Hyperon Resonance Studies from Charm Baryon Decays

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Overview

1. Formalism

2. Quasi-two-body $\Lambda_c^+$ decays:
   - Study of the $\Xi(1530)^0$ in the decay $\Lambda_c^+ \rightarrow (\Xi^- \pi^+) K^+$
   - Properties of the $\Xi(1690)^0$ from an isobar model analysis of the $\Lambda_c^+ \rightarrow (\Lambda \bar{K}^0) K^+$ Dalitz plot
     (hep-ex/0607043, SLAC R-868)

3. Summary & Conclusions
Helicity Formalism used in Analysis of Hyperons produced from charm baryon decay

Spin measurement of $\Omega^-$ from $\Xi_c^0 \rightarrow \Omega^- K^+$, $\Omega^- \rightarrow \Lambda K^-$ decays

- Initial helicity, $\lambda_i = \lambda(\Omega) = \pm \frac{1}{2}$
- Final state helicity, $\lambda_f = \lambda(\Lambda) - \lambda(\text{pseudoscalar}) = \pm \frac{1}{2}$
- Decay amplitude for $\Omega^- \rightarrow \Lambda K$: $A_{\lambda_i \lambda_f}^{J_f} = D_{\lambda_i \lambda_f}^{J_f} (\phi, \theta, 0) A_{\lambda_f}$

$$I \propto \frac{1}{2} \sum_{\lambda_i, \lambda_f} \rho_{\lambda_i} \left| A_{\lambda_i \lambda_f}^{J_f} \right|^2 = \frac{1}{2} \sum_{\lambda_i, \lambda_f} \rho_{\lambda_i} \left| D_{\lambda_i \lambda_f}^{J_f} (\phi, \theta, 0) A_{\lambda_f} \right|^2$$

[density matrix element for $\Omega^-$ spin projection $\lambda_i$
$density matrix element for charm baryon parent$]

$\Omega^- \rightarrow \Lambda K$ spin projection $\pm \frac{1}{2}$ only
$\Omega^-$ decay angular dist. different for each assumed spin, $J$

Background-Subtracted
Efficiency-Corrected

$\Xi_c^0$ $\rightarrow$ $\Omega^- K^+$, $\Omega^- \rightarrow \Lambda K^-$ decays

- $J_\Omega = 1/2$ $\Rightarrow I \propto 1$ $\Rightarrow$ Fit Prob $= 10^{-17}$
- $J_\Omega = 3/2$ $\Rightarrow I \propto (1 + 3 \cos^2 \theta)$ $\Rightarrow$ Fit Prob $= 0.64$
- $J_\Omega = 5/2$ $\Rightarrow I \propto (1 - 2 \cos^2 \theta + 5 \cos^4 \theta)$ $\Rightarrow$ Fit Prob $= 10^{-7}$
- $J_\Omega \geq 7/2$ also excluded: angular distribution increases more steeply near $\cos \theta \sim \pm 1$ and has $(2 J_\Omega - 2)$ turning points.
Study of Cascade Resonances Using 3-body $\Lambda_c^+$ Charm Baryon Decays

The $\Xi(1690)^0$ From $\Lambda_c^+ \rightarrow \Lambda \bar{K}^0 K^+$ Decay
Reconstructed $\Lambda_c^+ \rightarrow \Lambda K_S K^+$ Events

Selection Criteria:

- PID Information
  - Proton
  - Kaon
  - $\pi^+$, $\pi^-$
  - dE/dx & Cherenkov info (DIRC)

- 3-$\sigma$ mass cut on intermediate states

- interm.$^d$ states mass-constrained [\(\Lambda \), \(K_S\)]

- $p^*(\Lambda_c^+) > 1.5$ GeV/c (reduces background)

- $L_\Lambda$, $L_{K_S} > +2.0$, +1.0 mm [sign $\Rightarrow$ outgoing]
The $\Xi(1690)^0$ from $\Lambda_c^+ \rightarrow (\Lambda K_S) K^+$ Decay

