HYPERON SPECTROSCOPY WITH A K_L BEAM

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Quark Model
Missing Resonances
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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 QCD calculations have shown that the predicted spectrum of excited states is *not arbitrary*; instead it 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:

$$\begin{array}{ll}
(1s)^2(2p) & L = 1 \\
(1s)^2(1f) & L = 3 \\
\hline
(1s)(1p)(2s) & L = 1 \\
(1s)(1p)(1d) & L = 1, 2, 3 \\
\hline
(1p)^3 & L = 1, 3
\end{array}$$

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				

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

^{4}10	Δ(1910)	****	^{4}10	Δ(1920)	***
$1/2^+$	Σ		$3/2^+$	Σ	
	Ξ			Ξ	
	Ω			Ω	

^{4}10	Δ(1905)	***	^{4}10	Δ(1950)	****
$5/2^+$	Σ		$7/2^+$	Σ(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-Gordan 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.
- $K_L^0 p \rightarrow K_S^0 p$ 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 $K_L^0 p \to K_S^0 p$

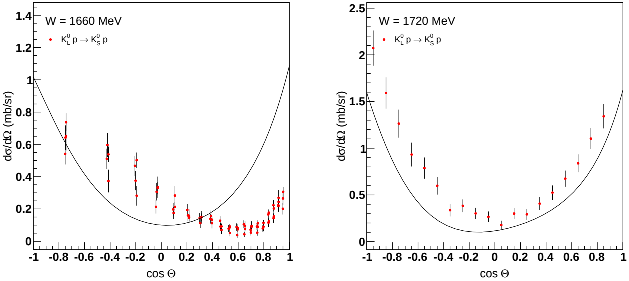


Figure: Selected data for $K_L^0 p \to K_S^0 p$ at 1660 MeV and 1720 MeV. The curves are predictions using amplitudes from our previous PWA of $\overline{K}N \to \overline{K}N$ combined with $KN \to KN$ amplitudes from SAID solution.

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 $K^0_Lp \to \pi^+\Lambda$

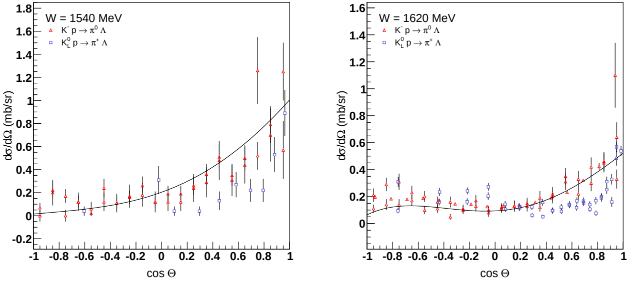


Figure: Comparison of selected $d\sigma/d\Omega$ data for $K^-p \to \pi^0\Lambda$ (red) and $K^0_Lp \to \pi^+\Lambda$ (blue) at 1540 MeV and 1620 MeV. The curves are from our previous PWA of $K^-p \to \pi^0\Lambda$ data.

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

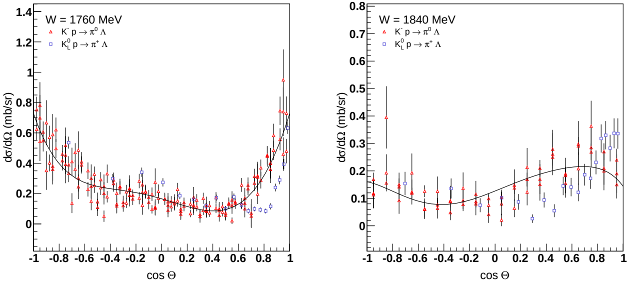


Figure: Comparison of selected $d\sigma/d\Omega$ data for $K^- p \rightarrow \pi^0 \Lambda$ (red) and $K^0_L p \rightarrow \pi^+ \Lambda$ (blue) at 1760 MeV and 1840 MeV. The curves are from our previous PWA of $K^- p \rightarrow \pi^0 \Lambda$ data.

Polarization Data for $K^{-}p \rightarrow \pi^{0}\Lambda$ and $K_L^0 p \rightarrow \pi^{+}\Lambda$

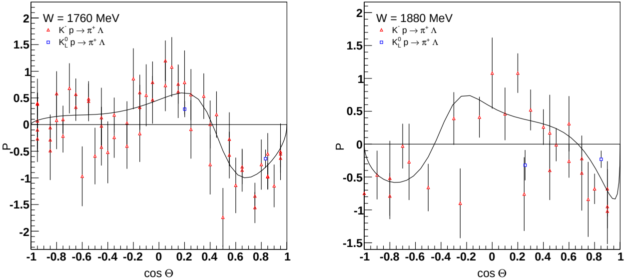


Figure: Comparison of selected polarization data for $K^{-}p \rightarrow \pi^{0}\Lambda$ (red) and $K_L^0 p \rightarrow \pi^{+}\Lambda$ (blue) at 1760 MeV and 1880 MeV. The curves are from our previous PWA of $K^{-}p \rightarrow \pi^{0}\Lambda$ data.

