Joint Experimental Theoretical Physics Seminar

Speaker: J. Duryea
University of Minnesota

Topic: “The Polarization and Magnetic Moment of the Cascade Minus Hyperon”

Date: Friday January 17, 1992

Time: 4:00 p.m.

Location: Fermi National Accelerator Laboratory
Wilson Hall
Curia II

-Wine and cheese will be served at 3:45 p.m.-

**PLEASE POST**
A PRECISION MEASUREMENT OF THE POLARIZATION AND MAGNETIC MOMENT OF THE $\Xi^-$ HYPERON

FERMILAB E-756

University of Minnesota

T. Diehl, S. Teige, G. Thomson, Y. Zou
Rutgers University

P. M. Ho, M. J. Longo, A. Nguyen
University of Michigan

C. James, K. B. Luk, R. Rameika
Fermilab

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grad students
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post docs
OUTLINE

(1) History and Theory

(2) Detection Apparatus

(3) Analysis Procedure

(4) Results and Conclusions
Spin polarization and magnetic moments are two related but separate phenomena.

Polarization:

\[ P = \frac{N_{\uparrow}-N_{\downarrow}}{N_{\uparrow}+N_{\downarrow}} \]

Produced in an interaction.

Magnetic moment:

A static property which deals with quark confinement.
FERMILAB E-8 DISCOVERS Λ POLARIZATION*

300 GeV unpolarized proton beam

Polarized Λ's

Be Target

This is not expected!

Subsequently, this method has been used to make polarized Σ's, Ξ's Λ's, and Ξ⁺'s

\[ P = \frac{(f^*g)}{f^2 + g^2} \]

- \( f \)- spin independent part
- \( g \)- spin dependent part

At low energies there are few dominant amplitudes but at high energies there are many.

So why are high energy hyperons polarized?
Kinematic Variables $x_F$ and $p_T$

Inclusive reaction: $p + p \rightarrow \Xi^- + ?$

1) $x_F$:

\[ x_F = \frac{P_L}{P_{L_{\text{max}}}} \text{ defined in c.o.m. frame} \]

\[ x_F \approx \frac{P_{\text{out}}}{P_{\text{beam}}} \text{ (lab) for } x_F > 0.2 \]

2) $p_T$: Transverse momentum

\[ p_T = P_{\text{out}} \sin \theta_P = P_{\text{out}} \theta_P \quad (\sin \theta = \theta) \]

Tells how "hard" the interaction is.
$\Xi^-$ and $\Lambda$ production

Diagram:

```
  p --- STRONG INTERACTION
  |    
  |    
  |    
  p --- STUFF
```

```
  p --- STRONG INTERACTION
  |    
  |    
  |    
  p --- STUFF
```
$\Xi^0$ and $\Xi^-$ production

Models predict $P_{\Xi^-} = P_{\Xi^0}$
What's so special about $P_T = 1 \text{ GeV}$?

$m_p = 0.94 \text{ GeV} \quad m_A = 1.1 \text{ GeV}$
P_{T \pi} data with \( p_T > 1 \text{ GeV} \)
Why measure $\mu_{\Xi}$?

As for any particle, measuring $\mu$ should give some information about its internal structure and interactions.

Also, $\mu_{\text{hyperon}}$ measurements provide a testing ground for theoretical models.
### Broken SU(6) Model

<table>
<thead>
<tr>
<th>Baryon</th>
<th>Quark wave function</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p^+$</td>
<td>$\sqrt{2/3}u\uparrow d\downarrow - \sqrt{1/6} (u\uparrow u\downarrow + u\downarrow u\uparrow) d\uparrow$</td>
</tr>
<tr>
<td>$n^+$</td>
<td>$\sqrt{2/3}d\uparrow u\downarrow - \sqrt{1/6} (d\uparrow d\downarrow + d\downarrow d\uparrow) u\uparrow$</td>
</tr>
<tr>
<td>$\Lambda^+$</td>
<td>$\sqrt{1/2}(u\uparrow d\downarrow - u\downarrow d\uparrow) s\uparrow$</td>
</tr>
<tr>
<td>$\Sigma^+$</td>
<td>$\sqrt{2/3}u\uparrow u\downarrow s\downarrow - \sqrt{1/6} (u\uparrow u\downarrow + u\downarrow u\uparrow) s\uparrow$</td>
</tr>
<tr>
<td>$\Sigma^0$</td>
<td>$\sqrt{2/3}u\uparrow d\downarrow s\uparrow - \sqrt{1/6} (u\uparrow d\downarrow + u\downarrow d\uparrow) s\uparrow$</td>
</tr>
<tr>
<td>$\Sigma^-$</td>
<td>$\sqrt{2/3}d\uparrow d\downarrow s\downarrow - \sqrt{1/6} (d\uparrow d\downarrow + d\downarrow d\uparrow) s\uparrow$</td>
</tr>
<tr>
<td>$\Xi^0$</td>
<td>$\sqrt{2/3}s\uparrow u\downarrow s\uparrow - \sqrt{1/6} (s\uparrow s\downarrow + s\downarrow s\uparrow) u\uparrow$</td>
</tr>
<tr>
<td>$\Xi^-$</td>
<td>$\sqrt{2/3}s\uparrow d\downarrow s\uparrow - \sqrt{1/6} (s\uparrow d\downarrow + s\downarrow d\uparrow) d\uparrow$</td>
</tr>
<tr>
<td>$\Omega^-$</td>
<td>$s\uparrow s\downarrow s\uparrow$</td>
</tr>
</tbody>
</table>

