Transverse Lambda Polarization at HERMES

S. Belostotski

Team:
S. Belostotski
Yu. Naryshkin
D. Veretennikov
O. Grebenjuk

Help and support
K. Rith
N. Makins
G. Schnell

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**Sokolov-Ternov effect**

- Magnetic field
- Electron polarization
- Electron momentum

Directed along magnetic field

Mechanism understood in the frame of QED

**Transverse polarization in hadron scattering**

- Unpolarized beam
- Unpolarized target
- Scattered, produced hadron

\[ \vec{P} \sim \vec{S} \cdot \vec{n} \quad \vec{n} = \vec{p}_{\text{beam}} \times \vec{p}_T \]

T – odd combination

Polarization along normal \( \vec{n} \) to scattering (production) plane

Well known phenomenon in pp, πp, pA scattering in GeV energy domain.

In general Single Spin Asymmetry SSA
SSA at High Energies

Perturbative QCD in collinear factorization approach, e.g. contribution subprocess qg → qg: quark of p_{beam} interacts with gluon of p_{target}

\[ \sigma \sim q(x_b) \otimes g(x_t) \otimes \hat{\sigma}_{qg \rightarrow qg} \otimes D_{q \rightarrow \Lambda}(z) \quad (D_{q \rightarrow \Lambda}(z) \text{ in collinear approach}) \]

\[ P_{qg \rightarrow qg} \sim \alpha_s \frac{m_q}{\sqrt{S}} \quad \text{small} \Rightarrow 0 \text{ at } m_q \rightarrow 0 \]

G.L.Kane, et al PRL 1978

At high energy substantial spin effects phenomena of produced hyperons are observed in disagreement with naïve perturbative QCD expectation

In order to see transverse spin transverse momentum to take into account:

\[ D_{q \rightarrow \Lambda}(z) \Rightarrow D_{q \rightarrow \Lambda}(k_{\perp},z) = D_{q \rightarrow \Lambda}^{\uparrow}(k_{\perp},z) + D_{q \rightarrow \Lambda}^{\downarrow}(k_{\perp},z) \]

\[ P_{\Lambda} = \frac{\sigma_{\Lambda}^{\uparrow} - \sigma_{\Lambda}^{\downarrow}}{\sigma_{\Lambda}^{\uparrow} + \sigma_{\Lambda}^{\downarrow}} \sim \frac{D_{q \rightarrow \Lambda}^{\uparrow}(k_{\perp},z) - D_{q \rightarrow \Lambda}^{\downarrow}(k_{\perp},z)}{D_{q \rightarrow \Lambda}^{\uparrow}(k_{\perp},z) + D_{q \rightarrow \Lambda}^{\downarrow}(k_{\perp},z)} \]

Collins Fragmentation Function,
P.J.Mulders and R.D.Tangerman,
Nucl.Phys 1996

Transverse polarization is nonperturbative effect.
Unpolarized quark becomes polarized in hadronization process.
Recently: twist-3 FF (qark-gluon correlations) → SSA
K.Kanazawa and Y.Koike 2013-2015 based on idea of Efremov and Teryaev
Hyperon Polarization: Famous Fermilab Data.

Interpretation: DeGrand and Mettinen  PRD 1981,1985

$P_T = 1.5$ GeV

$P_\Lambda \approx 0$
### Hyperon Octet Spin Structure $SU(3)_f$

<table>
<thead>
<tr>
<th>Hyperon</th>
<th>$\Delta (u+\bar{u})$</th>
<th>$\Delta (d+\bar{d})$</th>
<th>$\Delta (s+\bar{s})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p(uud)$</td>
<td>0.84</td>
<td>-0.43</td>
<td>-0.09</td>
</tr>
<tr>
<td>$n(udd)$</td>
<td>-0.43</td>
<td>0.84</td>
<td>-0.09</td>
</tr>
<tr>
<td>$\Lambda^0(uds)$</td>
<td>-0.16</td>
<td>-0.16</td>
<td>0.64</td>
</tr>
<tr>
<td>$\Sigma^+(uus)$</td>
<td>0.84</td>
<td>-0.09</td>
<td>-0.43</td>
</tr>
<tr>
<td>$\Sigma^0(uds)$</td>
<td>0.375</td>
<td>0.375</td>
<td>-0.43</td>
</tr>
<tr>
<td>$\Sigma^-(dds)$</td>
<td>-0.09</td>
<td>0.84</td>
<td>-0.43</td>
</tr>
<tr>
<td>$\Xi^0(uus)$</td>
<td>-0.43</td>
<td>-0.09</td>
<td>0.84</td>
</tr>
<tr>
<td>$\Xi^-(dss)$</td>
<td>-0.09</td>
<td>-0.43</td>
<td>0.84</td>
</tr>
</tbody>
</table>

