CAN K-LONG BEAMS FIND MISSING HYPERON RESONANCES?

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Outline

- Quark Model
- Missing Resonances
- PWA Formalism
- Discussion
- Current Data
- Summary and Conclusions
- Acknowledgments

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Quark Shell Model for Baryons

It is convenient to describe baryons with a "quark shell model" in which each quark moves in a mean field generated mainly by the gluons in the hadron. Lattice gauge calculations have shown that the predicted spectrum of excited states is more-or-less consistent with what is expected from SU(6) symmetry.

In such models, baryons are grouped into three possible SU(6) multiplets:

$$\begin{aligned}\mathbf{56}_S &= {}^2 8 + {}^4 10 \\ \mathbf{70}_M &= {}^2 8 + {}^4 8 + {}^2 10 + {}^2 1 \\ \mathbf{20}_A &= {}^2 8 + {}^4 1\end{aligned}$$

SU(6) Multiplets in the Harmonic-Oscillator Model for Baryons*

$$
\begin{array}{llcl}
N=0 & \psi(\mathbf{56},0^+) & = & (1s)^3 \\
N=1 & \psi(\mathbf{70},1^-) & = & (1s)^2(1p) \\
N=2 & \psi(\mathbf{56},0^+) & = & \sqrt{\frac{2}{3}}(1s)^2(2s)+\sqrt{\frac{1}{3}}(1s)(1p)^2 \\
 & \psi(\mathbf{70},0^+) & = & \sqrt{\frac{1}{3}}(1s)^2(2s)+\sqrt{\frac{2}{3}}(1s)(1p)^2 \\
 & \psi(\mathbf{56},2^+) & = & \sqrt{\frac{2}{3}}(1s)^2(1d)-\sqrt{\frac{1}{3}}(1s)(1p)^2 \\
 & \psi(\mathbf{70},2^+) & = & \sqrt{\frac{1}{3}}(1s)^2(1d)-\sqrt{\frac{2}{3}}(1s)(1p)^2 \\
 & \psi(\mathbf{20},1^+) & = & (1s)(1p)^2
\end{array}
$$

*D. Faiman and A.W. Hendry, PRD **173**, 1720 (1968).

N=3 Baryons

The eight SU(6) multiplets that are allowed in the $N = 3$ band are:

$$\begin{array}{lll}
(\mathbf{56}, 1^-) & (\mathbf{70}, 2^-) & (\mathbf{56}, 3^-) \\
(\mathbf{70}, 1^-) & & (\mathbf{70}, 3^-) \\
(\mathbf{70}, 1^-) & & (\mathbf{20}, 3^-) \\
(\mathbf{20}, 1^-) & &
\end{array}$$

and the allowed shell-model configurations are:

$(1s)^2(2p)$	$L = 1$
$(1s)^2(1f)$	$L = 3$
$(1s)(1p)(2s)$	$L = 1$
$(1s)(1p)(1d)$	$L = 1, 2, 3$
$(1p)^3$	$L = 1, 3$

Splitting Pattern of SU(6) Multiplets*

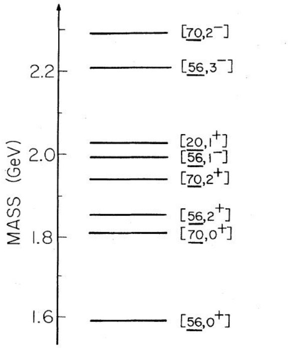

FIG. 1. Splitting pattern caused by the anharmonic perturbation U for the $N=2$ multiplets and some of the $N=3$ multiplets using the parameters of Ref. 7.

*K.C Bowler *et al.*, PRD **24**, 197 (1981).