$\Lambda_c^+$ Low-mass sideband limit

$N \sim 2900$ events

HWHM $\sim (3.1 \pm 0.5)$ MeV/c²

Note skewing

Uncorrected

$\Lambda_c^+ \leftrightarrow \Lambda_c^+$ mass-sideband region

$\Lambda_c^+ \leftrightarrow \Lambda_c^+$ mass-sideband-subtracted

$\Xi(1690)^0 \rightarrow \Lambda K_S$
Using Legendre Polynomial Moments to Obtain $\Xi(1690)$ Spin Information

- efficiency-corrected, background-subtracted unweighted $m(\Lambda K_S)$ distribution in data

$\Xi(1690)^0 \rightarrow \Lambda_c^+ \rightarrow w_j = \sqrt{10} P_2(\cos \theta)$ from $\Lambda_c^+$ signal region

Spin 3/2 Test

Fit Dalitz plot with Spin $\frac{1}{2}$ assumption
Dalitz plot for $\Lambda_c^+ \rightarrow \Lambda K_S K^+$

Accumulation of events in $K_S K^+$ near threshold ⇔ evidence of $a_0(980)^+$

Rectangular Dalitz plot

- Easy background ($\Lambda_c^+$ mass sidebands) parametrization
- Same kinematic variables used for efficiency parametrization

$\text{Phase-space is: } m_c \left( \frac{p}{m_{\Lambda_c}} \frac{q}{m} \right)$

where $p =$ momentum of $K^+$ in $\Lambda_c^+$ rest-frame;
and $q =$ momentum of $\Lambda$ in ($\Lambda K_S$) rest-frame.
Isobar Model Description of the $\Lambda_c^+ \rightarrow \Lambda K^0 K^+$ Dalitz Plot

$$A(\Xi[1690]) = \frac{p^l \cdot q^l}{(m_0^2 - m^2) - im_0\Gamma(m)}$$

$$\Gamma(m) = \Gamma(m_0)\frac{q}{m}m_0^{2l+1}$$

Fit for $m_0$ & $\Gamma(m_0)$ with $L=0$, $l=0$

$$A(a_0[980]) = \frac{g_{\bar{K}K}}{m_a^2 - m_{\bar{K}K}^2 - ig_{\bar{K}K}^2 \left[\rho_{\bar{K}K} + \frac{1}{r^2}\rho_{\eta\pi}\right]}$$

$$m_a = 999 \text{ MeV/}c^2 \quad \rho_j(m) = 2q_j/m \quad r = g_{\bar{K}K}/g_{\eta\pi}$$

Fit for $g_{\bar{K}K}$ & $r$ with $m_a$ fixed

For $J(\Xi[1690]) = 1/2$

$g_{\bar{K}K} = 473 \pm 49 \text{ MeV}$
[BaBar Exp.]

$g_{\eta\pi} = 324 \pm 15 \text{ MeV}$
[Crystal Barrel Exp.]
Comparison of Max. Likelihood Fit Result to the Signal Projections

**BABAR**

- Background-subtracted, efficiency-corrected data
- Integrated signal function **smeared** by mass resolution [Histogram]
- Signal function with no **resolution smearing**
- \(|A(a_{0}(980)|^2\) contribution
- \(|A(\Xi(1690)|^2\) contribution
- **Interference** term contribution

- Excellent reproduction of skewed lineshape and of \(\cos\theta_{\Lambda}\) distribution

Fit \(\chi^2/NDF = 188.4/192\)

Prob. = 56.4%
m(\Lambda K_S) mass cut-off
[1.62 < m(\Lambda K_S) < 1.765 GeV/c^2]
introduces a kink
because of restricted range of (\Lambda K^+) helicity cosine
Fit Results‡ (different relative intensity scale)

