Measurement of the nuclear-mass dependence of spontaneous (transverse) Λ polarisation in quasi-real photoproduction at HERMES

Stan Belostotski, Yury Naryshkin and Denis Veretennikov (on behalf of the HERMES collaboration)
PNPI RAS Gatchina, Leningrad district 188300, Russia.
E-mail: belostot@mail.desy.de, naryshk@mail.desy.de, denis_v@mail.desy.de

Abstract. The HERMES experiment has measured the transverse polarization of Lambda and Lambda-bar hyperons produced inclusively at a positron beam energy of 27.6 GeV in quasi-real photon interactions with various nuclear targets in a wide range of atomic numbers (\(^1\)H, \(^2\)H, \(^3\)He, \(^4\)He, N, Ne, Kr, and Xe). The transverse Lambda polarization was found to decrease with A and to be compatible with zero for the heaviest nuclei.

1. Introduction
The transverse polarization of Λ, \(\bar{\Lambda}\) and other hyperons has been studied in many inclusive high-energy scattering experiments, with a wide variety of hadron beams and atomic numbers of targets [1, 2, 3, 4]. The polarization of Λ hyperons is found to be negative in essentially all experiments, apart from those with \(K^-\) and \(\Sigma^-\) beams where it is positive. In inclusive photoproduction of Λs and \(\bar{\Lambda}\)s, previous data are not conclusive because of their limited statistical accuracy [5, 6]. The mechanisms for the origin of the spontaneous polarization were reviewed e.g. in Refs. [2] and [7].

![Figure 1. Schematic diagram of inclusive Λ production and decay. The angle \(\theta_p\) of the decay proton with respect to the normal \(\hat{n}\) to the scattering plane is defined in the Λ rest frame.](image-url)

The Λ hyperon is a uniquely useful particle in spin physics: the parity-violating nature of its weak decay \(\Lambda \rightarrow p\pi^-\) results in an angular distribution where the protons are preferentially emitted along the spin direction of their parent Λ. The angular distribution of the Λ decay...
products may thus be used to measure its polarization, providing a rare opportunity to explore spin degrees of freedom in the fragmentation process. In the rest frame of the Λ it has the form:

$$\frac{dN}{d\Omega_p} = \frac{dN_0}{d\Omega_p}(1 + \alpha P_n \cdot \cos \theta_p).$$ (1)

Here, $\theta_p$ is the angle between the proton momentum and the polarization direction in the Λ rest frame (Fig.1). $P_n^\Lambda$ is the transverse polarization of the Λ, and $\alpha = 0.642 \pm 0.013$ is the analyzing power of the parity-violating weak decay. The symbols $dN/d\Omega_p$ and $dN_0/d\Omega_p$ denote the distributions for the decay of polarized and unpolarized Λ samples, respectively. Because of the parity-conserving nature of the strong interaction, any final-state hadron polarization in a reaction with unpolarized beam and target must point along a pseudo-vector direction. In the case of inclusive hyperon production with a positron beam, the only available direction of this type is the normal $\hat{n}$ to the production plane formed by the cross-product of the vectors along the laboratory-frame momenta of the beam ($\vec{p}_e$) and the Λ ($\vec{p}_\Lambda$):

$$\hat{n} = \frac{\vec{p}_e \times \vec{p}_\Lambda}{|\vec{p}_e \times \vec{p}_\Lambda|}.$$ (2)

2. Measurement of transverse Λ and $\bar{\Lambda}$ polarization

The experiment has been performed using the HERMES spectrometer described in detail in Ref. [8]. The 27.6 GeV positron beam of the HERA e-p accelerator facility passed through an open-ended tubular storage cell into which polarized or unpolarized gaseous target atoms ($^1$H, $^2$H, $^3$He, $^4$He, and the heavier gases N, Ne, Kr and Xe in natural abundance) were continuously injected. The positron beam was always longitudinally polarized. The longitudinally polarized beam and $^1$H and $^2$H target polarization cannot affect transverse polarization analyzed in this study. The polarization of longitudinally polarized $^1$H and $^2$H and transversely polarized $^1$H target was flipped at 1-3 minute time intervals and therefore the average target polarization was negligibly small.