Discussion

- Pure hyperon states in the $N = 2$ $(\mathbf{20}, 1^+)$ multiplet cannot couple to $\overline{K}N$ via a single-quark transition operator. They will not be considered further.
- Pure hyperon states in the $N = 3$ $(\mathbf{20}, 1^-)$, $(\mathbf{70}, 2^-)$, and $(\mathbf{20}, 3^-)$ multiplets cannot couple to $\overline{K}N$ via a single-quark transition operator. They will not be considered further.
- The next several slides compare experimental observations with predictions for low-lying states in the other multiplets (not including $N = 3$)

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N=0 ($\mathbf{56}$,0$^+$) Ground-State Baryons

^{2}8	$N(939)$	****
1/2$^+$	$\Lambda(1116)$	****
	$\Sigma(1193)$	****
	$\Xi(1322)$	****

^{4}10	$\Delta(1232)$	****
3/2$^+$	$\Sigma(1385)$	****
	$\Xi(1530)$	****
	$\Omega(1672)$	****

N=1 $(\mathbf{70},1^-)$ Negative-Parity Excited States

$^{2}8$	$N(1535)$	****	
$1/2^-$	$\Lambda(1670)$	****	
	$\Sigma(1620)$	*	
	$\Xi(1690)$	***	spin-parity undetermined

$^{2}8$	$N(1520)$	****
$3/2^-$	$\Lambda(1690)$	****
	$\Sigma(1670)$	****
	$\Xi(1820)$	***

N=1 $(\mathbf{70},1^-)$ Negative-Parity Excited States

$^4 8$	$N(1650)$	****	
$1/2^-$	$\Lambda(1800)$	***	
	$\Sigma(1750)$	***	
	$\Xi(1950)$	***	spin-parity undetermined

$^4 8$	$N(1700)$	***	
$3/2^-$	Λ		
	Σ		
	Ξ		

$^4 8$	$N(1675)$	****	
$5/2^-$	$\Lambda(1830)$	****	
	$\Sigma(1775)$	****	
	$\Xi(2030)$	***	spin-parity undetermined

N=1 $(\mathbf{70},1^-)$ Negative-Parity Excited States

^{2}10	Δ(1620)	****	^{2}1	Λ(1405)	****
1/2⁻	Σ		1/2⁻		
	Ξ				
	Ω				
^{2}10	Δ(1700)	****	^{2}1	Λ(1520)	****
3/2⁻	Σ(1940)	***	3/2⁻		
	Ξ				
	Ω				

N=2 ($\mathbf{56}$,0^+) Positive-Parity Excited States

^{2}8	$N(1440)$	****
$1/2^+$	$\Lambda(1600)$	***
	$\Sigma(1660)$	***
	Ξ	

^{4}10	$\Delta(1600)$	***
$3/2^+$	Σ	
	Ξ	
	Ω	

N=2 ($\mathbf{56}$,2^+) Positive-Parity Excited States

^{2}8	$N(1720)$	****
$3/2^+$	$\Lambda(1890)$	****
	Σ	
	Ξ	

^{2}8	$N(1680)$	****
$5/2^+$	$\Lambda(1820)$	****
	$\Sigma(1915)$	****
	Ξ	

N=2 (**56**,2^+) Positive-Parity Excited States

$^4 10$	$\Delta(1910)$	****	$^4 10$	$\Delta(1920)$	***
$1/2^+$	Σ		$3/2^+$	Σ	
	Ξ			Ξ	
	Ω			Ω	

$^4 10$	$\Delta(1905)$	***	$^4 10$	$\Delta(1950)$	****
$5/2^+$	Σ		$7/2^+$	$\Sigma(2030)$	****
	Ξ			Ξ	
	Ω			Ω	

N=2 ($\mathbf{70}$,0^+) Positive-Parity Excited States

^{2}8	$N(1710)$	***	^{4}8	N		
$1/2^+$	$\Lambda(1810)$	***	$3/2^+$	Λ		
	$\Sigma(1880)$	**		Σ		
	Ξ			Ξ		
^{2}10	$\Delta(1750)$	*	^{2}1	$\Lambda(1710)$	*	
$1/2^+$	Σ		$1/2^+$			
	Ξ					
	Ω					

N=2 ($\mathbf{70}$,2^+) Positive-Parity Excited States

^{4}8	$N(1880)$	**	^{4}8	$N(1900)$	***
$1/2^+$	Λ		$3/2^+$	Λ	
	Σ			Σ	
	Ξ			Ξ	
^{4}8	$N(2000)$	**	^{4}8	$N(1990)$	**
$5/2^+$	Λ		$7/2^+$	$\Lambda(2020)$	*
	Σ			Σ	
	Ξ			Ξ	