Table 1.1: The baryon SU(6) wave functions.

\[ \mu_i = g_i \frac{e_i}{2m_i c} s_i \]

\[ \mu_B = \langle B | \sum_i \mu_i | B \rangle \]

$\mu_p$, $\mu_n$, and $\mu$ are used as input to get $\nu_3/\nu_4/\nu_5$ (Broken SU(6) and Expt.)

[Diagram of nuclear magnetons showing $\Sigma^+$, $\Sigma^0$, $\Lambda^0$, $\Xi^0$, and $\Omega^-$ hyperons]
More sophisticated models don't do much better.
EVENT TOPOLOGY

\[ \Xi^- \rightarrow \Lambda^0 \pi^- \rightarrow p^+ \pi^- \]
Plan View of the E756 Spectrometer
RUNNING CONDITIONS

1) 5 Sweeper magnet fields. This means 5 different field integral values and momentum spectra.

2) Use both signs of the analyzing magnets.

3) Change targeting angle.
   ± angle
   0 mrad targeting
   horizontal targeting
POLARIZATION ANALYSIS

1) \[ \vec{P}_\Lambda = \frac{(\alpha_\Xi + \hat{\lambda} \cdot \vec{P}_\Xi) \hat{\lambda} + \beta_\Xi (\vec{P}_\Xi \times \hat{\lambda}) + \gamma_\Xi (\hat{\lambda} \times \vec{P}_\Xi) \times \hat{\lambda}}{1 + \alpha_\Xi \hat{\lambda} \cdot \vec{P}_\Xi} \]

2) \[ \frac{dn}{d\cos\theta_i} = \frac{1}{2}(1 + \alpha_\Lambda P_{\Lambda i} \cos\theta_i) \]

\( \theta_i \) is the angle between the axis i and the proton direction in the \( \Lambda \) rest frame.

Additional points:

A) Use the Hybrid Monte Carlo technique to account for the acceptance.

B) Bias cancelation:
\[ A_+ = B + P \]
\[ A_- = B - P \]
\[ P = \frac{A_+ - A_-}{2} \]
\[ B = \frac{A_+ + A_-}{2} \]
MAGNETIC MOMENT ANALYSIS

\[ \Phi = tan^{-1} \left( \frac{P_z}{P_x} \right) = \frac{q}{\beta m_e c^2} \left( \frac{-\mu E m_e}{\mu_N m_p} - 1 \right) \int B dl \]

\[ \beta = 1, \ q = -e \]

\( m_p \) is the mass of the proton
\( \mu_N \) is the nuclear magneton: \((e\hbar/2m_pc)\)

But how can you tell whether \( \vec{\Phi} \) has rotated through an extra 360° or flipped its sign?

\[ \Phi = \Phi \pm n180° \]
RESULTS

1) 4.37 \times 10^6 \Xi^-'s produced with a vertical production angle

2) 229K \Xi^-'s produced with a horizontal production angle of 1.3 mrad

3) 514K \Xi^-'s produced with a 0 mrad production angle
Best fit for $n = 0$
\( \chi^2 \) / d.o.f. = 0.7
(4 d.o.f.)