The Λ ($\bar{\Lambda}$) hyperons were identified in the analysis through their $\pi\pi^-$ ($\bar{\pi}\pi^+$) decay channel. The kinematics of the Λ ($\bar{\Lambda}$) decay products is such that the proton (antiproton) momentum is always much higher than that of the pion. Two spatial vertices were reconstructed for each event. First the secondary (decay) vertex was determined from the intersection (i.e., point of closest approach) of the proton (antiproton) and pion tracks. Then the intersection of the reconstructed hyperon track with the nominal beam axis was used to determine the primary (production) vertex. The distance between the two vertices was required to be larger than 15 cm. The invariant-mass distribution was fitted with a Gaussian distribution plus a second order polynomial. Events within a window of ±3.5σ around the mean value of the Gaussian fit were selected for further analysis. The extraction of the Λ polarization from the data was accomplished using the method of the moment(s) which exploits the top/bottom symmetry of the detector [9, 10]. There was no Monte Carlo simulation involved in the analysis for the acceptance correction. In order to estimate the systematic uncertainty of the measurement, a similar analysis was carried out for reconstructed $h^+h^-$ hadron pairs, both with leading positive hadrons (like in Λ kinematics) and with leading negative hadrons (like in $\bar{\Lambda}$ kinematics). Events within two mass windows above and below the Λ ($\bar{\Lambda}$) mass window ($1.093 \text{ GeV} < M_{h^+h^-} < 1.180 \text{ GeV}$, and $1.124 \text{ GeV} < M_{h^+h^-} < 1.139 \text{ GeV}$) were selected with the hadron point of closest approach required to be inside the target region. False polarization values of $0.012 \pm 0.002$ ($0.018 \pm 0.002$) were found in the Λ-like ($\bar{\Lambda}$-like) case, and were used as estimates of the systematic uncertainty of the Λ ($\bar{\Lambda}$) polarization. As an additional check the decay $K^0 \rightarrow \pi^+\pi^-$ was studied. The false polarization of the $K^0$ sample was found to be $0.012 \pm 0.004$ ($0.002 \pm 0.004$) in the Λ-like ($\bar{\Lambda}$-like) case.
3. Results

The scattered positron was not requested for this analysis and therefore the data sample is dominated by events from quasi-real photoproduction \((Q^2 \approx 0 \text{ GeV}^2\), where \(-Q^2\) is the four-momentum squared of the virtual photon).
As no information on the virtual photon kinematics was available in this inclusive measurement, the kinematic dependence of the polarization could only be studied as a function of variables derived from the positron-nucleon system. The selected variables were $p_T$ and $\zeta = (E_\Lambda + p_{z\Lambda})/(E_e + p_e)$, where $p_T$ ($p_{z\Lambda}$) is the transverse (longitudinal) component of the $\Lambda$ momentum with respect to the beam direction, $E_\Lambda$ is the $\Lambda$ energy and $E_e$, $p_e$ are the beam energy and momentum.

The light cone variable $\zeta$ provides an approximate measure of whether a hyperon was produced in the forward or backward region in the center-of-mass frame of the $\gamma^*\text{-nucleon}$ reaction. It was used instead of the conventional Feynman variable $x_F = p_{\parallel \Lambda}/p_{\parallel \Lambda}^{\text{max}}$ which is not available in this inclusive measurement. A Monte-Carlo simulation with the PYTHIA event generator shows a reasonable correlation between these two variables. Thus at $\zeta > 0.2$ $x_F$ is predominantly positive, at $\zeta \approx 0.1$ $x_F$ ranges from -0.2 to 0.2 and at $\zeta < 0.08$ $x_F$ is negative. In Fig. 2, the transverse $\Lambda$ and $\bar{\Lambda}$ polarization $P_n$ is shown versus $p_T$ for the two kinematical regimes $\zeta < 0.25$ and $\zeta > 0.25$. In both cases, the $\Lambda$ polarization rises linearly with $p_T$. Fig. 3 shows $P_n$ versus $\zeta$. The $\Lambda$ polarization appears to increase in the low-$\zeta$ region while the $\bar{\Lambda}$ polarization shows no visible dependence on either $\zeta$ or $p_T$ within available statistics. For a subsample of the data collected in the years 1996-2000 mostly on $^1H$ and $^2H$ targets the net transverse $\Lambda$ polarization , averaged over the experimental kinematics, was found to be significantly positive while the net $\bar{\Lambda}$ polarization was consistent with zero: $P_{n\Lambda}^\Lambda = 0.078 \pm 0.006(\text{stat}) \pm 0.012(\text{syst})$. and $P_{n\bar{\Lambda}}^\Lambda = -0.025 \pm 0.015(\text{stat}) \pm 0.018(\text{syst})$ [10].