N=2 ($\mathbf{70}$,2^+) Positive-Parity Excited States

^{2}8	N	^{2}8	$N(1860)$	**
$3/2^+$	Λ	$5/2^+$	Λ	
	Σ		Σ	
	Ξ		Ξ	
^{2}10	Δ	^{2}10	$\Delta(2000)$	**
$3/2^+$	Σ	$5/2^+$	Σ	
	Ξ		Ξ	
	Ω		Ω	
^{2}1	Λ	^{2}1	$\Lambda(2110)$	***
$3/2^+$		$5/2^+$		

Summary of Missing Resonances

(one-star states are included as "missing")

	$N = 0$	$N = 1$	$N = 2$
N	0	0	2
Δ	0	0	2
Λ	0	1	9
Σ	0	3	15
Ξ	0	3	19
Ω	0	2	8

PWA Formalism

- Here, we summarize some of the physics issues involved with $K_L^0 p$ scattering.
- The differential cross section and polarization for $K_L^0 p$ scattering are given by

$$\frac{d\sigma}{d\Omega} = \lambda\!\!\!^{-2}(|f|^2 + |g|^2),$$

$$P\frac{d\sigma}{d\Omega} = 2\lambda\!\!\!^{-2}\mathrm{Im}(fg^*),$$

where $\lambda\!\!\!^{-} = \hbar/k$, with k the magnitude of c.m. momentum for the incoming meson. Here $f = f(W, \theta)$ and $g = g(W, \theta)$ are the usual spin-nonflip and spin-flip amplitudes at c.m. energy W and meson c.m. scattering angle θ.

Partial-Wave Expansion

- In terms of partial waves, f and g can be expanded as

$$f(W,\theta) = \sum_{l=0}^{\infty}[(l+1)T_{l+} + lT_{l-}]P_l(\cos\theta),$$

$$g(W,\theta) = \sum_{l=1}^{\infty}[T_{l+} - T_{l-}]P_l^1(\cos\theta).$$

- Here l is the initial orbital angular momentum, $P_l(\cos\theta)$ is a Legendre polynomial, and $P_l^1(\cos\theta) = \sin\theta \times dP_l(\cos\theta)/d(\cos\theta)$ is an associated Legendre function.
- The total angular momentum for T_{l+} is $J = l + \frac{1}{2}$, while that for T_{l-} is $J = l - \frac{1}{2}$.

Isospin Amplitudes

- We may ignore small CP-violating terms and write

$$K_L^0 = \frac{1}{\sqrt{2}}(K^0 - \overline{K^0}),$$

$$K_S^0 = \frac{1}{\sqrt{2}}(K^0 + \overline{K^0}).$$

- We have both $I = 0$ and $I = 1$ amplitudes for KN and $\overline{K}N$ scattering, so that amplitudes $T_{l\pm}$ can be expanded in isospin amplitudes as

$$T_{l\pm} = C_0 T_{l\pm}^0 + C_1 T_{l\pm}^1,$$

where $T_{l\pm}^I$ are partial-wave amplitudes with isospin I and total angular momentum $J = l \pm \frac{1}{2}$, with C_I the appropriate isospin Clebsch-Gordon coefficients.

Isospin Amplitudes (cont'd)

$$
\begin{aligned}
T(K_L^0 p \to K_S^0 p) &= \frac{1}{2}\left(\frac{1}{2}T^1(KN \to KN) + \frac{1}{2}T^0(KN \to KN)\right) \\
&- \frac{1}{2}T^1(\overline{K}N \to \overline{K}N) \\
T(K_L^0 p \to \pi^+\Lambda) &= -\frac{1}{\sqrt{2}}T^1(\overline{K}N \to \pi\Lambda) \\
T(K_L^0 p \to \pi^+\Sigma^0) &= -\frac{1}{2}T^1(\overline{K}N \to \pi\Sigma) \\
T(K_L^0 p \to \pi^0\Sigma^+) &= \frac{1}{2}T^1(\overline{K}N \to \pi\Sigma) \\
T(K_L^0 p \to K^+\Xi^0) &= -\frac{1}{\sqrt{2}}T^1(\overline{K}N \to K\Xi)
\end{aligned}
$$

Discussion

- Only Σ^* resonances are formed as intermediate states in $K_L^0 p$ reactions.
- $K_L^0 p \to K_S^0 p$ is not ideal for finding missing Σ^* states that couple weakly to $\overline{K}N$ because of nonresonant KN background and because amplitude involves $\overline{K}N$ in both initial and final states.
- The inelastic 2-body reactions that can be studied with a K_L^0 beam would be better probes for finding missing Σ^* states due to isospin selectivity, absence of nonresonant KN background, and fact that their amplitudes only involve $\overline{K}N$ coupling in initial state.