**ΔΣ = 0.32**  HERMES/COMPASS

**ΔΣ = Δ (u + ū) + Δ (d + d̄) + Δ (s + s̄)**

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Assuming that
- $u(d)$ quark positively polarized
- $\Lambda^0 \Xi^0 \Xi^-$ polarization negative
- $\Sigma^+ \Sigma^-$ polarization positive

**Lattice-QCD**

$\Delta u = \Delta d = \mathbf{-0.02}$  \hspace{1cm}  $\Delta s = \mathbf{0.68}$ (±0.04)
More about Λ polarization. LHC/ATLAS Results.

**$X_F$ variable**

$$X_F = \frac{\tilde{p}_{\Lambda z}}{\tilde{p}_\Lambda} \quad -1 < X_F < +1$$

$\tilde{p}_{\Lambda z}, \tilde{p}_\Lambda$ in beam-target c.m. frame, $z$ along beam particle momentum

FIG. 8. The Λ transverse polarization measured by ATLAS compared to measurements from lower center-of-mass energy experiments. HERA-B data are taken from Ref. [5], NA48 from Ref. [4], E799 data from Ref. [3], and M2 from Ref. [2]. The HERA-B results are transformed to positive values of $x_F$ using Eq. (1).
Transverse $\Lambda$ polarization summary

- $P_\Lambda$ weakly depending of the beam momentum

- Its magnitude rises with $p_T$ and $x_F$ up to $P_\Lambda \approx 0.3\div0.4$ at $p_T = 1$ GeV

- At $1 < p_T < 3$ GeV $P_\Lambda$ stays constant (at larger $p_T$ no data available)

- In $pp$, $pA$ inclusive production $P_\Lambda$ negative

- Polarization of anti-$\Lambda$ compatible with zero

- For $K^-$, $\Sigma$ beams $P_\Lambda$ positive (valence $s$-quark)

- $P_\Lambda$ shows a tendency to decrease with $A$ (by 20% for Cu vs Be)

- At heavy ion collisions $P_\Lambda$ similar to $pp$ at $p_T > 2$ GeV

- $P_\Lambda$ in electro/photo production practically unknown (2 tagged experiments CERN, SLAC very poor statistics)
Transverse $\Lambda$ polarization in photoproduction at HERMES

Deep Inelastic Scattering regime

$$e + p, A \rightarrow e' + \Lambda + X \quad Q^2 > 1 \text{GeV}^2 \quad \text{DLL}$$
both detected, $Q^2$ defined

$$Q^2 = -4E_eE_{e'}\sin^2\frac{\theta_{\text{Lab}}}{2} \quad Q^2 \rightarrow 0 \quad \text{at } \theta_{\text{Lab}} \rightarrow 0$$

Quasi-real photoproduction regime

$$e + p, A \rightarrow \Lambda + X \quad Q^2 \approx 0$$
only detected (inclusively)

Most of $\Lambda(\bar{\Lambda})$ events within photo production peak (for 80% events $Q^2<0.05 \text{ GeV}^2$)
Kinematics of Quasi-Real Photoproduction

\[
\gamma^* + p, A \rightarrow \Lambda + X \quad \Lambda \Rightarrow p\pi^- \quad \left( E_{\gamma^*} \right) \approx 15 \text{ GeV} \quad \text{at HERMES}
\]

\[
\gamma^* + p, A \rightarrow \bar{\Lambda} + X \quad \bar{\Lambda} \Rightarrow \bar{p}\pi^+
\]