‡ no smearing

**Signal function**

- $|A(a_0(980)|^2$ contribution
- $|A(\Xi(1690)|^2$ contribution

**Interference term contribution**

- Region of destructive interference
Comparison of Max. Likelihood Fit Result to the Signal Projections

Under the assumption of spin 3/2 for the $\Xi(1690)$:

- $1.615 < m(\Lambda K_s) < 1.765 \text{ GeV/c}^2$
- $\chi^2/NDF = 234.3/192$
- C. L. = 1.9 %

Under the assumption of spin 5/2 for the $\Xi(1690)$:

- $1.615 < m(\Lambda K_s) < 1.765 \text{ GeV/c}^2$
- $\chi^2/NDF = 210.3/192$
- C. L. = 17.4 %

- Skewing of the lineshape not reproduced
- Net interference term very small $\Rightarrow$ equiv. to incoherent superposition of amplitudes
Model based on coherent superposition of amplitudes describing $\Lambda_c^+$ isobar modes describes the data well.

- $J[\Xi(1690)] = 1/2$ favored by the data (C.L. 56.4%)
- $J[\Xi(1690)] = 3/2$ (C.L. 1.9%) & $5/2$ (C.L. 17.4%) yield poorer fits and systematically fail to reproduce the skewed $\Xi(1690)^0$ lineshape.
The $\Xi(1530)^0$ From $\Lambda_c^+ \rightarrow \Xi^- \pi^+ K^+$ Decay
Reconstructed $\Lambda_c^+ \rightarrow \Xi^- \pi^+ K^+$, $\Xi^- \rightarrow \Lambda \pi^-$ Events

- PID Information
  - Proton
  - Kaon
  - $\pi^+, \pi^-$

- $\Delta E/dx$ & Cherenkov info (DIRC)

- 3-$\sigma$ mass cut on intermediate states
- Intermed. states mass-constrained [$\Lambda, \Xi$]

- $p^* > 2.0$ GeV/c [reduces background].
- $L_\Lambda > 2.0$ mm $r_\Xi > +1.5$ mm [outgoing].

- $m(\Xi^-\pi^+) \leftrightarrow \Lambda_c^+$ mass-signal region
- $m(\Xi^-\pi^+) \leftrightarrow \Lambda_c^+$ mass-sideband region

- $m(\Xi^-\pi^+) \leftrightarrow (\Lambda_c^+)$ mass-sideband-subtracted

### Uncorrected

$N \sim 13800$ events

HWHM $\sim 6$ MeV/c²

### BABAR

Data $\sim 230$ fb⁻¹

### $\Lambda_c^+ \rightarrow \Xi^- \pi^+ K^+$

### $(\Lambda_c^+)$ Mass-sideband-subtracted

$\Xi(1530)^0 \rightarrow \Xi^- \pi^+$

PDG mass

$\tau_{\Lambda_c^+} = 7.9$ cm

$\tau_{\Xi^-} = 60$ $\mu$m

$\tau_{\Xi^-} = 4.9$ cm
Analysis of $\Lambda_c^+ \rightarrow \Xi^- \pi^+ K^+$ to obtain $\Xi(1530)$ spin information

**Only obvious structure:**

$\Xi(1530)^0 \rightarrow \Xi^- \pi^+$

Rectangular Dalitz plot

Note: $m^2(\Xi^- K^+)$ depends linearly on $\cos\theta_\Xi$
Using Legendre Polynomial Moments to Obtain $\Xi(1530)$ Spin Information

Efficiency-corrected unweighted $m(\Xi^- \pi^+)$ distribution in data

$\Xi(1530)^0$

$w_j = \sqrt{10} P_2(\cos \theta)$ from $\Lambda_c^+$ signal region

Spin 3/2 Test

Efficiency-corrected $P_4$ Moment Dist.