Discussion

- To search for missing Σ^* states that couple weakly to $\overline{K}N$, use production reactions such as $K_L^0 p \to \pi^+\Sigma^{0*}$, with $\Sigma^{0*} \to \pi^0\Lambda$, or use $K_L^0 p \to \pi^0\Sigma^{+*}$, with $\Sigma^{+*} \to \pi^+\Lambda$. (Note that the $\pi\Lambda$ decays establish Σ^* states $(I = 1)$ uniquely.)
- To search for missing Λ^* states that couple weakly to $\overline{K}N$, use production reactions such as $K_L^0 p \to \pi^+\Lambda^*$, with $\Lambda^* \to \pi^+\Sigma^-$, $\Lambda^* \to \pi^-\Sigma^+$, or $\Lambda^* \to \pi^0\Sigma^0$. (Note that the $\pi^0\Sigma^0$ decays establish Λ^* states $(I = 0)$ uniquely.)
- To search for missing Ξ^* or Ω^* states, use production reactions such as $K_L^0 p \to K^+\Xi^{0*}$, $K_L^0 p \to \pi^+K^+\Xi^{-*}$, and $K_L^0 p \to K^+K^+\Omega^{-*}$.

$d\sigma/d\Omega$ Data for $K_L^0 p \to K_S^0 p$

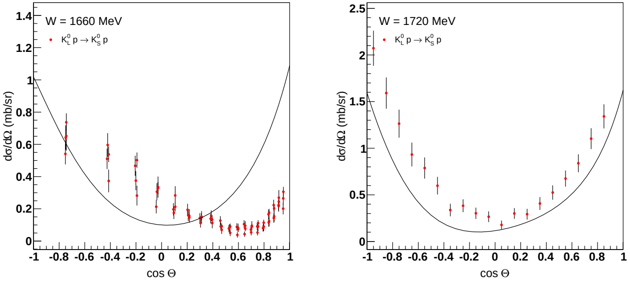


Figure: Selected data for $K_L^0 p \to K_S^0 p$ at 1660 MeV and 1720 MeV. The curves are predictions using amplitudes from our previous PWA of $\overline{K}N \to \overline{K}N$ combined with $KN \to KN$ amplitudes from SAID solution.

Discussion

- $K^- p \to \pi^0 \Lambda$ and $K_L^0 p \to \pi^+ \Lambda$ amplitudes imply that their observables measured at same energy should be identical except for small differences due to isospin-violating mass differences in the hadrons.
- At 1540 MeV and higher, $d\sigma/d\Omega$ and polarization data for the two reactions are in fair agreement, as shown in the following slides.

$d\sigma/d\Omega$ Data for $K^- p \to \pi^0 \Lambda$ and $K_L^0 p \to \pi^+ \Lambda$

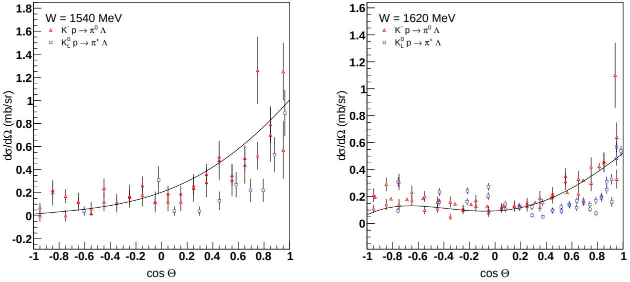
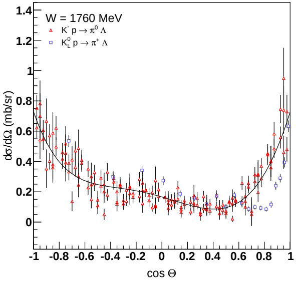


Figure: Comparison of selected $d\sigma/d\Omega$ data for $K^- p \to \pi^0 \Lambda$ (red) and $K_L^0 p \to \pi^+ \Lambda$ (blue) at 1540 MeV and 1620 MeV. The curves are from our previous PWA of $K^- p \to \pi^0 \Lambda$ data.

