Hyperon Photoproduction: What Has Been Learned at Jefferson Lab?

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for the CLAS & GlueX Collaborations

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Strangeness and the N* spectrum of states
- \( \Lambda \) & \( \Sigma \) photo- and electro-production spin observables

Dimensional scaling of \( K\Lambda \) photoproduction
- Constituent-counting rule supported

Excited \( Y^* \) cross sections measured at CLAS
- \( \Sigma^0(1385) \) \((J^P = 3/2^+)\); \( \Lambda(1405) \) \((J^P = 1/2^-)\); \( \Lambda(1520) \) \((J^P = 3/2^-)\)

Structure of the \( \Lambda(1405) \): \( \Sigma \pi \) line shapes; \( J^P \)
- Support for chiral unitary models: 2-pole structure

Strangeness suppression in exclusive electro-production
- Low and high energy reactions similar behavior

Outlook at GlueX and CLAS12
Jefferson Lab

- Located in Newport News, Virginia
- Ran for ~14 yrs at 6 GeV in Halls A, B, C
- Upgrading to 12 GeV, new Hall D

- Most $Y, Y^*$ publications from Hall B
  - Upgrading as CLAS12 for 12 GeV
CLAS Experiment
Photoproduction:
- Targets: unpolarized LH$_2$, polarized p, & HD-ice
- Beams: unpolarized, circular, linear, to ~5 GeV
- Reconstructed $K^+ p \pi^- (\pi^0)$ or $K^+ \pi^+ \pi^- (n)$
- 20x10$^9$ triggers $\rightarrow$ 1.41x10$^6$ KY$\pi$ events in g11a

Electroproduction:
- $Q^2$ from ~0.5 to ~3 (GeV/c)$^2$
- Structure functions from Rosenbluth and beam-helicity separations
Strangeness and the N* Spectrum of States - Photoproduction
Strangeness in $N^*$ Physics: Status

What role has JLab strangeness physics in unraveling $N^*$ and $\Delta$ properties?

Worldwide effort to determine resonance poles, branching fractions, helicity couplings, etc.

Bottom line: “Stars” & new resonances added to world database

Define the Spin Observables
(for unpolarized nucleon)

\[
\begin{align*}
\frac{d\sigma}{d\Omega} &= \sigma_0 \left\{ \begin{array}{l}
1 - P_{y\Sigma} \cos 2\phi \\
- \alpha \cos \theta_{x'} \sin 2\phi P_{y} O_{x'} - \alpha \cos \theta_{x'} P_{\perp} C_{x'} \\
- \alpha \cos \theta_{z'} \sin 2\phi P_{y} O_{z'} - \alpha \cos \theta_{z'} P_{\perp} C_{z'} \\
+ \alpha \cos \theta_{y'} P - \alpha \cos \theta_{y'} P_{T} \cos 2\phi
\end{array} \right. 
\end{align*}
\]
Pseudoscalar Meson Photoproduction

4 Complex amplitudes: **16** real polarization observables.

Complete measurement with at least **8** suitably chosen observables.

\( \pi N \) has large cross section but in \( KY \) recoil is **self-analysing**

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<th>Transversity representation</th>
<th>Experiment required</th>
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Theory: Bonn Gatchina Model

(Just one of several models on the market)

- **Coupled channels (K-matrix) framework**
  - **Input:** from $\pi N$, $K N$ elastic; $\gamma N$, $\pi N$ inelastic to $\pi^{\pm 0} N$, $\eta N$, $\eta' N$, $K^{\pm 0} Y$, $\pi \pi N$
    - Use ALL experimental channels, including the strangeness channels & spin observables

- **Partial Wave Analysis**
  - First extract each $J^P$ wave
  - Fit $N^*$ and $\Delta$ resonance pole parameters

---

Short list of References:
\[ \gamma p \rightarrow K^+ \Lambda: \text{cross section} \]

Forward peaking indicates t-channel processes at high \( W \)

