Transverse Polarization of Λ and $\bar{\Lambda}$ in Quasi-Real Photon-Nucleon Scattering

In 1976, an experiment at Fermilab measured a remarkable thing. This remarkable observation has to do with spin, the fragmentation process, and the Λ baryon. If you're unfamiliar with the first two concepts, please have a look at the appendix, where some explanation is provided! Otherwise, let's start by introducing our main character: the Λ baryon.

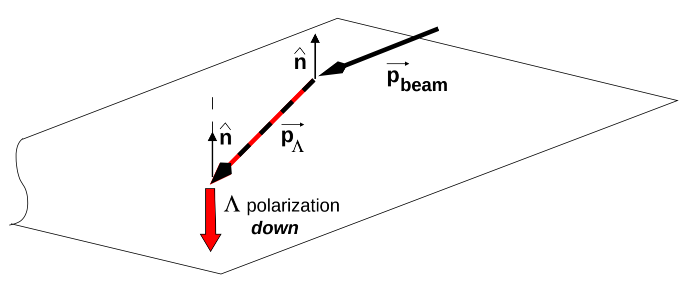
The Λ Baryon

Baryons are composite particles that are built out of three quarks. The most familiar examples are the proton (2 up quarks and 1 down quark) and the neutron (2 down quarks and 1 up quark) that are found in all atomic nuclei. A less familiar example is the Λ (pronounced "Lambda"). This particle has the same spin as the proton and neutron but is about 20% heavier. The reason that it's a bit heavier is that it contains and up quark (u), a down quark (d), and the slightly heavier **strange** quark (s). There are many other baryons that contain strange quarks, such as the $\Sigma's$ with one s quark, the Ξ's with two, and the Ω^- with three. These strange baryons are collectively called **hyperons**, and the Λ is the lightest of them.

The Λ is an unstable particle: it decays in about 3×10^{-10} seconds, usually to $\Lambda \rightarrow p\pi^-$, and we detect it via these decay products. Neither the proton (p) nor the negative pion (π^-) contain any s quarks, so where did the s quark in the Λ go? Well, it decayed too, via the only force in nature that can change quark flavor: the **weak force**. The weak interaction is also the only one which **violates parity**, and that gives the decay of the Λ a very useful property: when a Λ decays to $p\pi^-$, *the proton prefers to come out in the same direction as the spin of the* Λ. Therefore by measuring where the protons go, we can determine what the spin direction of the Λ is! To be precise, we don't measure the spin direction of each individual Λ but rather Λ **polarization**, which describes the statistical probability for the Λ spin to point in one direction or another.

There's one last thing you need to know about the Λ baryon: its spin structure. If you've read some of our other papers, you probably know that one of the main goals of the HERMES experiment is to determine how the quark spins are lined up within the proton. We now know that, on average, the up quarks spin in the same direction as their parent proton, while the down quark spins point in the opposite direction. No one has measured this information for the Λ yet. Nevertheless, we can make an educated guess. Based on our knowledge of proton spin structure and some symmetries of nature, it is a pretty safe bet that only the strange quark is strongly polarized inside the Λ: our best guess is that the s quark spins in the same direction as the Λ while the u and d quarks have more-or-less random spin orientations.