As photons not tagged and only measured are \(\Lambda\) (anti\(\Lambda\)) momentum components \(p_{\Lambda T}\) and \(p_{\Lambda z}\), \(x_F\) cannot be built (!)

\[
x_F \rightarrow \zeta = \frac{E_\Lambda + p_{z\Lambda}}{E_c + p_{z\Lambda}} \quad \text{light cone variable}
\]

two variables define reaction kinematics

transverse momentum \(p_{\Lambda T}\)

and

light - cone variable \(\zeta\)

\(x_F\) vs light –cone variable for HERMES from PYTHIA MC
**Λ detection with HERMES spectrometer**

- Forward spectrometer with $\Delta p/p=0.01$ and $\Delta \theta=0.001$
- Polarized beam and H,D targets
- Gas targets H, D, He, Ne, Kr, Xe
- Up/down mirror symmetry (except solenoid fields)
- $0.6 < p_\pi < 2.5$ GeV cutoff low momentum pions
- Well-operational RICH, effective bgr suppression
Standard way to measure particle polarization is scattering off analyzing target:

\[ \frac{d\sigma}{d\Omega_{\text{anal}}} = \frac{d\sigma}{d\Omega_0} (1 + P A \cos \phi) \]

P from azimuthal (left-right) asymmetry measurements.

Difficulty: at high energy A small

\[ \Lambda \rightarrow p\pi \text{ weak decay is self–analyzing:} \]

\[ \frac{d\sigma}{d\Omega_p} (\Lambda \rightarrow p\pi) = \frac{d\sigma}{d\Omega_{p0}} (1 + P_{\Lambda} \alpha \cos \theta_p) \text{ in } \Lambda \text{ rest frame} \]

\[ \alpha = 0.642 \pm 0.13 \text{ for } \Lambda \rightarrow p\pi^- \]

and \[ \alpha = -0.642 \text{ for } \Lambda \rightarrow \bar{p}\pi^+ \]

\( p_{\Lambda} \) from forward – backward decay asymmetry in \( \Lambda \) rest frame
Extraction of $\Lambda$ polarization

$$\frac{dN}{d\Omega_p} = \frac{dN_0(\cos \theta_p)}{d\Omega_p} (1 + \alpha P_\Lambda \cos \theta_p)$$

$$\frac{dN_0(\cos \theta_p)}{d\Omega_p} \sim \varepsilon(\cos \theta_p)$$

**Maximum likelihood (Moment method)**

Normalized probability to detect $\Lambda$ event

$$\omega_i = \frac{1 + \alpha P_\Lambda \cos \theta_{pi}}{1 + \alpha P_\Lambda \varepsilon \theta_{pi}}$$

$$\varepsilon(\cos \theta_p) = \int \frac{\varepsilon(\cos \theta_p) \cos \theta_p d\Omega}{\int \varepsilon(\cos \theta_p) d\Omega} = 1$$

$$\omega_i = 1 + \alpha P_\Lambda \cos \theta_{pi}$$

$$L = \prod_{i=1}^{N_\Lambda} (1 + \alpha P_\Lambda \cos \theta_{pi})$$

$$\frac{\partial \ln L}{\partial P_\Lambda} = \sum_{i=1}^{N_\Lambda} \frac{\alpha \cos \theta_{pi}}{1 + \alpha P_\Lambda \cos \theta_{pi}} = 0$$

$$\sum_{i=1}^{N_\Lambda} \frac{\alpha \cos \theta_{pi}}{1 + \alpha P_\Lambda \cos \theta_{pi}} = \sum_{i=1}^{N_\Lambda} \alpha \cos \theta_{pi} (1 - \alpha P_\Lambda \cos \theta_{pi}) = 0$$

$$\Rightarrow$$

$$\varepsilon(\cos \theta_p)$$

$$\cos \theta_p \rightarrow -\cos \theta_p$$ at $y \rightarrow -y$

$$\sum_{i=1}^{N_\Lambda} \cos \theta_{pi}$$

$$P_\Lambda = \frac{\sum_{i=1}^{N_\Lambda} \cos \theta_{pi}}{\alpha \sum_{i=1}^{N_\Lambda} \cos^2 \theta_{pi}}$$
Results