$d\sigma/d\Omega$ Data for $K^-p \to \pi^0\Lambda$ and $K^0_Lp \to \pi^+\Lambda$



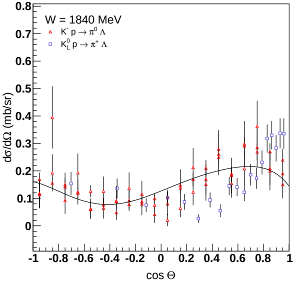


Figure: Comparison of selected $d\sigma/d\Omega$ data for $K^-p \to \pi^0\Lambda$ (red) and $K^0_Lp \to \pi^+\Lambda$ (blue) at 1760 MeV and 1840 MeV. The curves are from our previous PWA of $K^-p \to \pi^0\Lambda$ data.

Polarization Data for $K^- p \to \pi^0 \Lambda$ and $K^0_L p \to \pi^+ \Lambda$

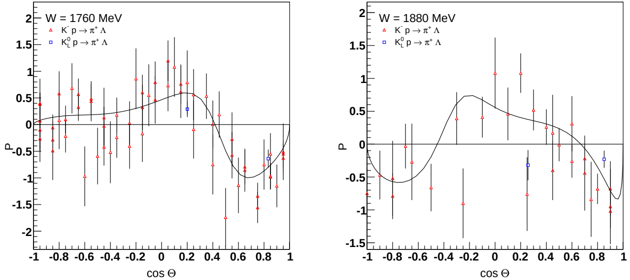


Figure: Comparison of selected polarization data for $K^- p \to \pi^0 \Lambda$ (red) and $K^0_L p \to \pi^+ \Lambda$ (blue) at 1760 MeV and 1880 MeV. The curves are from our previous PWA of $K^- p \to \pi^0 \Lambda$ data.

Discussion

- Reactions $K_L^0 p \to \pi^+ \Sigma^0$ and $K_L^0 p \to \pi^0 \Sigma^+$ are isospin selective (only $I = 1$ amplitudes are involved) whereas reactions $K^- p \to \pi^- \Sigma^+$ and $K^- p \to \pi^+ \Sigma^-$ are not. New measurements with a K_L^0 beam would lead to better understanding of Σ^* states and help constrain amplitudes for $K^- p \to \pi \Sigma$ reactions

Discussion

- Threshold for $K^- p$ and $K^0_L p$ reactions leading to $K\Xi$ final states is fairly high ($W_{\text{thresh}} = 1816$ MeV)
- There are no $d\sigma/d\Omega$ data available for $K^0_L p \to K^+ \Xi^0$ and very few (none recent) for $K^- p \to K^0 \Xi^0$ or $K^- p \to K^+ \Xi^-$
- Measurements for these reactions would be very helpful, especially for comparing with predictions from dynamical coupled-channel (DCC) models
- $K^0_L p \to K^+ \Xi^0$ is isospin-1 selective, whereas the reactions $K^- p \to K^0 \Xi^0$ and $K^- p \to K^+ \Xi^-$ involve both $I = 0$ and $I = 1$ amplitudes

Summary and Conclusions

- New data for inelastic $K_L^0 p$ scattering would significantly improve our knowledge of Σ^* Resonances
- Very few polarization data are available for any $K_L^0 p$ reactions but are needed to help remove ambiguities in PWAs
- To search for missing hyperon resonances, we need measurements of production reactions:

$$\begin{array}{ll} \Sigma^*: & K_L^0 p \to \pi\Sigma^* \to \pi\pi\Lambda \\ \Lambda^*: & K_L^0 p \to \pi\Lambda^* \to \pi\pi\Sigma \\ \Xi^*: & K_L^0 p \to K\Xi^*, \pi K\Xi^* \\ \Omega^*: & K_L^0 p \to K^+K^+\Omega^* \end{array}$$

- If such measurements can be performed with good energy & angle coverage & good statistics, then it is very likely that measurements with K_L^0 beams would find several missing hyperon resonances.

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  Ξ^*: $K_L^0 p \to K\Xi^*, \pi K\Xi^*$

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