rangle, \\ C_i &= \frac{1}{\alpha}\frac{\langle P_b D_i\,(y)\cos\theta_x\rangle - [\![P_b]\!]\,\langle D_i\,(y)\cos\theta_x\rangle}{[\![P_b^2]\!] - [\![P_b]\!]^2}. \end{aligned} \tag{6}$$

Here, $\cos\theta_x$, $\cos\theta_z$ are the cosines of the angle between the decay-proton momentum and the axis X or Z, respectively (cf. Fig. 1). Luminosity-weighted average values $[\![P_b]\!]^2$ and $[\![P_b^2]\!]$ are evaluated from event samples in similar experimental configurations (e.g., data-taking years), and the values in brackets ⟨...⟩ denote mean values calculated on an event basis taking averages over such experimental data samples, e.g.,

$$\langle P_b D_i(y)\cos\theta_i\rangle = \frac{1}{N}\sum_{n=1}^{N_\Lambda}\left[P_b D_i(y)\cos\theta_i\right]_n, \tag{7}$$

summing over all Λ events in the data set.

From Eq. (6) it becomes clear that the matrix elements themselves contain the spin-transfer coefficients D_{LX} and D_{LZ} that one wants to extract. As such it is not possible to directly solve the system of equations (5) as a system of linear equations. However, following iteration procedure used to find the spin-transfer coefficients D_{LX} and D_{LZ} has been employed successfully:

(1) Set initial value of the spin-transfer coefficients, e.g., $D_{LX} = D_{LZ} = 0$;
(2) Calculate matrix elements using Eq. (6);
(3) Solve system of equations in Eq. (5);
(4) Using values from previous step, calculate again matrix elements (cf. step 2);
(5) Iterate until convergence is reached, which in case of the HERMES data sets used happens after very few iterations.

5. Results

Finalization of the data analysis is ongoing with results expected to come out soon. Comparing with our previous publication [16] statistical uncertainty is reduced more then twice and additional component D_{LX}, i.e. spin-transfer perpendicular to beam direction within production plane is calculated.

References

[1] P.J. Mulders and R.D. Tangerman, Nucl. Phys. **B461**, 197–237 (1996).
[2] M. Burkardt and R.L. Jaffe, Phys. Rev. Lett. **70** 2537 (1993).
[3] QCDSF Collaboration, M. Göckeler et al., Phys. Lett. B **545** 112 (2002).
[4] HERMES Collaboration, A Airapetian et al., Phys. Rev. Lett. **92**, 012005 (2004); Phys.Rev. D **71** (2005).
[5] OPAL Collaboration, K. Ackerstaff et al., Eur. Phys. J. C **2**, 49 (1998).
[6] ALEPH Collaboration, D. Buskulic et al., Phys. Lett. B **374**, 319 (1996).
[7] HERMES Collaboration, A. Airapetian et al., Phys.Rev., D **90**, 072007 (2014).
[8] K. Kanazawa, Y. Koike, A. Metz, and D. Pitonyak, Phys. Rev. D **89**, 111501 (2014).
[9] Belle Collaboration, Y. Guan et al., Phys. Rev. Lett. **122**, 042001 (2019).
[10] D.P. Barber et al., Phys. Lett. B **343**, 436 (1995).
[11] HERMES Collaboration, K Ackerstaff et al., Nucl. Instrum. Methods A **417**, 230 (1998).
[12] J. R. Ellis, D. Kharzeev and A. Kotzinian, Z. Phys. C **69**, 467-474 (1996).
[13] Particle Data Group, P.A. Zyla et al., Prog. Theor. Exp. Phys. **2020**, 083C01 (2020).
[14] S. Belostotski and D. Veretennikov. Formalism of extraction of longitudinal spin transfer dll in semi-inclusive lambda production in 3d formalism and flickering coordinate systems. HERMES Technical Report 11-006 (2011).
[15] S. Belostotski. Extraction of polarization observables from helicity balanced data sample. HERMES Technical Report 09-009 (2009).
[16] HERMES Collaboration, A. Airapetian et al., Phys. Rev., D **64**, 112005 (2001).
[17] HERMES Collaboration, A. Airapetian et al., Phys. Rev. D **74**, 072004 (2006).