\( \phi_3^* = -0.6505 \pm 0.025 \text{ nm} \)

\( \chi^2 \) / d.o.f. = 1.3 for 62 d.o.f.
\[ P_T = \Theta \theta \]
Polarization

Momentum (GeV)

-0.15
-0.10
-0.05
0.00

-0.15
-0.10
-0.05
0.00

2.5 mrad
(2.22 M events)
an error of 1° in $\phi$ corresponds to a $d\phi$ of about 0.002
\[ P_y = 0.0005 \pm 0.0011 \]

Since there's no component of \( P \) in the \( y \) view, \( P_y \) should equal zero.
$\psi = K(\nu) \int BDL$

\begin{figure}
\centering
\includegraphics[width=\textwidth]{chart.png}
\end{figure}
$X^2/d.o.f. = 0.9 \rightarrow 9 \text{ d.o.f.}$

$\mu = 0.6516 \pm 0.0070 \text{ nm} \quad (I = -2500 \text{ Amp})$

$\nu = 0.6488 \pm 0.0037 \text{ nm} \quad (I = +2500 \text{ Amp})$

0.6σ
How to compare 800 GeV to 400 GeV results?

\[ x_F = \frac{P}{E} \]

\[ p_T = P\theta \]

so:

\[ p_T = x_F\theta E \]

Hence, if you double E then use \( \frac{\theta}{2} \)
Energy Dependence

![Graph showing energy dependence with data points and error bars for polarization against $p_T$ (GeV/c). Data points indicate $\Xi^-$ at 2.5 mrad and 800 GeV, and $\Xi^-$ at 5.0 mrad and 400 GeV.]
Compare to $P_A$
Compare to \( P_n \)

No \( x_F \) dependence!
Compare to $p_n$

$P_T \geq 1 \text{ GeV}$

![Graph showing polarization versus $x_F$ with data points for $\Xi^-$ (2.5 mrad 800 GeV) and $\Lambda$ (400 GeV).]
$p_{\Xi^-}$ vs. $p_{\Xi^-}$

![Graph showing polarization vs. $x_F$](image)

- $\Xi^-$ (2.5 mrad. @ 800 GeV)
- $\Xi^0$ (3.5 mrad. @ 400 GeV)
- $\Xi^0$ (7.2 mrad. @ 400 GeV)
$P_{\Xi^-}$ vs. $P_{\Xi^0}$

$\Xi^-$ (5.0 mrad. @ 400 GeV)
$\Xi^0$ (3.5 mrad. @ 400 GeV)
$\Xi^0$ (7.2 mrad. @ 400 GeV)
$P_{\Lambda} \text{ vs } P_{\Xi^0}$

3.5 mrad.

![Graph showing polarization versus $p_T$ (GeV/c)]
$P_\Lambda \text{ vs. } P_{\Xi^0}$

7.2 mrad.

![Graph showing polarization vs. $p_T$ (GeV/c)]
$P_\Lambda$ vs. $P_{\Xi^0}$

9.8 mrad.

Polarization vs. $p_T$ (GeV/c)
$P_\gamma$ vs $P_{\Xi^0}$

$P_T > 1$ (GeV)

```
Need to measure $P_{\Xi^0}$ for $x_F > 0.6$
and $P_T > 1$ GeV
```
$P_{\Xi^-} \ vs. \ P_{\Sigma^-}$
$P_{E^-} \ vs. \ P_{Z^-}$

$X_F = 0.65$
Summary of Polarization Results

1) \( P_{\Xi^-} \) is not energy independent.

2) Unlike \( P_\Lambda \), \( P_{\Xi^-} \) is independent of \( x_F \).

3) 800 GeV \( P_{\Xi^-} \) is consistent with 400 GeV \( P_{\Xi^0} \).

4) \( P_\Lambda \) is consistent with \( P_{\Xi^0} \) in the kinematic region where \( P_{\Xi^0} \) is measured. What happens for \( p_T > 1 \text{GeV} \) and \( x_F > 0.6 \)?
MAGNETIC MOMENT RESULT

\[ \mu_{\Xi^{-}} = -0.6505 \pm 0.0025 \text{nm} \]

Best measurement of \( \mu_{\text{hyperon}} \)

Confirms somewhat controversial result. Earlier models predicted \( |\mu_{\Xi^{-}}| < |\mu_{\Lambda}| \).
\( (\mu_{\Lambda} = -0.613 \pm 0.004 \text{nm}) \)

Three magnetic moments are very well measured (< 1% error): \( \mu_{\Xi^{-}}, \mu_{\Lambda}, \) and \( \mu_{\text{proton}} \)

\[ \begin{array}{ccc}
\text{P} & \Lambda & \Xi^{-} \\
\text{uud} & \text{usd} & \text{sds} \\
\end{array} \]
CASCADe MAGNETIC MOMENT

3σ uncertainties

1. De Grand P.R.D. 12 1156 (1978)