Transverse Polarization in Hyperons Produced in Unpolarized p+N Collisions

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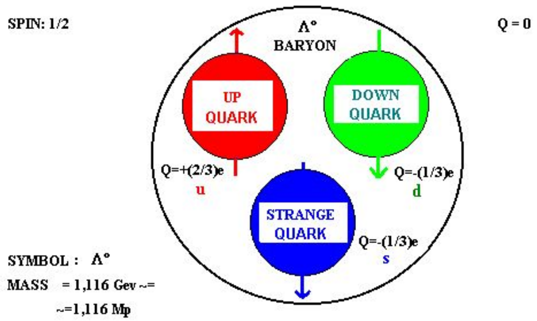
What are Hyperons?

- 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?

Particle	Symbol	Makeup	Rest Mass (MeV/c^2)
Lambda	Λ^0	uds	1115.683
Sigma	Σ^+	uus	1189.37
Sigma	Σ^0	uds	1192.642
Sigma	Σ^-	dds	1197.449
Xi	Ξ^0	uss	1314.86
Xi	Ξ^-	dss	1321.71
Omega	Ω^-	sss	1672.45

The Lambda Baryon (Λ^0)

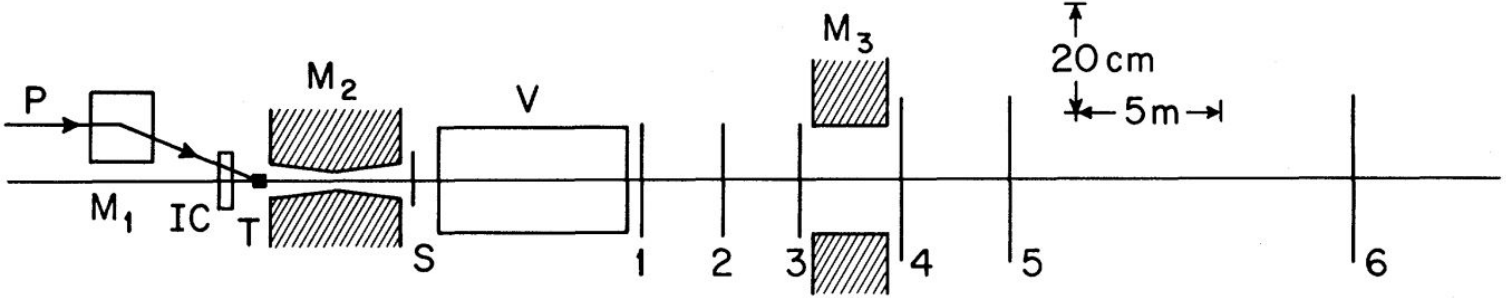


http://www.peoplephysics.com/images/particles/barionelambda0.gif

- The lightest of the hyperons
- Decays in 2.602 × 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



- 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 Λ^0, the proton angular distribution is described by:

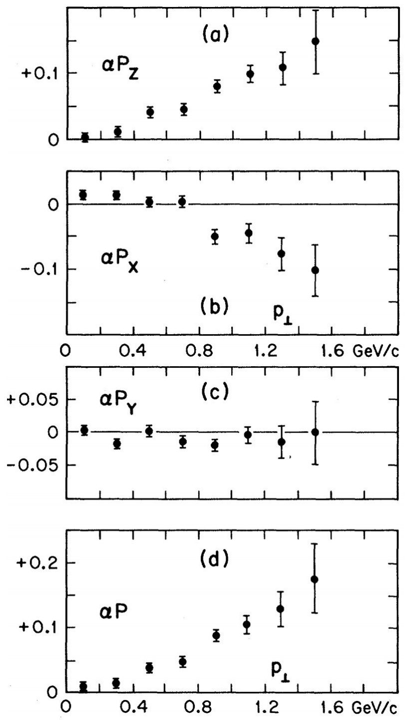
$$\frac{dN}{d\Omega} = \frac{1}{4\pi}(1 + \alpha P \cos\theta)$$

- θ is the angle between the proton momentum and the Λ^0 spin/polarization
- *P* is the magnitude of the hyperon polarization
- α is the asymmetry parameter, which is 0.647 ± 0.013 for the Λ^0
  - This has been experimentally measured and changes depending on the hyperon
  - Related to the form factors of the effective hadronic weak electromagnetic vertex

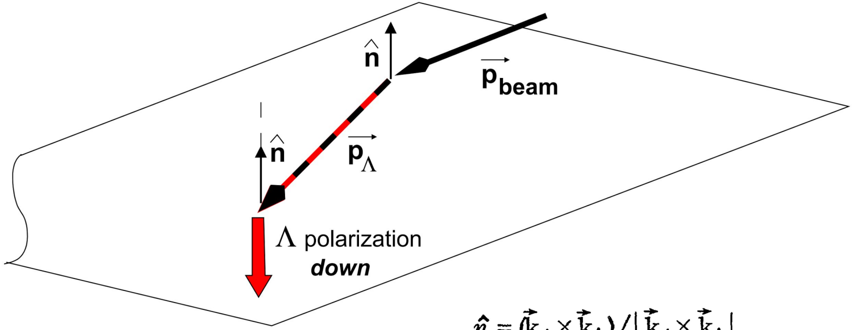
$$\alpha_\gamma = \frac{2\,\mathrm{Re}[G(0)F_M^*(0)]}{|G(0)|^2 + |F_M(0)|^2}$$