Angular dependence at lower \( W \) consistent with s- and u-channel processes.
\[ \gamma^*_{K^+} \gamma p \rightarrow K^+ \Lambda : \text{recoil polarization} \]

- Kaon-MAID model (green)
  - Single-channel BW resonance fits
  - No longer up-to-date

- Bonn-Gatchina model (blue)
  - Multi-channel, unitary, BW resonance fit
  - Large suite of N* contributions
  - Was not predictive for recoil polarization

\( \gamma K^+ \rightarrow p K^+ \Lambda : \text{beam asymmetry } \Sigma \)
$\gamma^*_{K^+} \gamma p \rightarrow K^+ \Lambda : target\ asymmetry\ T$

$\gamma + p \rightarrow K^+ \Lambda$

Bonn-Gatchina model is not predictive in newly-measured kinematics.

CLAS/Glasgow Preliminary

R. A. Schumacher, Carnegie Mellon University
The Bonn-Gatchina model is not predictive at newly-measured kinematics.
$\gamma^*K^+ \rightarrow p \rightarrow K^+\Lambda$ Beam-Recoil $C_x$ and $C_z$

- Nikanov et al.'s refit of Bonn-Gatchina coupled-channel isobar model
  - mix includes: $S_{11}$-wave, $P_{13}(1720)$, $P_{13}(1900)$, $P_{11}(1840)$
  - $K^+\Sigma^0$ cross sections also better described with $P_{13}(1900)$

$C_x, C_z$ without $N^*(1900) P_{13}$

$C_x, C_z$ with $N^*(1900) P_{13}$

### Seeking New $S=0$ Baryons via Mesons off the Proton:

**published, acquired, FroST(g9b)**

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Source: V. D. Burkert
Lots more could be said...

- Omit results for $\Sigma$ photoproduction
- Omit discussion of reactions on the neutron (deuteron), which accesses photon coupling isospin dependence.
- Overall goal: measure enough observables for “complete” determination of amplitudes $\Rightarrow$ extract $N^*$ and $\Delta$ content
Strangeness and the N* Spectrum of States - Electroproduction
Structure Functions

For unpolarized target & polarized e beam:

\[ \frac{d^4\sigma}{dQ^2 dW d\Omega_K} = \Gamma(Q^2, W) \times \frac{d\sigma}{d\Omega_K}(Q^2, W, \Theta_K, \varepsilon, \phi) \]

- Virtual photon flux
- Meson cross section

Transverse
Transverse-transverse interference
\[ \sigma_T + \varepsilon_L \sigma_L + \varepsilon_{TT} \cos(2\phi) \]

Longitudinal (sensitive to J=0\textsuperscript{±} exchange in t-channel: kaons, diquarks)
\[ \sigma_L \cos(\phi) + h\sqrt{2\varepsilon_L (1-\varepsilon)} \sigma_{LT} \]

“Unseparated”

Helicity structure

Transverse-longitudinal interference

R. A. Schumacher, Carnegie Mellon University
$\gamma^*_{\nu^+} K^+ \Lambda$ Structure Functions

$E = 5.5 \text{ GeV}, \ W: \text{thr} - 2.6 \text{ GeV}, \ Q^2 = 1.80, 2.60, 3.45 \text{ GeV}^2$

[Carman et al., PR C 87, 025204 (2013)]
\[ \gamma K^+ \rightarrow L/T \text{ Separation} \]

\[ K^+ \Lambda \quad K^+ \Sigma^0 \]

\[ \sigma_T (\text{nb/sr}) \]

\[ W = 1.75 \, \text{GeV} \]

\[ W = 1.85 \, \text{GeV} \]

\[ W = 1.95 \, \text{GeV} \]

\[ \cos \theta_K^* \]

\[ \sigma_T (\text{nb/sr}) \]

\[ \sigma_L (\text{nb/sr}) \]

\[ \cos \theta_K^* \]

\[ [\text{P. Ambrożewicz et al., PR C} 75, 045203 (2007)] \]
### CLAS $e^p$ Data Set Overview

