Results on $\Lambda^0$ Production at HERMES

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Abstract

The production of $\Lambda^0$'s at the HERMES experiment is presented. Prospects for the future of $\Lambda$ measurements at HERMES are discussed.

1 Introduction

The HERMES Experiment was designed primarily to study the spin structure of the nucleon in polarized deep inelastic electron/positron nucleon scattering. It uses the polarized positron beam at HERA and an internal gas target. For more details, see the other HERMES contributions to these proceedings, Ref. [1, 2, 3, 4]

The strength of HERMES lies in its ability to detect the scattered positron and the hadronic final state. At HERMES many particles such as $\Lambda^0$’s can be reconstructed from the final state hadrons in numbers that make detailed analysis of their properties possible. Since the $\Lambda$ decay violates parity, the polarization can be reconstructed from the angular distribution of the decay products. At HERMES the target and beam polarization will affect the $\Lambda$ polarization, either by transfer of polarization from the nucleon’s quarks, or through the polarized virtual photon. HERMES can detect the current and target fragmentation region of $\Lambda$ production. The current fragmentation will give information about the $u$ quark fragmentation and the target fragmentation will provide insight into the polarization of the strange sea.

2 Lambda Observables

2.1 Current Fragmentation

In the current fragmentation region ($x_f > 0$, $x_f$ is the fraction of available longitudinal momentum, defined to be along the beam line, transferred to
the hadron in the $\gamma^* N$ center of mass frame) $\Lambda$'s acquire their polarization during the polarized quark fragmentation. ALEPH [5] and OPAL [6] have recent significant negative results for longitudinal polarization from $Z^0$ decays in $e^+e^-$ collisions. This is due to the fragmentation of $s$ quarks which are highly polarized [5]. For deep inelastic scattering, the $u$ is the dominant quark [7] and a substantial longitudinal $\Lambda$ polarization would be a signature for spin transfer of the virtual photon to the $u$ quark and correspondingly of the $u$-quark polarization in the $\Lambda$.

For a positron or electron beam of polarization $P_B$ on an unpolarized target the resulting $\Lambda$ polarization is predicted to be (for a small positron scattering angle) [4]:

$$P_L^\Lambda = P_B D_y \tau_B = P_B \frac{1 - (1 - y)^2}{1 + (1 - y)^2 \tau_B}$$

where $D_y$ is the depolarization factor, $D_y \tau_B$ is the polarization transferred from the beam positrons to the $\Lambda$, $e_q$ is the charge for quark $q$, $q_N(x)$ is the spin average quark distribution for the nucleon, $\Delta D_q^\Lambda(z)$ is the spin dependent fragmentation function for a quark fragmenting into a $\Lambda$, and $D_q^\Lambda(z)$ are the corresponding spin-independent fragmentation functions. Information about the $u$-quark fragmentation function ratio $\Delta D_u^\Lambda(z)/D_u^\Lambda(z)$ in the current fragmentation region can be obtained. Estimates of precision for an experiment like HERMES based on the $u$ quark dominance have been calculated elsewhere [6].

### 2.2 Target Fragmentation

In the target fragmentation region ($x_f < 0$) the struck quark has non-zero net longitudinal polarization, and Ellis' model [8] suggests that the remnant $s$ quark will have a *negatively-correlated* polarization which is transferred to the $\Lambda$. The polarization in the target fragmentation region is predicted to be [8]:

$$P_L^\Lambda = \frac{\sum_q e_q^2 [P_B D_y q(x) + P_T \Delta q(x)] c_{sq}}{\sum_q e_q^2 [q(x) + P_B P_T D_y \Delta q(x)]}$$

$\Delta q(x)$ is the helicity difference quark distribution, $D_y$ is the same depolarization factor as for current fragmentation, $c_{sq}$ is the spin-correlation coefficient:

$$c_{sq} = \frac{P_{s+q} - P_{s-q}}{P_{s+q} + P_{s-q}}$$

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and $P_{s+q}(P_{s-q})$ represents the probability that the spin of the remnant $s$ quark is parallel(antiparallel) to the spin of the struck quark. Measurement of $P_{\Lambda}$ in the target fragmentation region will give insight into the polarization of the strange sea quarks.

### 2.3 Measurement

Since the $\Lambda \rightarrow p\pi$ decay violates parity, its polarization can be determined by the angular distribution of its decay products. To measure longitudinal $\Lambda$ polarization, the cosine of the angle between the direction of the $\Lambda$ momentum in the lab and the proton ($\cos \theta_0$) in the $\Lambda$ rest frame is reconstructed and the mean value calculated ($\langle \cos \theta_0 \rangle$). However, the acceptance of the HERMES spectrometer is asymmetric in $\cos \theta_0$. This is because the pion’s momentum is much softer than that of the proton, and the pion is more likely to miss all or part of the HERMES acceptance. It is necessary, therefore, to reverse the beam polarization and compare $\cos \theta_0$ distributions for both helicities to obtain the polarization.