Original Experiment in 1976

- Measured the three components of the polarization independently
- Definition of coordinate axes
  - z: parallel to the Λ^0 momentum vector
  - x: parallel to the cross product Λ^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 Λ^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



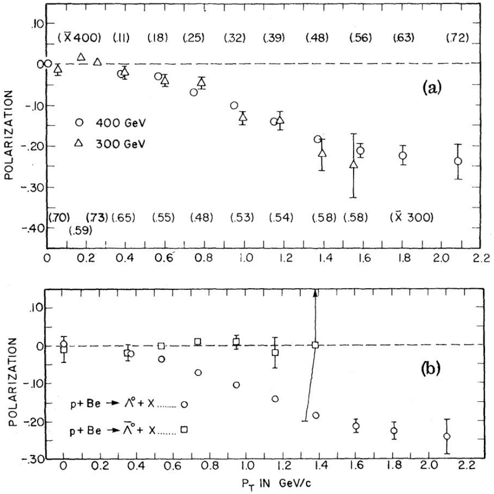
- This was an unexpected result!
- Perturbative QCD conserves helicity
  - This leads to a very small expected polarization (at the time), which applies to general hyperons from unpolarized beams/targets

$$P \sim \frac{\alpha_s m_q}{Q^2}$$

- Instead, we are getting a large transverse polarization, which is negative for the Λ in unpolarized p+N (convention)
- This is just one hyperon, what about the rest?

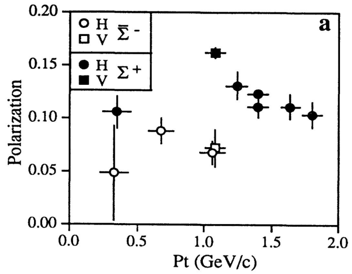
The Polarization of $\bar{\Lambda}^0$

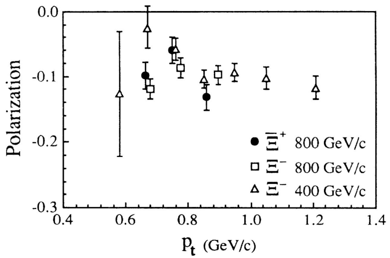
- The $\bar{\Lambda}^0$ is made up of $\overline{uds}$
- K. Heller, et. al. carried out an experiment measuring the polarization of both Λ^0 and $\bar{\Lambda}^0$ via a 400 GeV proton beam incident on a Be target (1978)
- The Λ^0 transverse polarization was found to be about -24%, agreeing with previous 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?

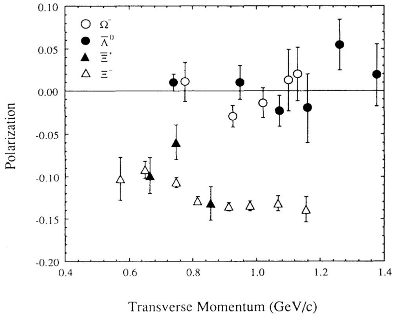


Polarizations of Other Hyperons

- In 1993, A. Morelos, et. al. found that both Σ^+ and $\bar{\Sigma}^-$ had nonzero (positive) polarizations
  - Σ^+ 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 $\bar{\Xi}^+$ had negative polarization of about the same magnitude as the Ξ^-
  - 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 Ω^- had zero polarization, with behavior similar to that of $\bar{\Lambda}^0$
  - At the time, no model could explain the different transverse polarizations of hyperons