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**Publications:**

- $K^+\Lambda$ beam-recoil pol. transfer
  - $W = 1.6 - 2.15$ GeV, $Q^2 = 0.3 - 1.5$ GeV^2  
    [Carman et al., PRL 90, 131804 (2003)]

- $K^+\Lambda \sigma_L/\sigma_T$ ratio from pol. transfer data
  - $W = 1.72 - 1.98$ GeV, $Q^2 \approx 0.7$ GeV^2  
    [Raue & Carman, PR C 71, 065209 (2005)]

- $K^+\Lambda$, $K^+\Sigma^0$ separated structure functions
  - $W = \text{thr} - 2.4$ GeV, $Q^2 = 0.5 - 2.8$ GeV^2  
    [Ambrozewicz et al., PR C 75, 045203 (2007)]
  - $W = \text{thr} - 2.6$ GeV, $Q^2 = 1.4 - 3.9$ GeV^2  
    [Carman et al., PRC 87, 025204 (2013)]

- $K^+\Lambda$ fifth structure function $\sigma_{LT}$
  - $W = 1.6 - 2.1$ GeV, $Q^2 = 0.65$, 1.0 GeV^2  
    [Nasseripour et al., PR C 77, 065208 (2008)]

- $K^+\Lambda$, $K^+\Sigma^0$ beam-recoil pol. transfer
  - $W = \text{thr} - 2.6$ GeV, $Q^2 = 1.6 - 2.6$ GeV^2  
    [Carman et al., PR C 79, 065205 (2009)]
Dimensional Scaling of $K\Lambda$

Constituent-Counting Scaling

\[ \frac{d\sigma}{dt} = f \left( \frac{t}{s} \right) s^{2-n} \]

- Constituent counting rules for exclusive scattering
- Valid for \( s \rightarrow \infty \) and \( t/s \) fixed
  - \( t/s \sim \cos(\theta_{cm}) \) as \( s \rightarrow \infty \)
- \( n = \text{number of point-like constituents} \)
- Follows from pQCD... but also other models
- Does it work for \( K\Lambda \) ?
Resonance Fit to Cross Section

\[ \gamma + p \rightarrow K^+ + \Lambda \]

\[ S_{11}(1690) \quad P_{13}(1920) \quad D_{13}(2100) \]

pQCD-like scaling

\[ \cos \theta \]

\[ +1 \quad 0 \quad -1 \quad -2 \quad -3 \quad -4 \quad -5 \]
Excited $\gamma^*$ Cross Sections

Publication: Differential Photoproduction Cross Sections of $\Sigma^0(1385)$, $\Lambda(1405)$ and $\Lambda(1520)$, K. Moriya et al. (CLAS Collaboration), Phys. Rev. C 88, 045201 (2013).
\gamma K^+ \rightarrow K^+ p \pi^-(\pi^0) or K^+ \pi^+ \pi^- (n)

\[ \Sigma(1385) \]

\[ \Lambda(1405) \]

\[ \Lambda(1520) \]

\( \Sigma(1385) \) has small branching fraction into the \( \Sigma \pi \) states

Counts/5 MeV MM(\( \gamma, K^+ \))

MM(\( \gamma, K^+ \)) (GeV)
\[ \gamma + p \rightarrow K^+ + \Sigma^0(1385) \]

- Experiment: see $t$-channel-like forward peaking & $u$-channel backward rise
  - Agreement with LEPS
- Theory by Oh et al.\(^1\): contact term dominant; included four high-mass $N^*$ and $\Delta$ resonances
  - Prediction was fitted to preliminary CLAS total cross section (years ago)


\[ \gamma + p \rightarrow K^+ + \Lambda (1520) \]