$\zeta = 0.25 \quad \Lambda / \overline{\Lambda}$

$\zeta < 0.25$

$\zeta > 0.25$
Possible Interpretation

Current fragmentation

\( \Lambda \) production \( s(\text{beam}) + (ud)_{0,1}(\text{string}) \)

\( \bar{\Lambda} \) production \( \bar{s}(\text{beam}) + (ud)_{0,1}(\text{string}) \)

Target fragmentation

\( \Lambda \) production \( s(\text{beam}) + (ud)_{0,1}(\text{target}) \)

\( \bar{\Lambda} \) production \( \bar{s}(\text{beam}) + (ud)_{0,1}(\text{target sea}) \)
A-dependence

A-dependence plots showing the dependence of a certain parameter on atomic mass number A for different elements such as H, D, He, Ne, Kr, and Xe. The plots indicate variations in the parameter $p_n^A$ with respect to the atomic mass number A and the momentum transfer $p_t$ [GeV]. The data points are accompanied by error bars, and different symbols represent different conditions or categories, such as H+D, $\xi < 0.2$, H+D, $\xi > 0.3$, and Kr+Xe, $0 < \xi < 1$. The plots provide insights into the behavior of the parameter across different mass numbers and momentum transfers.
Conclusion

- Polarization of $\Lambda$ in inclusive photoproduction at $p_T<1$GeV
  \[ P_\Lambda = 0.078 \pm 0.006_{\text{stat}} \pm 0.012_{\text{stat}} \]
  positive as in the case of $K^-$ or $\Sigma^-$ beam
- $\bar{\Lambda}$ polarization compatible with zero:
  \[ P_{\bar{\Lambda}} = -0.025 \pm 0.015_{\text{stat}} \pm 0.018_{\text{stat}} \]
- $\Lambda$ polarization in target fragmentation ($\zeta<0.25$) essentially larger than that in current fragment ($\zeta>0.25$)
- Yield of $\Lambda$ in target fragmentation surpasses substantially $\bar{\Lambda}$
- A possible interpretation of production mechanism and (partly) observed polarizations relates photon dissociation to quark-antiquark pair
- $A$-dependence: polarization vanishes for $A\approx 100$
- Polarizations for H and D targets coincides within error bars
BACKUP
$\langle E_\gamma \rangle = \langle E_e - E_\gamma \rangle = 15.6 \text{ GeV}$

$\gamma \rightarrow q\bar{q} \ (ss)$

$\zeta^\Lambda = \frac{E_\Lambda}{E_e} < 0.25 \text{ or } \sqrt{t} < 3.31 \text{ GeV}$
$\Lambda$ and $\bar{\Lambda}$ events selection

main bgr is $\pi^+\pi^-$ and $K\pi$ pairs production;

**bgr supression cuts:**
- Vertex separation.
  Distance between V1 and V2 vertices > 5 cm
Extraction of $D_{Li}$ components from experimental data sample

\[
\frac{dN}{d\Omega_p} = \frac{dN_0}{d\Omega_p} (1 + \alpha P \cdot k_p) = \frac{dN_0}{d\Omega_p} (1 + \alpha_\Lambda P_B \sum_{i=x,y,z} D_{Li}^\Lambda \cos \theta_i) \text{ in } \Lambda \text{ rest frame}
\]

\[
\alpha_{\Lambda \rightarrow p+\pi^-} = 0.642 \pm 0.013 \quad \alpha_{\Lambda \rightarrow p+\pi^+} = -0.642 \pm 0.013
\]

Spectrometer acceptance results in strong distortion of decay angular distribution, intensive MC acceptance simulation (COMPSS)

For beam helicity balance case $[P_B] = 0$

MC simulation of spectrometer acceptance is not needed, acceptance correction does not affect measured asymmetries. $D_{Li}$ components are extracted using experimental data sample only !!