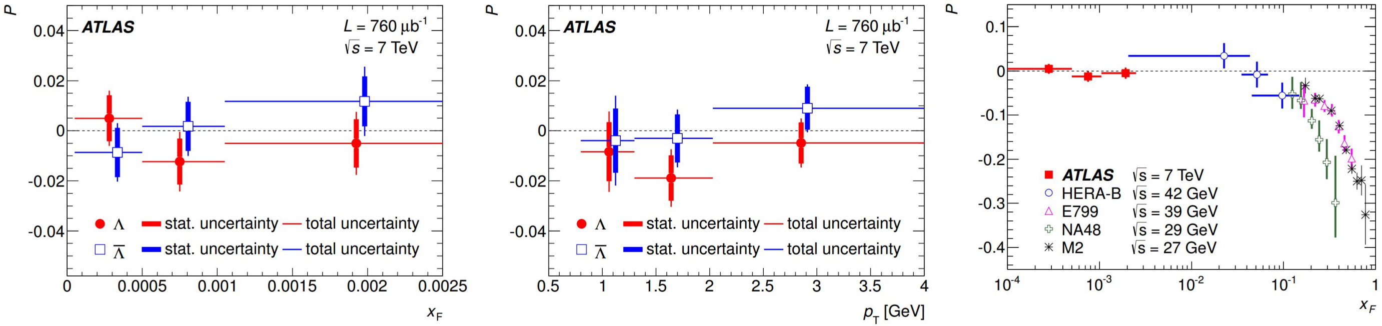


Common Characteristics of Hyperon Polarizations

- 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

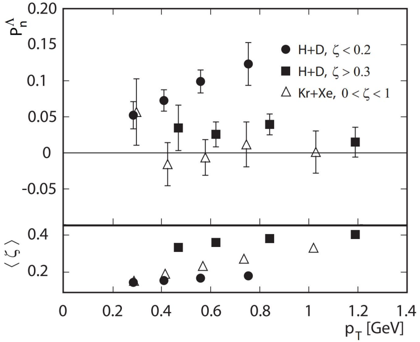
What has happened since the 90s?

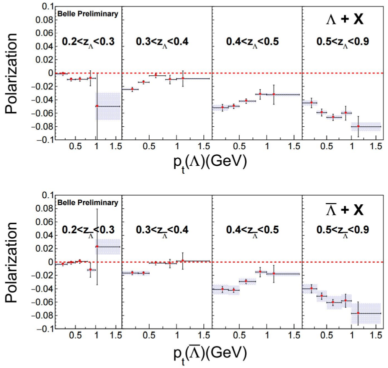
- Various experiments have studied hyperon and other hadron polarizations
  - Types of beams have varied among these experiments, as well as goals
- STAR at RHIC
  - Used Au+Au collisions to measure the polarization of Λ's while studying the flow characteristics of quark-gluon plasma
- ATLAS
  - Studied 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

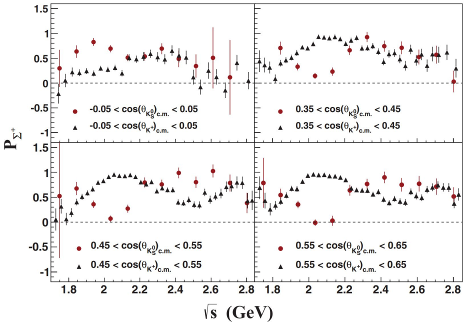


What has happened since the 90s?

- 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



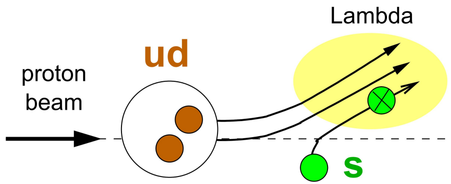




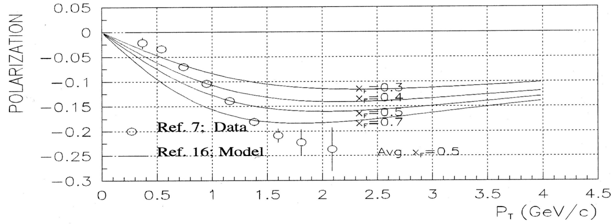
Possible Models

- Many models have been offered as possible explanations for these results
- Heller model, DeGrand-Miettinen (DGM) model, Moriarity model, Andersson model, Szwed model, Troshin model, Soffer model, Hama model, Barni model, Dharmaratna model, Troshin-Tyurin model, Zuo-Tang model
- 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 Λ^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 $p\ p \rightarrow \Lambda\ X$
- 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. $q\bar{q}g$, gg, and ggg correlators

$$
\begin{aligned}
P_h^0 \frac{d\sigma(P_h, S_\perp)}{d^3 P_h} &= \frac{2\alpha_s^2 M_h}{s^2} \epsilon^{P_h p p' S_\perp} \int \frac{dx}{x} f_1(x) \int \frac{dx'}{x'} f_1(x') \\
&\times \int \frac{dz}{z^3} \delta(\hat{s} + \hat{t} + \hat{u}) \left[\frac{D_T(z)}{z} \hat{\sigma}_1 - \left\{ \frac{d}{d(1/z)} \frac{D_{1T}^{\perp(1)}(z)}{z} \right\} \hat{\sigma}_2 \right. \\
&\quad - D_{1T}^{\perp(1)}(z) \hat{\sigma}_3 + \int_z^\infty \frac{dz_1}{z_1^2} \left(\frac{z_1}{1/z - 1/z_1} \right) \\
&\quad \left. \times \left(\mathrm{Im} \widehat{D}_{FT}(z, z_1) + \mathrm{Im} \widehat{G}_{FT}(z, z_1) \right) \hat{\sigma}_4 \right]
\end{aligned}
$$

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?

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