Measurement of Magnetic Moments of Charmed Baryons

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Overview

- Magnetic moments and measurements
- Challenges for charmed baryons
- Experimental approach
  - Crystal channeling
  - Requirements
- Count rate estimates
Status and Predictions of Magnetic Moments

- **Basic quantity** characterising fermion
- The case of strange baryons
  - Predictions: $\mu_{\Lambda_c} = 0.3 - 0.5 \mu_N$
  - Mostly: $\mu_{\Lambda_c} \sim 0.37 \mu_N$ and $\mu_{\Lambda_c} \sim 0.42 \mu_N$
  - Predictions: $\mu_{\Xi_c} = 0.3 - 0.8 \mu_N$

<table>
<thead>
<tr>
<th>$B$</th>
<th>$M_{\text{exp}}/\mu_N$</th>
<th>$M_{\text{SU(3)}\text{breaking}}/\mu_N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>$2.793 \pm 0.000$</td>
<td>$2.793$</td>
</tr>
<tr>
<td>$n$</td>
<td>$-1.91 \pm 0.000$</td>
<td>$-1.969$</td>
</tr>
<tr>
<td>$\Lambda$</td>
<td>$-0.613 \pm 0.004$</td>
<td>$-0.604$</td>
</tr>
<tr>
<td>$\Sigma^+$</td>
<td>$2.458 \pm 0.010$</td>
<td>$2.481$</td>
</tr>
<tr>
<td>$\Sigma^0$</td>
<td>$--$</td>
<td>$0.66$</td>
</tr>
<tr>
<td>$\Sigma^-$</td>
<td>$-1.160 \pm 0.025$</td>
<td>$-1.155$</td>
</tr>
<tr>
<td>$\Xi^0$</td>
<td>$-1.250 \pm 0.014$</td>
<td>$-1.274$</td>
</tr>
<tr>
<td>$\Xi^-$</td>
<td>$-0.6507 \pm 0.0025$</td>
<td>$-0.6507$</td>
</tr>
<tr>
<td>$\Sigma^0 - \Lambda$</td>
<td>$\pm 1.61 \pm 0.08$</td>
<td>$1.541$</td>
</tr>
</tbody>
</table>

Good description possible but problems with XPT (loops)

$$\bar{\mu}_Q = \frac{\vec{S} \cdot q \cdot e}{2m_Q}$$
Measurement Technique

• ‘Standard’ method for short lived particles (hyperons)
  – Produce polarized hyperons with high energy proton beams
    • High $x_F$ and high $p_T$ required
    • Polarization observed transverse to production plane
    • Mechanism theoretically not understood but many models
  – Hyperon extraction via magnetic channel
    • Spin precession in guiding B-field

• Spin analysis
  • Use parity violating decays (interference of S- and P-waves in decay amplitudes)
  • Use decays with high analyzing power
    – $\Lambda \to p \pi^- (\alpha = 0.642)$
    – $\Sigma^+ \to p \pi^0 (\alpha = -0.980)$
  – Vary B-field to vary spin precession angle
Challenge for Charmed Particles

- **Lifetime** of charmed baryons small (200-400fs)
  - Flight path \( (c\tau\gamma\beta) \) of \( \Lambda^+_c \sim 0.8\text{cm} \) @300 GeV; 8 cm @3 TeV
  - Flight path \( (c\tau\gamma\beta) \) of \( \Xi^+_c \sim 1.6\text{cm} \) @300 GeV; 16 cm @3 TeV

- **Production** cross section very small
  - \( \sigma(\Lambda_c) \sim 40 \mu\text{b/nucleon} \) \((10^{-3} \sigma_{\text{tot}})\) at 300 GeV
  - \( \sigma(\Lambda_c) \sim 400 \mu\text{b/nucleon} \) \((10^{-2} \sigma_{\text{tot}})\) at 8 TeV) crude extrapolation

- **Polarisation** unknown (except for R608 experiment)