### 3 Data

HERMES had two periods of dedicated unpolarized target running in 1996 and 1997 between which the beam helicity was reversed. An unpolarized target allows for a higher density ($Luminosity \sim 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$) than the polarized target, so that a large number of deep inelastic events can be collected over a short period of time. In addition, the $\Lambda$ analysis becomes simplified since it does not have to take into account the polarization transfer from the target nucleons. A short summary of the events collected for the two periods of running is shown in Table I.

In each candidate $\Lambda$ event:

$$e + N \rightarrow e' + \Lambda(\bar{\Lambda}) + X$$

HERMES identifies a positron and two hadrons from the $\Lambda$ decay. Momenta $\vec{p}_{e'}$, $\vec{p}_p$, $\vec{p}_\pi$ are measured, vertices $v_1$, $v_2$, and invariant mass $M_{p\pi}$ are reconstructed. How the vertices are defined is shown in Figure I. After reconstruction of the event, several basic requirements must be met for the event to be considered a $\Lambda$ event. There must be at least three tracks in the detector, one track a positron, and a decay vertex with two oppositely charged
Table 1: Summary of HERMES statistics collected during unpolarized target running.

|        | 1996     | 1997     |
|--------|----------|----------|
| Target Types: | H,D,³He | H,D,N    |
| Number of DIS: | 5.4×10⁶  | 4.5×10⁶  |
| Number of Lambdas: | 3960     | 4711     |
| With DIS Cuts: | 2695     | 2609     |

Figure 1: A simplified diagram of a Λ event, showing how the different vertices are defined.

hadron tracks. In addition, deep inelastic scattering (DIS) cuts are made on the data: negative four-momentum transfer of the lepton $Q^2 > 1.0$ GeV$^2$, invariant mass of the hadronic system $W^2 > 4.0$ GeV$^2$, fractional energy transfer of the lepton $y < 0.85$, and the momentum fraction of the struck quark $0.02 < x_{Bj} < 0.8$ [9].

After all these requirements, however, there still remains a substantial background. This can be significantly reduced by requiring a set of tighter cuts which take into account the properties of Λ decays. These include: the direction of Λ momentum ($\vec{p}_\Lambda$) should be close to direction ($\vec{v}$) defined by primary $e^+$ ($v_1$) and secondary $p\pi$ ($v_2$) vertices:

$$x_{vp} = \frac{(\vec{v}, \vec{p}_\Lambda)}{|\vec{v}| \cdot |\vec{p}_\Lambda|} > 0.9995,$$

the separation of tracks $d_2$ at the secondary Λ vertex $v_2$ should be small:

$$d_2 < 1.5\text{cm},$$
the calculated decay length of the Λ should be:

\[ c\tau > 2 \text{ cm}, \]

and a requirement that the invariant mass of the decay vertex on the assumption of a \( \pi^+\pi^- \) instead of \( p^+\pi^- \) does not give a \( K_s^0 \) mass:

\[ M_{\pi\pi} < 0.48 \text{ or } M_{\pi\pi} > 0.52. \]

The effects of the basic cuts and the stricter cuts is shown for 1996 data in Figure 2 [9]. The reduction of the background can clearly be seen.

Figure 2: 1996 Λ invariant mass distributions for two different sets of cuts. The upper portion is with DIS cuts only, and the lower plot has the additional cuts imposed. Both plots are for the entire 1996 running. The reduction of the background is significant. (HERMES detects about 1/5 as many \( \Lambda^0 \)'s.)
3.1 Event Types

Figure 3 shows two types of HERMES events. HERMES can reconstruct tracks where the particle may leave the detector acceptance before it reaches the calorimeter, these are called short tracks. However, the momentum reconstruction is not as good because there is not a track in the rear tracking chambers of the detector. The track’s bend in the magnet only goes through the magnet proportional chambers and leaves before it is tracked in the rear tracking chambers. In both kinds of events the positron always has a full track through the detector. A long track event is when the $\pi^-$ and $p$ have full tracks in HERMES. A short track event is when either the $\pi^-$, $p$, or both particles have tracks only recorded in the front region of HERMES.

The short track events allow access to the target fragmentation region, shown for data in Figure 3. In addition, the asymmetric $\cos \theta_0$ distribution, caused by the experimental acceptance, is reduced as can be seen in Figure 4 for Monte Carlo unpolarized $\Lambda$’s.