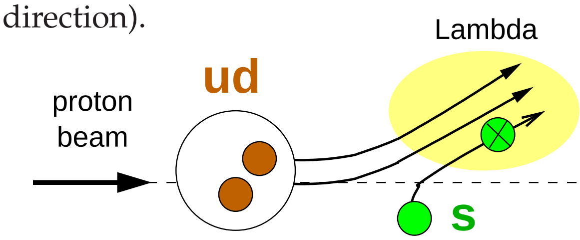
The Wacky World of Hyperon Polarization



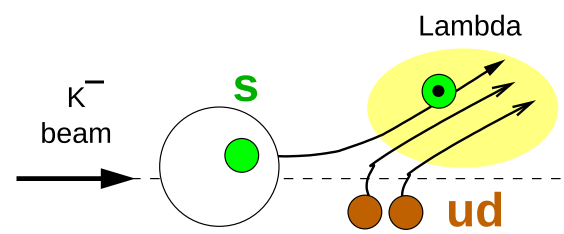
We're now ready to describe the remarkable observation first made at Fermilab in 1976. The experiment in question scattered high energy protons of 300 GeV from a Beryllium target and looked for Λ baryons in the final state. To be precise, they measured the *polarization* of these Λ particles, by analyzing the angular distribution of the proton and pion from the decay $\Lambda \rightarrow p\pi^-$ as described above. Both the proton beam and Beryllium target were unpolarized, meaning that the spins of these particles were randomly oriented. Nevertheless, the Λ particles produced in the final state were found to be highly polarized! Somehow, the Λ's had managed to *polarize themselves* during the production process. This spontaneous polarization was in the transverse (or "normal") direction $-\hat{n}$, where $\hat{n}$ is obtained by taking the cross-product $\hat{p}_{\text{beam}} \times \hat{p}_\Lambda$ of the beam and Λ momentum directions.

At first sight, the concept of a particle polarizing itself in a scattering reaction seems so bizarre as to be magical. But the phenomenon does occur in a more familiar setting. Imagine that you throw a tennis ball against a brick wall at an angle of 45° or so. If you're careful, you can throw the ball so that it isn't turning at all as it sails through the air. The wall isn't turning either, obviously. Nevertheless, after the tennis ball bounces off the wall, it will come off spinning in a particular direction. The axis around which it's spinning will be perpendicular to the plane made by its incoming and outgoing directions — that's the normal to the scattering plane. To be exact, the direction of the tennis ball's angular momentum vector will be $-\hat{n} = -\hat{p}_{\text{initial}} \times \hat{p}_{\text{final}}$, just like the Λ!

Since 1976, many experiments have observed the transverse self-polarization of Λ baryons with proton beams. Similar effects have been observed when other hadronic beams are used, and in the production of other hyperons too. The polarization is found to vary in magnitude and sign depending on which beam and which final-state particle are involved. An important feature of the data is that the polarization is always strongest when the hyperons are produced with a large momentum component in the *forward* direction (where "forward" means the original beam direction).



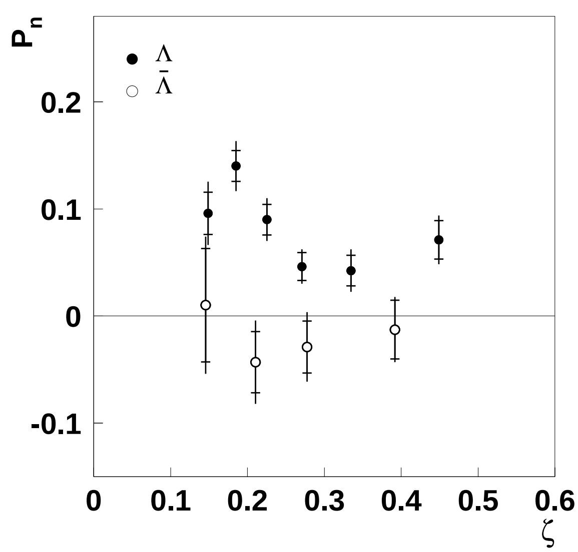
A number of models have been developed to try and explain the accumulated body of hyperon polarization data. The **DGM model** (named after its authors DeGrand and Miettinen) is the most successful to date. It is based on the different polarization of u, d, and s quarks within the hyperons, and on a well-established phenomenon called **Thomas precession**. Thomas precession is an effect that can be derived purely from the theory of special relativity and is described in such standard textbooks as J.D. Jackson. Basically it tells us that when a particle turns a corner at relatistic speeds, its spin vector tends to align with the direction of angular momentum. The drawing above shows how the DGM model explains Λ polarization. Since the Λ's which display the largest polarization have high momentum in the forward direction, we assume that they contain the maximum number of valence quarks available from the beam. When a proton beam is used, only the u and d quarks are shared with the Λ as shown in the diagram. The strange quark is assumed to arise from somewhere within the fragmentation process. As illustrated in the figure, this strange quark has to accelerate to catch up with the u and d quarks from the beam and become part of the fast Λ. As it does so, it "turns a corner", in the clockwise direction. The Thomas precession force then polarizes the s quark into the page. The normal vector $\hat{n}$ points out of the page. Since the spin of the s quark determines the spin of the Λ, we get a Λ polarization in the $-\hat{n}$ direction.