$w_j = (7/\sqrt{2}) P_4(\cos \theta)$ from $\Lambda_c^+$ signal region

Spin 5/2 Test

- $P_L$ moments ($L \geq 6$) give no signal
- Spin 3/2 clearly established
- Spin 5/2 ruled out


"Spin-parity 3/2$^+$ is favored by the

Present analysis by establishing $J=3/2$ will also establish positive parity by implication"
Evidence for S-P wave interference in the ($\Xi^- \pi^+$) system produced in the decay $\Lambda_c^+ \rightarrow \Xi^- \pi^+ K^+$

Efficiency-corrected $m(\Xi^- \pi^+)$ distributions weighted by $P_1(\cos \theta)$:

- $\Xi(1530)^0$ signal region
- $\Lambda_c^+$ high mass sidebands
- $\Lambda_c^+$ low mass sidebands

Classic S-P wave interference pattern as a function of $m(\Xi^- \pi^+)$

- Oscillation due to rapid Breit-Wigner P-wave phase motion & slowly varying S-wave phase.

- First clear evidence of $\Xi(1530)^0$ Breit-Wigner phase motion
Evidence for S-P wave interference in the $(\Xi^- \pi^+)$ system produced in the decay $\Lambda_c^+ \to \Xi^- \pi^+ K^+$

Efficiency-corrected $P_1(\cos \theta)$ moment

Background-subtracted Efficiency-corrected $P_0(\cos \theta)$ moment

$\Xi(1530)^0$

$\Xi(1690)^0$

S-wave accelerates & catches up on the P-wave

Speculation:

Dip (~1680 MeV/c$^2$) may be due to resonant $\Xi(1690)^0$

S-wave $\Rightarrow$ negative parity for $\Xi(1690)^0$

$\Xi(1530)^0$ → $\Xi^- \pi^+$ decay rate make sense?
**Ξ(1690)^0 Decay to Ξ^- π^+**

345 GeV/c Σ^- beam on Cu and C


\[ M = 1686 \pm 4 \text{ MeV/c}^2 \]

\[ \Gamma = 10 \pm 6 \text{ MeV} \]

\[ \{ \text{consistent with BaBar values} \}

- This Ξ(1690) decay mode exists

- Product of the production cross section and branching fraction, \( \sigma \cdot BF \), is small compared to that for Ξ(1530)^0:

\[
\frac{\sigma \cdot BF(\Xi(1690)^0 \rightarrow \Xi^- \pi^+)}{\sigma \cdot BF(\Xi(1530)^0 \rightarrow \Xi^- \pi^+)} = (2.2 \pm 0.5)\%
\]
Summary of Results

Assuming that the $\Lambda_c^+$ has spin 1/2:

- used the decay mode $\Lambda_c^+ \rightarrow \Xi^- \pi^+ K^+$
  - to show that the spin of the $\Xi(1530)$ is $3/2$
  - there is some indication that the $\Xi(1690)$ has negative parity

- used the decay mode $\Lambda_c^+ \rightarrow \Lambda K_S^0 K^+$
  - to obtain precise ($M$, $\Gamma$) measurements for the $\Xi(1690)^0$
  - to show that the preferred spin of the $\Xi(1690)$ is $1/2$
Partial wave amplitude description of the \( (\Xi^-\pi^+) \) system produced in the decay \( \Lambda_c^+ \rightarrow \Xi^-\pi^+K^+ \)

Amplitudes of the \( (\Xi^-\pi^+) \) system: \( A_{\lambda_f}^{3/2} (\Xi(1530)) \) & \( A_{\lambda_f}^{1/2} \) (non-resonant)