- Experiment: see \( t \)-channel-like forward peaking & \( u \)-channel backward rise
  - Agreement with LEPS\(^{1,2}\)
- Theories:
  - Nam & Kao\(^3\): contact term dominant; no \( K^* \) or \( u \)-channel exchanges
  - He & Chen\(^4\): \( K^* \) and \( N(2080)D_{13} \) \( J^P=3/2^- \) added

2. N. Muramatsu et al. (LEPS) Phys Rev 103, 012001 (2009)
\[ \gamma^* \gamma \to K^+ + \Lambda(1405) \]

- Experiment: first-ever measurements
- Low W: See strong isospin dependence
  - Charge channels differ
  - WHY?!
- High W: See \( t \)-channel-like forward peaking & \( u \)-channel backward rise at high W
- Channels merge together at high W

All three $Y^*$s have similar total cross sections

Ground state $\Lambda$ and $\Sigma^0$ are comparable to $Y^*$ in size\(^1\)


\( \Lambda(1405) \) Structure

Publications: Measurement of the \( \Sigma \pi \) Photo-production Line Shapes Near the \( \Lambda(1405) \), K. Moriya et al. (CLAS Collaboration), Phys. Rev. C 87, 035206 (2013);
Isospin Decomposition of the Photoproduced \( \Sigma \pi \) System near the \( \Lambda(1405) \), R. A. Sch. & K. Moriya, Nucl. Phys A 914, 51 (2013) .
What “is” the $\Lambda(1405)$?

- An issue since its prediction/discovery
  - Dynamically generated resonance, via unitary meson-baryon channel coupling
    - Chiral unitary models (present-day theoretical industry!)
  - $SU(3)$ singlet $3q$ state, $I=0$, $J^\pi = \frac{1}{2}^-$

- $K\bar{N}$ sub-threshold state

- Signal may be an overlay of $I=0$ and $I=1$ states
Chiral Unitary Models

- SU(3) baryons irreps \(1+8_s+8_a\) combine with \(0^-\) Goldstone bosons to generate:
  - Two octets and a singlet of \(\frac{1}{2}^-\) baryons generated dynamically in SU(3) limit
  - SU(3) breaking leads to two \(S = -1, I = 0\) poles near 1405 MeV
    - \(\sim 1420\) mostly \(\bar{K}N\)
    - \(\sim 1390\) mostly \(\pi\Sigma\)
  - Possible weak \(I=1\) pole also predicted


Fig. 1. Trajectories of the poles in the scattering amplitudes obtained by changing the SU(3) breaking parameter \(\chi\) gradually. At the SU(3) symmetric limit \((\chi = 0)\), only two poles appear, one is for the singlet and the other for the octets. The symbols correspond to the step size \(\delta \chi = 0.1\).
Example at $W=2.30$ GeV

$I=0$ contributions with $N\bar{K}$ threshold break

$I=1$ contribution

\[ \gamma^{*}_{K^+} \]
Isospin Interference

Three charge combinations:

\[
|T_{\pi^- \Sigma^+}|^2 = \frac{1}{3}|t_0|^2 + \frac{1}{2}|t_1|^2 - \frac{2}{\sqrt{6}}|t_0||t_1| \cos \phi_{01},
\]

\[
|T_{\pi^0 \Sigma^0}|^2 = \frac{1}{3}|t_0|^2,
\]

\[
|T_{\pi^+ \Sigma^-}|^2 = \frac{1}{3}|t_0|^2 + \frac{1}{2}|t_1|^2 + \frac{2}{\sqrt{6}}|t_0||t_1| \cos \phi_{01}.
\]
Charge-dependence is NOT seen for the $\Lambda(1520)$.
No model calculation has computed cross section and line shapes together.
What “is” the $I=1$ piece?

- $I=1$ resonance? $I=1$ continuum amplitude?
- L. Roca and E. Oset model\(^1\):
  - Possible $I=1$ resonance in vicinity of $N\bar{K}$ threshold
- B.-S. Zou et al. model\(^2\):
  - $\Sigma\left(\frac{1}{2}^+\right)$ is a $|[ud][us]\bar{s}\rangle$ state: part of a new nonet
  - No interference seen in $\Lambda(1520)$ mass range: therefore it’s not a continuum amplitude
- More investigation needed!