The dependence of $\Lambda$ polarization on the atomic mass number $A$ of the target has been investigated in many experiments with hadron beams and only small effects of the nuclear medium on the measured polarization have been observed [11, 12, 13].

The HERMES results for $P_{n\Lambda}^\Lambda$, integrated over the kinematic variables, are presented in Fig. 4 (A-dependence left panel, and $A/Z$-dependence right panel). A clear indication of dependence of $P_{n\Lambda}^\Lambda$ on $A$ is observed: the polarization for light nuclei ($^1H, ^2H$) is statistically significant positive, while it is compatible with zero within the statistical uncertainty for the heavier nuclei Kr and Xe. Note that the kinematical distributions for various nuclei are very similar such that the
average values of $\langle p_T \rangle$ and $\langle \zeta \rangle$ are practically $A$-independent, i.e., the observed effect cannot be trivially explained by the kinematical dependencies of $P^A_n$.

Strong dependence of the $\Lambda$ polarization on atomic number of target in the case of quasi-real photoproduction might be resulted from the fact that the primary photon may produce a polarized $\Lambda$ hyperon inside the nucleus which then loses its polarization due to rescattering in nuclear matter.

Other ideas are based on final state interactions of the leading quark or diquark with some collective color field (see e.g., Refs. [14, 15]).

4. Acknowledgments

We gratefully acknowledge the DESY staff and the staffs of the collaborating institutions. This work was supported by the Russian Academy of Science and the Russian Federal Agency for Science and Innovations.

References

[1] Heller K “Proceedings of the 12th International Symposium on High-Energy Spin Physics (SPIN 96)”, Mulders P J, Oberski J E J, Oskam-Tamboezer M (World Scientific, Singapore, 1997) 23
[2] Panagiotou A D 1990 Int. J. Mod. Phys. A5 1197
[3] Lach J 1996 Nucl. Phys. (Proc. Suppl.) 50 216
[4] WA89 Collaboration Adamovich M I 2004 Eur. Phys. J. C32 221
[5] SLAC-BC-072 Collaboration Abe K et al 1984 Phys. Rev. D 29 1877
[6] CERN-WA-004 Collaboration Aston D et al 1982 Nucl. Phys. B195 189
[7] Soffer J “Proceedings of the Hyperon Physics Symposium on High-Energy (Hyperon 99)”, edited by Jensen D A and Monnier E (Fermi National Accelerator Laboratory, Batavia, Ill, 1999) 121
[8] HERMES Collaboration, Ackerstaff K et al 1998 Nucl. Instrum. Methods A417 230
[9] Belostotski S Prepared for "58th Scottish Universities Summer School in Physics (SUSSP58): A NATO Advanced Study Institute and EU Hadron Physics 13 Summer Institute, St. Andrews, Scotland, 22-29 Aug 2004" DESY-HERMES-06-57
[10] HERMES Collaboration, Airapetian A et al 2007 Phys. Rev. D 76 092008
[11] Raychaudhuri K et al 1980 Phys. Lett. 90B 319
[12] Pondrom L 1985 Phys. Rep. 122 57
[13] R Bellwied (for the E896 Collaboration) 2002 Nucl. Phys. A698 499
[14] Abramov V V 2009 Physics of Atomic Nuclei: 72 1872
[15] Hannafious B and Burkardt M 2008 PoS LC2008 032411