Transverse Polarization in Hyperons Produced in Unpolarized p+N Collisions

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What are Hyperons?

- Hyperons are a type of baryon
- Baryons are made up of three quarks
- A hyperon has at least one strange quark and no charm, bottom, or top quarks
- Hyperons decay weakly with non-conserved parity
What are Hyperons?

<table>
<thead>
<tr>
<th>Particle</th>
<th>Symbol</th>
<th>Makeup</th>
<th>Rest Mass (MeV/c²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lambda</td>
<td>$\Lambda^0$</td>
<td>uds</td>
<td>1115.683</td>
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<tr>
<td>Sigma</td>
<td>$\Sigma^+$</td>
<td>uus</td>
<td>1189.37</td>
</tr>
<tr>
<td>Sigma</td>
<td>$\Sigma^0$</td>
<td>uds</td>
<td>1192.642</td>
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<tr>
<td>Sigma</td>
<td>$\Sigma^-$</td>
<td>dds</td>
<td>1197.449</td>
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<tr>
<td>Xi</td>
<td>$\Xi^0$</td>
<td>uss</td>
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<tr>
<td>Xi</td>
<td>$\Xi^-$</td>
<td>dss</td>
<td>1321.71</td>
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<tr>
<td>Omega</td>
<td>$\Omega^-$</td>
<td>sss</td>
<td>1672.45</td>
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The Lambda Baryon ($\Lambda^0$)

- The lightest of the hyperons
- Decays in $2.602 \times 10^{-10}$ s
- Decays to a proton and pion most of the time
  - Branching ratio of 63.9%
- Protons and pions do not have a strange quark
  - This implies that quark flavor changed in the process (weak decay)
- Lambdas have a useful property
  - They are self-analyzing
  - That is, the proton from the decay prefers to have the same polarization as the lambda
  - Measuring the proton’s polarization is the same as a measurement of the lambda’s polarization
Original Experiment in 1976

- G. Bunce, et. al. fired a 300 GeV unpolarized proton beam at a fixed Be target
- Apparatus is shown below, creates a neutral hyperon beam

![Diagram of experimental setup]

- Important parts
  - P = proton beam, $M_1$ = restoring magnet for production-angle variation, T = target, $M_2$ = collimator and sweeper for hyperon beam, rest is for decay reconstruction
Original Experiment in 1976

- In the rest frame of the $\Lambda^0$, the proton angular distribution is described by:

\[
\frac{dN}{d\Omega} = \frac{1}{4\pi} \left( 1 + \alpha P \cos \theta \right)
\]

- $\theta$ is the angle between the proton momentum and the $\Lambda^0$ spin/polarization
- $P$ is the magnitude of the hyperon polarization
- $\alpha$ is the asymmetry parameter, which is $0.647 \pm 0.013$ for the $\Lambda^0$
  - This has been experimentally measured and changes depending on the hyperon
  - Related to the form factors of the effective hadronic weak electromagnetic vertex

\[
\alpha_\gamma = \frac{2 \text{Re}[G(0)F_M^*(0)]}{|G(0)|^2 + |F_M(0)|^2}
\]
Original Experiment in 1976

- Measured the three components of the polarization independently
- Definition of coordinate axes
  - $z$: parallel to the $\Lambda^0$ momentum vector
  - $x$: parallel to the cross product $\Lambda^0$ momentum vector and the proton beam vector
  - $y$: perpendicular to both $x$ and $z$
- Results plotted to the right as the polarization components and magnitude as a function of the $\Lambda^0$ transverse momentum
- Data is after the hyperon passed through a magnetic field, which caused precession of the spin
- Polarization magnitude of about 28%
Original Experiment in 1976

- This was an unexpected result!
- Perturbative QCD conserves helicity
  - This leads to a very small expected polarization (at the time), which applies to general hyperons from unpolarized beams/targets
  \[
  P \sim \frac{\alpha s m_q}{Q^2}
  \]
- Instead, we are getting a large transverse polarization, which is negative for the \( \Lambda \) in unpolarized p+N (convention)
- This is just one hyperon, what about the rest?
The Polarization of $\bar{\Lambda}^0$

- The $\bar{\Lambda}^0$ is made up of $\bar{u}\bar{d}\bar{s}$
- K. Heller, et. al. carried out an experiment measuring the polarization of both $\Lambda^0$ and $\bar{\Lambda}^0$ via a 400 GeV proton beam incident on a Be target (1978)
- The $\Lambda^0$ transverse polarization was found to be about -24%, agreeing with previous experiments
  - Measured up to a transverse momentum of 2.1 GeV/c
- The $\bar{\Lambda}^0$ was found to have zero polarization
  - Measured up to a transverse momentum of 1.2 GeV/c
- Are antihyperons unpolarized in these types of collisions?
Polarizations of Other Hyperons