Λ's produced with proton and pion beams always show a negative polarization. By comparison, beams of negative kaons (K^-) produce Λ's with *positive* polarization. The right-hand drawing above shows how the DGM model explains this observation. The K^- mesons in the beam are composed of one strange quark and one anti-up quark. These mesons share only the s quark with the Λ, so the u and d are assumed to come from the fragmentation process. As shown in the diagram, the s quark from the beam has to *decelerate* to become part of the fast Λ, turning a corner counterclockwise as it does so. Thomas precession polarizes this s quark out of the page, giving us a Λ polarization in the $+\hat{n}$ direction.

The DGM model (and others) explains a good fraction of the available data. However a couple of puzzles remain that no model has yet explained. One famous puzzle is the polarization of *anti-hyperons*. If the DGM model is correct, the direction of hyperon polarization depends entirely on two factors: (i) which quarks are shared between the beam and the hyperon, and (ii) the spin structure of the hyperon itself. Now imagine that we produce an anti-hyperon, with three valence antiquarks, from a proton beam. Clearly *no* valence quarks at all are shared with the beam in this situation! All three antiquarks must come from the fragmentation process, so sometimes they will accelerate and sometimes they will decelerate when forming antihyperons. This should lead to *zero* polarization. So what does the data say? Well, the $\bar{\Lambda} = \overline{uds}$ and the $\Omega^- = \overline{sss}$ are indeed unpolarized. But 10 years ago, two suprising measurements emerged: the $\bar{\Sigma}^+ = \overline{uus}$ and the $\bar{\Xi}^- = \overline{dss}$ displayed polarizations just as big as those of the "regular" Σ^+ and Ξ^-! Understanding these observations has been a decade-long puzzle that still lacks a convincing solution.

HERMES results



As described above, the transverse self-polarization of Λ's produced in the forward direction has been measured with a wide variety of hadronic beams. The sign and magnitude of the polarization changes depending on the beam type, providing important clues to the mechanism underlying this mysterious effect. Our paper presents the first observation of transverse Λ polarization with a **photon beam** (i.e. a beam of electromagnetic radiation, just like light or radio waves but of higher energy). If you've read any of our other papers, you're probably wondering where we got hold of a photon beam, since the HERMES experiment uses the *electron* beam from the HERA storage ring. Well, for this particular measurement, we studied events where the electron beam was only deflected by a very small angle when it scattered from the target. Under these conditions, the electron beam radiates a "nearly-real" photon which then scatters from the target. In other words, we get our photon beam directly from the electron beam, by electromagnetic radiation.

The figure shows the transverse polarization of Λ (closed circles) and $\bar{\Lambda}$ (open circles) hyperons measured with our "quasi-real" photon beam. The data are plotted versus the variable ζ, which represents (approximately) how far forward the Λ was produced. In the center-of-mass frame where the electron beam is coming from the left and the target is flying in from the right, $\zeta = 1$ means the Λ was produced to the right (along the beam direction), while $\zeta = 0$ means it was generated in the "backwards" direction, to the left. As described in the paper, $\zeta = 0.25$ roughly marks the boundary between the forward and backward production hemispheres.