Overview of Experimental Database

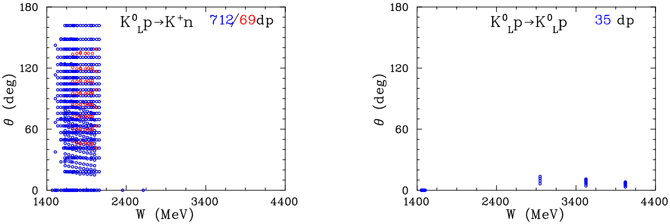


Figure: Experimental data available for $K^0_L p \to K^+ n$ and $K^0_L p \to K_L p$ as a function of c.m. energy W. The number of data points (dp) is given in the RHS of each subplot; blue (red) shows amount of unpolarized (polarized) observables. Total cross sections are plotted at $0°$.

Overview of Experimental Database (Cont'd)

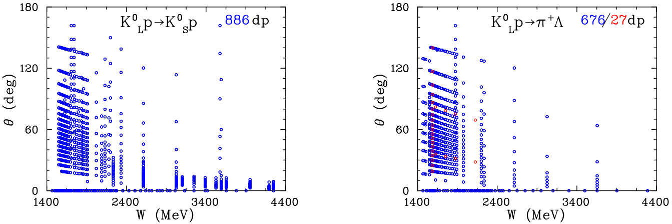


Figure: Experimental data available for $K^0_L p \to K^0_S p$ and $K^0_L p \to \pi^+ \Lambda$ as a function of c.m. energy W. The number of data points (dp) is given in the RHS of each subplot; blue (red) shows amount of unpolarized (polarized) observables. Total cross sections are plotted at 0°.

Overview of Experimental Database (Cont'd)

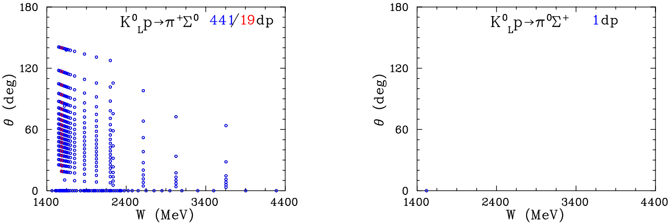


Figure: Experimental data available for $K_L^0 p \to \pi^+\Sigma^0$ and $K_L^0 p \to \pi^0\Sigma^+$ as a function of c.m. energy W. The number of data points (dp) is given in the RHS of each subplot; blue (red) shows amount of unpolarized (polarized) observables. Total cross sections are plotted at $0°$.

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 $K_L^0 p$ measurements would lead to better understanding of Σ^* states and help constrain amplitudes for $K^- p \to \pi\Sigma$ reactions.
- Similarly, $K_L^0 n$ measurements, combined with $K_L^0 p$ data, would improve our knowledge of Λ^* states. The existing $K_L^0 n$ database is nonexistent.

Discussion

- Threshold for K^-p and K_L^0p 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 $K_L^0p \to K^+\Xi^0$ 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
- $K_L^0p \to K^+\Xi^0$ 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

Expected $K_L p \to K_S p$ Results

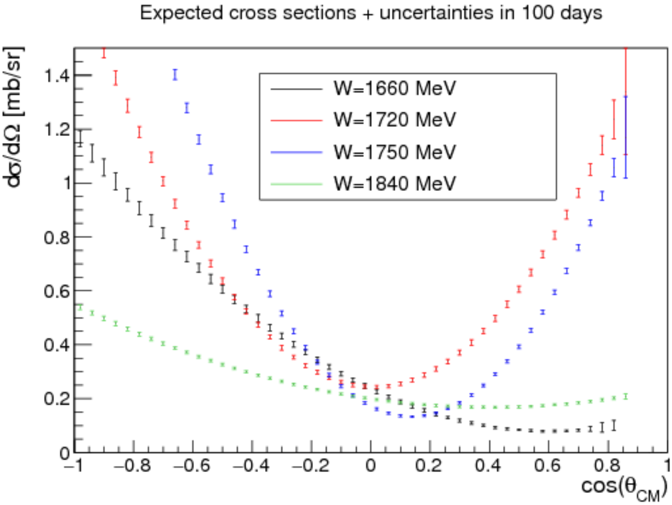


Figure: Reconstructed $K_L p \to K_S p$ $d\sigma/d\Omega$ values for various values of W for 100 days of running.