Angular distribution of the \( \Xi^- \) produced in the decay of the \( (\Xi^-\pi^+) \) system:

\[
\Rightarrow \text{Total Intensity } I = \sum_{\lambda_i = \pm 1/2, \lambda_f = \pm 1/2} \rho_{\lambda_i} \left| D_{\lambda_i \lambda_f}^{1/2*} (\phi, \theta, 0) A_{\lambda_f}^{1/2} + D_{\lambda_i \lambda_f}^{3/2*} (\phi, \theta, 0) A_{\lambda_f}^{3/2} \right|^2
\]

\[\rho_{\lambda_i} \text{ (i = \pm 1/2)} \rightarrow \text{density matrix elements describing the spin population of the } \Lambda_c^+\]

where, \( \lambda_i = \text{helicity of } (\Xi^-\pi^+) \) system = \( \lambda_i(\Lambda_c^+) \)

\( \lambda_f = \lambda_{\Xi^-} - \lambda_{\pi^+} = \lambda_{\Xi^-} \)
\[
I = \sum_{\lambda_1, \lambda_f = \pm \frac{1}{2}} \rho_{\lambda_1} \left| d^{1/2}_{\lambda_1 \lambda_f} (\theta) A^{1/2}_{\lambda_f} + d^{3/2}_{\lambda_1 \lambda_f} (\theta) A^{3/2}_{\lambda_f} \right|^2
\]

\[
= \rho_{1/2} \left[ \left| d^{1/2}_{1/2 1/2} (\theta) A^{1/2}_{1/2} + d^{3/2}_{1/2 1/2} (\theta) A^{3/2}_{1/2} \right|^2 + \left| d^{1/2}_{1/2 -1/2} (\theta) A^{1/2}_{-1/2} + d^{3/2}_{1/2 -1/2} (\theta) A^{3/2}_{-1/2} \right|^2 \right] + \rho_{-1/2} \left[ \left| d^{1/2}_{-1/2 1/2} (\theta) A^{1/2}_{1/2} + d^{3/2}_{-1/2 1/2} (\theta) A^{3/2}_{1/2} \right|^2 + \left| d^{1/2}_{-1/2 -1/2} (\theta) A^{1/2}_{-1/2} + d^{3/2}_{-1/2 -1/2} (\theta) A^{3/2}_{-1/2} \right|^2 \right]
\]

\[
|J M, \lambda_1 \lambda_2 \rangle = \sum_{L,S} \beta_{L \lambda} |J M, L S \rangle; \quad \beta_{L \lambda} = \langle J M, L S | J M, \lambda_1 \lambda_2 \rangle, \text{ where } \lambda_1 = \lambda(\Xi) \text{ and } \lambda_2 = \lambda(\pi) = 0,
\]

\[
= \sqrt{\frac{2L+1}{2J+1}} \langle L, 0; s, \lambda_1 - \lambda_2 | J, \lambda_1 - \lambda_2 \rangle \langle s_1, \lambda_1; s_2, -\lambda_2 | S, \lambda_1 - \lambda_2 \rangle.
\]

\[
\Rightarrow A^{1/2}_{1/2} = |1/2 1/2, 1/2 0\rangle = \frac{1}{\sqrt{2}} \left[ S^{1/2} - P^{1/2} \right]
\]

\[
\Rightarrow A^{-1/2}_{1/2} = |1/2 -1/2, -1/2 0\rangle = \frac{1}{\sqrt{2}} \left[ S^{1/2} + P^{1/2} \right]
\]

\[
\Rightarrow A^{3/2}_{1/2} = |3/2 1/2, 1/2 0\rangle = \frac{1}{\sqrt{2}} \left[ P^{3/2} - D^{3/2} \right]
\]

\[
\Rightarrow A^{-3/2}_{1/2} = |3/2 1/2, 1/2 0\rangle = \frac{1}{\sqrt{2}} \left[ P^{3/2} + D^{3/2} \right]
\]

\[
\frac{dN}{d \cos \theta} = \frac{1}{2} \left[ \left| S^{1/2} \right|^2 + \left| P^{3/2} \right|^2 \right] \left( \frac{1 + 3 \cos^2 \theta}{4} \right) + \sqrt{2} \Re \left( S^{1/2} P^{3/2*} \right) \cos \theta \quad \text{S-P interf.}
\]