The first thing to observe about the data is that the Λ polarization is *positive*. This is surprising: it is opposite to what happens with non-strange beams of protons or pions, and agrees instead with kaon-beam production. Could it be that there are strange quarks in our photon beam, as there were in the K^- beam? It is well known that real photons fluctuate quite frequently to quark-antiquark pairs before they interact with nuclear targets ... could the data be telling us that $\gamma \rightarrow s\bar{s}$ fluctuations are the dominant source of Λ production in our experiment? Another feature of the data is the increase in magnitude of the Λ polarization in the *backward-production* region. Very little data is available about hyperon polarization in this hemisphere. The fact that the polarization grows indicates that something very interesting may be happening! We'll have to see. A new detector called the "Lambda Wheels" was added to the HERMES experiment in 2001 and another detector called the "Recoil Dector" was added in late 2005 to help us explore this region in greater detail.

Appendix: Spin and Fragmentation

Concept 1: Spin

The concept of angular momentum is familiar to everyone who's ever spun a top as a child or taken a corner too fast as an adult. Angular momentum describes the *turning motion* of an object and comes in two distinct varieties. One is *orbital* motion, and the other is *rotational* motion. To explain the difference, consider the motion of our planet. The Earth travels around the sun in an elliptical orbit, causing the seasonal weather that we experience each year. This motion gives our planet *orbital* angular momentum, around the sun. Second, the Earth turns around its own axis, giving us light during the day and darkness at night. That motion gives the Earth *rotational* angular momentum.

Now let's zoom in to the world of elementary particles. Inside all materials are atoms ... inside all atoms are nuclei, made of nucleons (protons and neutrons) ... and inside all nucleons are quarks. As far as we know at the moment, that's as far as it goes: the quark seems to be a truly fundamental, indivisible particle of zero size. Yet despite its infinitesimal size, its life inside the proton resembles the life of the Earth inside our solar system in a number of ways. The Earth has rotational angular momentum because it's perpetually orbiting around its own axis. The quark has the same property: it has an *intrinsic* angular momentum that we call *spin*. It seems strange to think of a pointlike particle with no discernible radius rotating around its own axis (how can a point have an axis?) ... but to all intents and purposes, it appears that the quark is indeed rotating ceaselessly around its own axis. Is the quark also *orbiting* around the center of proton, as the Earth orbits around the sun? We presume that it is, but we've never seen it ... but that's another story, and is the subject of some of our other research papers.

The quark is not the only fundamental particle around. The electron is another, and it too has spin. So far, it seems that *all* fundamental particles with any degree of stability have spin: they are all rotating constantly around their own internal axes.

Concept 2: Fragmentation

In deep-inelastic scattering, a high energy beam strikes a proton or neutron with such force that the nucleon is blown apart. After this happens, a process called *fragmentation* (or hadronization) occurs whereby many new hadrons are created from the debris of the target. In the center-of-mass frame of the DIS reaction, a single quark is ejected from the target with high momentum while the target remnant escapes in the opposite direction. As the coloured quark and remnant separate from each other, a powerful colour "string" develops between them. As the system expands, energy from the stretched string is repeatedly converted into matter via the formation of quark-antiquark pairs, which ultimately coagulate into jets of hadrons. Hadronization is a complex, non-perturbative process which arises from the long-range dynamics of colour confinement.

How does *spin* participate in the fragmentation process? The struck quark which initiates a jet of hadrons has spin ... so do many of the hadrons that are formed in the jet. Do these hadrons have any *memory* of the spin of the struck quark? To measure the degree of spin transfer from the struck quark, you clearly need to know both the spin of the quark in the initial state, and the spin of the hadron in the final state. The quark's spin can be controlled using a spin-polarized electron beam, as we do at HERMES. But the spin of hadrons in the final state is much more difficult to determine. The only practical way of doing it in high energy experiments is to use our friend the Λ baryon. As described earlier, the Λ's spin-polarization can be determined by measuring the angular distribution of its decay products. This offers a rare window on how spin behaves in the fragmentation process!