\[
\alpha = \pm \alpha = \mp
\]

\[
A_i = \frac{1}{N^\Lambda} \sum_{v=1}^{N^\Lambda} \left(D^2(y) \cos \theta_i \cos \theta_k \right)_v
\]

\[
B_i = \frac{1}{N^\Lambda} \sum_{v=1}^{N^\Lambda} \left(P_B D(y) \cos \theta_i \right)_v
\]

\[
\left[ P_B^2 \right] = \frac{\int P^2(t)L(t)dt}{\int L(t)dt}
\]

average over experimental data sample
**HERMES is a forward spectrometer**

\[ p_{\Lambda}(\text{min}) \sim 1 \text{ GeV} \]
Angular distribution of decay protons in \( \Lambda \) rest frame

\[
\frac{dN_0}{d\Omega_p} = \text{const} \quad \text{for } 4\pi \text{ acceptance}
\]

for restricted acceptance

\[
\frac{dN_0}{d\Omega_p} \quad \text{depends on } \cos\theta_{pL'}
\]

Distorted by spectrometer acceptance

May in principle be calculated using MC

difficulty to avoid false asymmetry induced by MC acceptance simulation

\[
\frac{dN}{d\Omega_p} = \frac{dN_0}{d\Omega_p} (1 + \alpha P_{\text{Beam}} \cdot \vec{D}_{LL'} \cdot \hat{k}_p)
\]

\[\alpha = 0.642 \pm 0.013\]
Effect of longitudinal magnetic field (solenoid)

\[
\cos\theta_p = \frac{p_{\pi x}p_{py} - p_{\pi y}p_{px}}{p_{\Lambda T}q}
\]

\[
\cos\theta_p \rightarrow -\cos\theta_p \text{ at } y \rightarrow -y
\]

\[
\cos\theta_p \text{ in } \Lambda \text{ rest frame,}
\]

\[
q = 101 \text{ Mev decay momentum}
\]

\[
p_{\pi x,y}, p_{px,y}, p_{\Lambda T} \text{ in Lab frame (!)}
\]

Up/down mirror symmetry: acceptance function

\[
\varepsilon^{\text{up}}(\cos\theta_p, \ldots) \rightarrow \varepsilon^{\text{down}}(-\cos\theta_p, \ldots) \text{ at } y \rightarrow -y
\]

Transverse magnetic field of the dipole magnet (transverse pol target and spectrometer dipole)

\[
B_{x}^{\text{up}} = -B_{x}^{\text{down}} \quad B_{y}^{\text{up}} = B_{y}^{\text{down}} \quad B_{z}^{\text{up}} = -B_{z}^{\text{down}}
\]

Lorentz force

\[
F_{x}^{\text{up}} = F_{x}^{\text{down}} \quad F_{y}^{\text{up}} = -F_{y}^{\text{down}} \quad F_{z}^{\text{up}} = F_{z}^{\text{down}}
\]

up / down mirror symmetry

Longitudinal magnetic field of solenoid (longitudinal pol target and RD solenoid)

\[
B_{x}^{\text{up}} = B_{x}^{\text{down}} \quad B_{y}^{\text{up}} = -B_{y}^{\text{down}} \quad B_{z}^{\text{up}} = B_{z}^{\text{down}}
\]

Lorentz force

\[
F_{x}^{\text{up}} = -F_{x}^{\text{down}} \quad F_{y}^{\text{up}} = F_{y}^{\text{down}} \quad F_{z}^{\text{up}} = -F_{z}^{\text{down}}
\]

no up/down mirror symmetry
False polarization of hh pairs 00 and 06,07

Published false polarization of Ks is: $P_{Ks} = 0.012 \pm 0.004$

Published false polarization of hh pairs is: $P_{hh} = 0.012 \pm 0.002$
HERMES SPECTROMETER

HERMES dipole \( BL = 1.3 \) TM \( \frac{\Delta p}{p} \approx 1\% \) \( \Delta \theta_x, \Delta \theta_y \approx 1\text{mrad} \)

\(-170 < \theta_x < +170\text{mrad} \)
\(-140 < \theta_y < -40\text{mrad} \)
\(140 > \theta_y > 40\text{mrad} \)
\(40 < \theta < 220\text{mrad} \)

Very good PID !!