Ratios of Uncertainties in PW Amplitudes

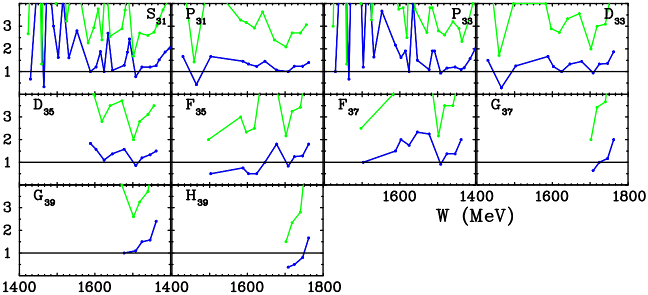


Figure: Ratios of uncertainties of single-energy PW amplitudes of proposed data for 20 days (green) and 100 days (blue) of running based on analogous PWA of $\pi^+ p \to \pi^+ p$ vs. single-energy solutions associated with SAID WI14 solution (a fit of the world database).

Impact of Proposed Data on SAID SES

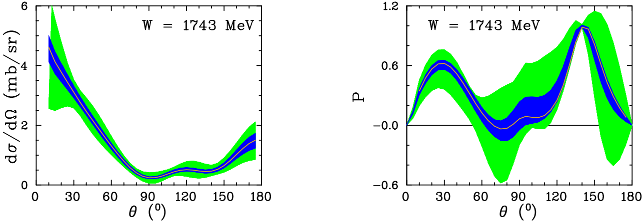
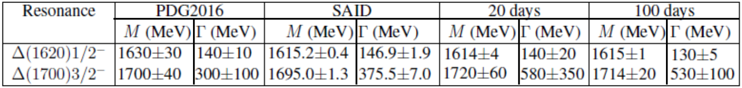


Figure: Two examples ($W = 1743$ MeV) showing impact of proposed data on SAID single-energy solutions. The green band indicates expected uncertainties for 20 days and the blue band for 100 days of running. The solid curve corresponds to the SAID WI14 solution.

Expected Precision of Resonance Parameters



Resonance	PDG2016		SAID		20 days		100 days	
	M (MeV)	Γ (MeV)	M (MeV)	Γ (MeV)	M (MeV)	Γ (MeV)	M (MeV)	Γ (MeV)
$\Delta(1620)1/2^-$	1630±30	140±10	1615.2±0.4	146.9±1.9	1614±4	140±20	1615±1	130±5
$\Delta(1700)3/2^-$	1700±40	300±100	1695.0±1.3	375.5±7.0	1720±60	580±350	1714±20	530±100

Figure: $S_{31}(1620)$ and $D_{33}(1700)$ Breit-Wigner parameters from PDG 2016 and SAID WI14 compared with corresponding values expected for 20 and 100 days of running time.

Summary and Conclusions

- New data for inelastic $K_L^0 p$ scattering would greatly improve our knowledge of Σ^* resonances. Measurements on a neutron target would similarly improve our knowledge of Λ^* 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 will carry out measurements of production reactions:

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

- Measurements with K_L^0 beams performed with good energy & angle coverage & good statistics would likely find several missing hyperon resonances.

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

  Ω^*: $K_L^0p \to K^+K^+\Omega^*$
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- Measurements with K_L^0 beams performed with good energy & angle coverage & good statistics would likely find several missing hyperon resonances.

Summary and Conclusions

- New data for inelastic $K_L^0 p$ scattering would greatly improve our knowledge of Σ^* resonances. Measurements on a neutron target would similarly improve our knowledge of Λ^* 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 will carry out measurements of production reactions:

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Summary and Conclusions (Cont'd)

- With 100 days of running time, we can provide reliable solution for all resonances having elastic branching ratios larger than 4%, at least up to $\ell = 4$. With 20 days of beamtime, we could only carry out simple "bump hunting".
- From our $\pi^+ p$ PWA study, we can conclude that the precision of resonance parameters extracted from PWAs of KLF data for the higher-mass Λ^* and Σ^* states that we propose to measure will deteriorate w/o sufficient running time. The spectrum of these states is expected to be densely populated with typical mass differences of about 100 MeV for states with the same quantum numbers; therefore, 100 days of beam time is needed to obtain the precision to disentangle the spectrum of observed hyperon states.

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