- **Branching ratio** for individual decays small
  - \( \text{BR} \Lambda_c \rightarrow \Lambda\pi^+ \sim 1\pm0.3\% \)
  - Analyzing power large \( (\alpha_{\Lambda\pi} = -0.91\pm0.15) \)
  - \( \text{BR} \Lambda_c \rightarrow \Lambda l^+\nu \sim 2\pm0.6\% \)
  - Analyzing power large \( (\alpha_{\Lambda l^+\nu} = -0.86\pm0.04) \)
  - \( \text{BR} \Lambda_c \rightarrow \Sigma^+\pi^0 \sim 1\pm0.34\% \)
  - Analyzing power large \( (\alpha_{\Sigma\pi} = -0.45\pm0.31) \)

- **Effect** expected to be small: \( \mu_c \sim 0.4 \mu_N \sim \mu_{\Lambda_c} \)
Experimental realization I

- Use channeling to produce high magnetic fields
- Need positively charged particle (scattering off nuclei for -)
- Straight crystal gives NO net E (B) field
- Need bent crystal
- Bending and particle gives effective B-field seen

Channeling for particles with $E_T < E_{crit}$

Channeling in bent crystal:
- Superimpose centrifugal potential
- Lower $E_{crit}$
Spin Rotation for Channeling Particles

- Measurement for charged particles in a static B-field
  - Sensitivity to $g-2$
  - $\Delta \omega = \omega_{\text{Larmor}} - \omega_{\text{cyclotron}}$
  - Typical B-fields: $\int B \cdot dl = 15 \text{ Tm}$

- For channeling in crystal:
  - E-fields: $10^{10}\text{V/cm}$, B-fields $10^3\text{T}$
  - $\int B \cdot dl = 10 \text{ Tm}$ for $l \sim 1\text{cm}$

\[ \Delta \phi_{\text{Spin}} = \frac{1}{2} (g - 2) \cdot \gamma \cdot \Delta \phi_{\text{Bending}} \]
\[ \Delta \phi = [1 - \mu_{\Lambda_c^+} \frac{m_{\Lambda_c^+}}{m_p}] \cdot \gamma \cdot \Delta \phi \]
\[ \Delta \phi_{\text{Spin}} \text{ is } \Box (\text{trajectory, spin}) \]
Experimental Realization

- Assume FNAL realization ($\Sigma^+$): $\Delta\phi_{\text{trajectory}} = 1.6 \text{ mr}$

<table>
<thead>
<tr>
<th>$\mu_c$</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.6</th>
<th>$[\mu_N]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 TeV $\Delta\Phi_{\Lambda c}$</td>
<td>-1500</td>
<td>-784</td>
<td>-73</td>
<td>1350</td>
<td>[mr]</td>
</tr>
<tr>
<td>6 TeV $\Delta\Phi_{\Lambda c}$</td>
<td>-2240</td>
<td>-1176</td>
<td>-110</td>
<td>2020</td>
<td>[mr]</td>
</tr>
</tbody>
</table>

$$d\Delta\phi_{\text{spin}} = \gamma\Delta\phi_{\text{trajectory}} \frac{m_{\Lambda c}}{m_N} \cdot d\mu_{\Lambda c} = 10.6 \cdot d\mu_{\Lambda c} \quad @ \ 6 \text{ TeV}$$

- 5% measurement on $\mu_{\Lambda c} \rightarrow 200\text{ mrad in } \Delta\Phi_{\text{spin}}$
- Wide range of momenta accepted
Count Rates Estimates I

- Assume
  - $8\text{TeV} \ (\hat{\sigma} \ s \sim 120 \ \text{GeV})$
  - $\sigma(\Lambda_c) \sim 400 \ \mu\text{b/nucleon}$
  - $x_F > 0.4 \ \text{and} \ p_T > 0.6 \ \text{GeV}/c \ (\text{as in hyperon polarization})$
  - $10^8 \ \text{p/s} \ (100 \ \text{days})$
  - assume R608 cross section and p spectrum
  - $N_{\Lambda_c} = 4 \ \Lambda_c /s / \%\lambda_1 (\rightarrow \Lambda\pi) \ \tilde{\gamma}10^7 \ \text{s}$
  - assume $L = 8\text{cm}$ for silicon and crystal (decay losses 63%)
  - Channeling efficiency:
    - Crystal height: 1cm
    - Crystal length 4-5cm
    - Crystal width 1mm
    - $\theta_{\text{vert}}: \ \text{no limits}$
    - $\theta_{\text{hori}}: \ \theta < \theta_{\text{crit}} \sim 10\mu\text{rad}$
    - $\varepsilon_{\text{channeling}} \sim 0.01$
Count Rates Estimates II