- In 1993, A. Morelos, et al. found that both $\Sigma^+$ and $\Sigma^-$ had nonzero (positive) polarizations
  - $\Sigma^+$ polarization increases up to 16% at $p_t=1.0$ GeV/c and then decreases to 10%
- In 1990, P. M. Ho, et al. found that the $\Xi^+$ had negative polarization of about the same magnitude as the $\Xi^-$
  - Called into question models that predict zero polarization for particles with no quarks in common with the incoming particle
- In 1993, K. B. Luk, et al. found that the $\Omega^-$ had zero polarization, with behavior similar to that of $\Lambda^0$
  - At the time, no model could explain the different transverse polarizations of hyperons
Common Characteristics of Hyperon Polarizations

- If an unpolarized beam is used, then the polarization of the hyperon will be zero in the forward (longitudinal) direction
  - This is required by rotational symmetry for production from an unpolarized beam and target
- Dependence on the transverse momentum of the hyperon with respect to the beam direction
- Dependence on the Feynman $x$
  - The ratio of the hyperon longitudinal momentum in COM frame divided by its maximum
What has happened since the 90s?

- Various experiments have studied hyperon and other hadron polarizations
  - Types of beams have varied among these experiments, as well as goals
- STAR at RHIC
  - Used Au+Au collisions to measure the polarization of Λ’s while studying the flow characteristics of quark-gluon plasma
- ATLAS
  - Studied the transverse polarizations of hyperons produced in proton-proton collisions with a center of mass energy of 7 TeV, allowing them to look at small Feynman x
What has happened since the 90s?

- **HERMES at HERA**
  - Used an 27.6 GeV electron beam to study quasi-real photoproduction on nuclei

- **BELLE at KEK**
  - Observed transverse polarizations of $\Lambda/\bar{\Lambda}$ hyperons in $e^+e^-$ annihilation with a center of mass energy of 10.58 GeV

- **CLAS at Jefferson Lab**
  - Studied hyperon polarization in photoproduction on a hydrogen target with a photon energy of 1.0 to 3.5 GeV
Possible Models

● Many models have been offered as possible explanations for these results
● These are a mix of semiclassical models and quantum models
● None of these models fit with all experimental data, just bits and pieces
  ○ Issues with the models vary from predicting independence of $P_T$, having the wrong shape when compared to data, predicted wrong polarizations for other hyperons, etc.
Example: DGM Model

- A semiclassical model, it takes some qualities from parton recombination models and explains the $\Lambda^0$ polarization as a Thomas precession effect
- The shared quarks between the proton and the Lambda are u and d
- Since the u and d are unpolarized, the s quark, which arises from the fragmentation process, must determine the polarization
- By Thomas precession, the spin vector of the s quark will tend to align with the angular momentum, which determines the sign and magnitude of the transverse polarization
- DGM model predicts zero polarization for all antihyperons (no shared quarks with the proton)
Twist-3 Collinear Factorization

- The twist of an operator is the difference between its dimensionality and its Lorentz spin
- In the original perturbative QCD, leading-twist parton correlators were used, which lead to small asymmetries (i.e. predicted zero polarization)
- It was realized that the asymmetries we see are a twist-3 effect and that we must include quark-gluon-quark correlations (i.e. more terms!)
- Recent work has been done in calculating twist-3 cross section for unpolarized p p → Λ X
- Calculation of all possible terms has yet to be completed for hyperons
- Once done, perhaps this will numerically fit with the data
An Example Twist-3 Cross Section

- This represents the complete result of the cross section caused by twist-3 effects of the qq and qgq fragmentation correlators.
- The calculation is incomplete, one needs to include other correlators, e.g. \( \bar{q}qg \), gg, and ggg correlators.

\[ P_h \frac{d\sigma(P_h, S_\perp)}{d^3P_h} = \frac{2\alpha_s^2 M_h}{s^2} e_{P_h pp'} S_\perp \int \frac{dx}{x} f_1(x) \int \frac{dx'}{x'} f_1(x') \]

\[ \times \int \frac{dz}{z^3} \delta(\hat{s} + \hat{t} + \hat{u}) \left[ \frac{D_T(z)}{z} \hat{\sigma}_1 - \left\{ \frac{d}{d(1/z)} \frac{D_{1T}^{(1)}(z)}{z} \right\} \hat{\sigma}_2 \right. \]

\[ \left. - D_{1T}^{(1)}(z) \hat{\sigma}_3 + \int_z^\infty \frac{dz_1}{z_1^2} \left( \frac{z_1}{1/z - 1/z_1} \right) \right. \]

\[ \left. \times \left( \text{Im} \hat{D}_{FT}(z, z_1) + \text{Im} \hat{G}_{FT}(z, z_1) \right) \hat{\sigma}_4 \right] \]
Summary

- The transverse polarization of hyperons in unpolarized proton + nucleus collisions continues to be a puzzle over the last 40 years
- Initial perturbative QCD expected it to be zero
- Hyperons generally have nonzero transverse polarization
- Antihyperons have a mix of zero and nonzero transverse polarization
- There are no models that can fully explain experimental observations
- Perhaps the twist-3 formalism will shed new light on this subject?
Sources

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Sources

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