4 Monte Carlo

An integral part of the study of $\Lambda$ physics at HERMES has been understanding the parent particle distributions and the experimental acceptance with the help of Monte Carlo simulation. For example, the $\Sigma^0$’s can depolarize the resulting $\Lambda$ about 30% of the time [7, 10]. Monte Carlo results, summarized in Table 2, show that only 16% are expected from this channel, resulting in a 5% correction of the measured total $\Lambda$ polarization.

| Parent | Decay Mode | Percentage |
|--------|------------|------------|
| $\Sigma(1385)$ | $\Lambda \pi$ | 30% |
| $\Sigma^0$ | $\Lambda \gamma$ | 16% |
| $\Xi^0, \Xi^-$ | $\Lambda \pi^0, \Lambda \pi^-$ | 5% |

Table 2: Monte Carlo parent particle fractions. The remaining 49% are produced by string fragmentation.

In addition, kinematic distributions must be compared to make sure the $\Lambda$ Monte Carlo reproduces the data. In Figure 3 the distributions, after DIS cuts, are shown for $Q^2$, $x_{Bj}$, $y$, and the Lorentz scaling variable $z = \frac{E_\nu}{\nu}$ which
Figure 3: The different $x_f$ distribution for short and long track events. The short track events are almost symmetric about $x_f = 0$ and are well within the target fragmentation region. The long tracks are mostly at $x_f > 0$ and in the current fragmentation region.

relates $E_{\Lambda}$ to the energy of the virtual photon. The Monte Carlo and data show reasonable agreement with some subtle differences.

5 Future Plans

5.1 Lambda Wheels

Currently there is a proposal to put two round silicon detectors, called Lambda Wheels (LW) downstream of the target before 1999 running. They will be mounted at about 50 cm from the center of the target. Each LW will be two layers with a total thickness of 300 $\mu$m silicon each. The inner radius will be 7 cm and the outer radius 17.5 cm, and an opening angle of
Figure 4: Monte Carlo $\cos \theta_0$ acceptance for short and long track events. The asymmetry from the HERMES acceptance reduces by 25% for the short track events in this group of MC events.

340 mrad. This will increase the detection of mostly large-angle pions which leave the HERMES acceptance. Protons will still be detected in the main HERMES spectrometer.

Simulation was done to test the effectiveness of adding the Lambda Wheels. For this, 32584 unpolarized $\Lambda$ events were generated. Improvements in the number of events detected, mean $x_f$, and $\langle \cos \theta_0 \rangle$ are summarized in Table 3. Overall there is a factor of 4 improvement in statistics, a larger

| Tracks:       | Mean $x_f$ | $\langle \cos \theta_0 \rangle$ | $N_{events}$ |
|---------------|------------|--------------------------------|--------------|
| Long          | 0.1325     | -0.341                         | 4100         |
| Short+Long    | 0.0811     | -0.184                         | 8300         |
| LW+Short+Long | -0.0287    | 0.004                          | 17100        |

Table 3: $x_f$ and $\langle \cos \theta_0 \rangle$ for the events based on their track and detection characteristics.

fraction of events are in the target fragmentation region, and a very good reduction of the acceptance-caused asymmetry in the $\cos \theta_0$ angular distribution.
Figure 5: Comparison of kinematic distributions for data (black circles) and MC (lines) normalized to the total number of events in both data sets. There is reasonable agreement between data and MC.

5.2 Transversely Polarized Target

It is also proposed to have a transversely polarized target. The transverse \( \Lambda \) polarization for a transversely polarized target and unpolarized electron beam is predicted to be\[^7\]:

\[
P^T_\Lambda = \frac{2(1-y)}{1 + (1-y)^2} \frac{\sum q \delta q_N(x, Q^2) \delta D_\Lambda(z, Q^2)}{\sum q \delta N(x, Q^2) \delta D_\Lambda(z, Q^2)}
\]

The \( \delta q_N(x) \) are the transversity difference quark distributions in the nucleon and the \( \delta D_\Lambda(z, Q^2) \) are the \( \Lambda \) transverse fragmentation functions. Using a transverse target will allow us to measure transverse \( \Lambda \) polarization \( P^T_\Lambda \). In addition, it might be possible to measure the transverse structure function \( h_1(x, Q^2) \) via \( \Lambda \) asymmetries\[^12\, ^13\, ^14\].
6 Conclusions

HERMES will extract a preliminary longitudinal $P_\Lambda$ from 1996 and 1997 data in the near future. The expected statistical accuracy for $P_\Lambda$ is about 0.013 for $\sim 2600 \Lambda$’s in each helicity data set. Continuing in 1999, HERMES will increase the $\Lambda$ statistics and explore target fragmentation with the Lambda Wheels. The possibility of running with a transversely polarized target promises more exploration of interesting $\Lambda$ physics.

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