\[
\frac{1}{2} \left[ \left| P^{1/2} \right|^2 + \left| D^{3/2} \right|^2 \right] \left( \frac{1 + 3 \cos^2 \theta}{4} \right) + \sqrt{2} \Re \left( P^{1/2} D^{3/2*} \right) \cos \theta \quad \text{P-D interf.}
\]
Amplitude Analysis Assuming S and P Waves

\[
\frac{dN}{d \cos \theta} = \left( \frac{|S^{1/2}|^2 + |P^{1/2}|^2 + |P^{3/2}|^2}{\sqrt{2}} \right) P_0(\cos \theta) + \frac{\sqrt{1/10}}{P_0(\cos \theta)} P_2(\cos \theta)
\]

\[
+ \frac{2}{\sqrt{3}} |S^{1/2}| |P^{3/2}| \cos(\varphi_S - \varphi_P) P_1(\cos \theta)
\]

\(\sqrt{2} P_0(\cos \theta)\) moment

\(\sqrt{10} P_2(\cos \theta)\) moment projects too much signal!!

\(\Rightarrow\) need more than S and P waves
Implication of Fits to the \( \Xi(1530)^0 \) Lineshape

Efficiency-corrected \( P_2(\cos\theta) \) moment

Efficiency-corrected \( P_0(\cos\theta) \) moment

\[
\langle P_2 \rangle = \sqrt{10} \left( |P^{3/2}|^2 + |D^{3/2}|^2 + \frac{8}{7} |D^{5/2}|^2 + \sqrt{20} \Re \left( S^{1/2} D^{5/2} \right) \right)
\]

\[
\langle P_4 \rangle = \frac{\sqrt{2}}{7} |D^{5/2}|^2
\]

Data - Fit

Residuals

Poor fit \( \Rightarrow \) due to interference with other waves?

Effect should disappear in \( P_0(\cos\theta) \) moment distribution

Expected improvement in fit quality not realized

Structure in \( \Xi^- K^+ \) i.e. another isobar? Or \( (K^+\pi^+) \) I=3/2 amplitude contribution?
Possible $\Xi$ Studies with $K_L^0$ Beam

- Possible production of multi-body systems with a $\Xi$, or a $\Xi^*$:

  e.g. $K_L^0 \, p \rightarrow (\Xi^- \pi^+) \, K^+ , \ (\Xi^0 \pi^0) \, K^+$
  $\rightarrow (\Lambda \, K_S^0) \, K^+$

  States analyzed in $\Lambda_c^+$ decay can be observed in different context

  e.g. $K_L^0 \, p \rightarrow \pi^+ \ (\Xi^- \pi^+) \, K^0 , \pi^+ \ (\Xi^- \pi^0) \, K^+$
  $\rightarrow \pi^+ \ (\Xi^0 \pi^-) \, K^+ , \pi^+ \ (\Xi^0 \pi^0) \, K^0$
  $\rightarrow \pi^+ \ (\Lambda \, K^-) \, K^+$
Summary

• Similar studies for Cascade resonance production and associated spectra done at BaBar using charm baryon production can be done at GlueX with $K_L$ beam.

• Three-body systems involving two-body Cascade resonance decays require analysis of the entire Dalitz plot when the statistical level is such that the shortcomings of a quasi-two-body approach become apparent. Therefore it is essential to have high statistics to allow for a proper to fit to the entire Dalitz plot.
BACKUPS
Effect of Constrained Kinematic Fits

LASS: $K^- p \rightarrow \Lambda K_S K_S$

Inclusive $\Lambda$ and $K_S$ studies required flight length $> 2$ cm.

For this exclusive reaction, after kinematic and topological fit, no flight length requirements necessary.

[Nucl.Phys.B 301, 525 (1988)]

Low statistics, but very clean!

$f_0(980) \leftarrow f_2'(1525)$

$a_2(1320)$