- Dechanneling (interactions with $e^-$): no problem
- Bending dechanneling (distortions due to jig)
  - $R_{\text{curv}} = 30\text{m}$ with $p \sim 6\text{ TeV}$: $f_{\text{dechannel}} \sim 0.5$

- $S_{\text{acc}}$: Surface acceptance: (channeling/total area: 0.5)
- Total acceptance: $\Delta \Omega \cdot f_{\text{dechannel}} \cdot S_{\text{acc}} \sim 2.5 \times 10^{-3} (\sim 5 \times 10^{-4})$
- $B = 45\text{ Tm}$ (2.5cm length, $\Delta m_{\text{beam}} = 1.6\text{mr}$) at FNAL
- $B \sim 300\text{ Tm}$ (mechanically tried $\rightarrow \Delta m_{\text{beam}} = 12\text{mr}$) at FNAL
- $\Delta x = 3-5\% \lambda_I$
- $N_{\text{total}} \sim 50000 \Lambda_c (\rightarrow \Lambda \pi)$
Set-up and ‘But’s:

- What is the polarization of \( \Lambda_c \)?
- Which final state to take?
  - \( \Lambda_c \rightarrow \Lambda \pi^+ \): flight path of \( \Lambda \) (\( c\tau = 7.8 \text{cm} \)) \( \sim 160 \text{m} \) (low detection efficiency)
  - \( \Lambda_c \rightarrow \Sigma^+ \pi^0 \): flight path of \( \Sigma \) (\( c\tau = 2.4 \text{cm} \)) \( \sim 45 \text{m} \)
  - \( \Lambda_c \rightarrow p K^- \pi^+ \): unknown analyzing power (but good sec. vertex)
  - .......

- Reconstruction efficiency (typical) 5-10%
• How to identify channeled particles
  – Deflection angle (short silicon telescope $\Delta L = 2-3$ cm)
  – Specific (reduced) energy loss in crystal (instrumented silicon crystal)

• Effective number of events: $N_{\Lambda_c}^{\Lambda_c} = N_{\text{tot}}^{\Lambda_c} P^2 \alpha^2$
  – $P(\Lambda_c) = 0.6$ (e.g. Bis-2)
  – $\alpha_{\Lambda_c} \tilde{\gamma} \alpha_{\Lambda} = 0.9 \times 0.64 = 0.57$
  – $\sigma$ for $\Delta \Phi_{\text{Spin}} = 200$ mr $\rightarrow \Delta P/P = 20\%$ ($\mu_{\Lambda_c} = 0.4 \mu_N$) $\rightarrow N_{\text{tot}}^{\Lambda_c} (\Lambda \pi) \sim 350$
Conclusion

- Charged weakly decaying members of charm/beauty baryons can be measured via crystal channeling
  - Charm: $\Lambda_c^+ \quad \Xi_c^+$
  - Beauty $\Xi_b^- \quad \bar{\Xi}_{cb}^+$
- Effect: $\Delta \theta: [-500,500]$mr
- Events needed: few hundred
- Need: very high energy beam (TeV)
  - Short lifetime
  - High effective field (spin precession)
- Cross section and polarization uncertain
- Analyzing power of most interesting channel unknown
- Seems feasible based on present knowledge
- Helps to understand heavy baryons
Estimates of $\mu_c$ from radiative D*-decays

• What do we know about $\mu_c$?
• Lets look at radiative decays

$$R_{\Gamma}^D = \frac{\Gamma_0^0}{\Gamma^+} = \frac{\Gamma(D^*0 \rightarrow D^0 \gamma)}{\Gamma(D^{*+} \rightarrow D^{+} \gamma)} = \left(\frac{E_0^0}{E^+}\right)^3 \left[\frac{\mu_u + \mu_c}{\mu_d + \mu_c}\right]^2$$

- Experiment: $R_{\Gamma}^D > 6$

- Predictions: $R_{\Gamma}^D \sim 12 - 92$ (see e.g. Lepage et al.)

• Agreement: but large uncertainties
References

- S. Paul (1993)  
  Talk given at an LHB meeting (spokesperson G. Carboni)