Spin and Parity of $\Lambda(1405)$

Parity and Spin of $\Lambda(1405)$

- How does one measure these things?
  - Find a reaction wherein $\Lambda^*$ is created polarized
  - Decay angular distribution to $\Sigma \pi$ relates to $J$
    - $J = 1/2$ : flat distribution is the best possible evidence
    - $J = 3/2$ : "smile or frown" distribution, where $p$ is the $m = \pm 3/2$ fraction
      \[
      I(\theta_Y) \propto 1 + \frac{3(1-2p)}{2p+1} \cos^2 \theta_Y
      \]
  - Parity given by polarization transfer to daughter
  - No model dependence: pure kinematics
**S-wave, P-wave Scenarios**

L=0 (s-wave)
\[ \mathbf{q} = \mathbf{p} \]

\[ J^P = \frac{1}{2}^- \]

L=1 (p-wave)
\[ \mathbf{q} = -\mathbf{p} + 2(\mathbf{p} \cdot \hat{q})\hat{q} \]

\[ J^P = \frac{1}{2}^+ \]

\[ \Lambda(1405) \to \Sigma \pi \]
Parity and Spin of $\Lambda(1405)$

- Polarization axis is along $\hat{z} = \hat{\gamma} \times \hat{K}$
- Used $W=2.55$ to 2.85 GeV, $\cos\theta_K^{c.m.} > 0.6$
- Decay $\Lambda(1405) \rightarrow \Sigma^+ \pi^-$ is isotropic ($p = 0.5$), so $J \rightarrow 1/2$
- Weak decay asymmetry for $\Sigma^+$ is $\alpha = -0.98$ (big!)
- Decay is s-wave, $\Rightarrow P = "negative"

$J^P = \frac{1}{2} -$ confirms quark model expectation

$\text{and } \Lambda(1405) \text{ is produced } \sim +45\% \text{ polarized}$
Electroproduction of $\Lambda(1405)$

- Two-bump structure seen
- Possible evidence for two $I=0$ poles
- PDG $\Lambda(1405)$ values fail utterly
- Calculation needed!

Strangeness Suppression of $q\bar{q}$ Creation in Exclusive Reactions

Motivation:
- Quark model picture of quark-pair creation and flux-tube breaking: does it apply in the low energy exclusive limit?

Measurements:
- Ratio of processes in which only one $q\bar{q}$ pair is produced: an $s\bar{s}$, $d\bar{d}$, or $u\bar{u}$, respectively
- In quark model picture, ratios are proportional to the relative production rates of $s\bar{s}$, $d\bar{d}$, or $u\bar{u}$

Physics conclusion:
- Ratio of $s\bar{s}$ pair creation relative to $u\bar{u}$ or $d\bar{d}$ is suppressed; $\approx 0.2 - 0.3$
- Consistent with high-energy results when 100’s of particles are produced
The Future: Outlook at GlueX and CLAS12
Lattice QCD Predictions

- Lattice QCD now predicts rich baryon families
- Most states not identified by experiment yet

- flavor singlet
- flavor octet
- flavor decouplet

R. Edwards et al., PRD 87, 054506 (2013)
**Baryon Spectroscopy**

- **JLab at 12 GeV** will surpass many $Y^*$ thresholds
- $S = -1, -2, -3$
- Many $\Lambda^*, \Sigma^*, \Xi^*, \Omega^*$ states remain undiscovered
- Charm threshold

(K. Moriya, priv. comm.)
JLab Hall D/GlueX

- New hall, finished construction
- Commissioning in progress now
- Approved for 220 days of high statistics running
Jlab Hall D/GlueX

- Real photon beam centered at 9 GeV
- Liquid hydrogen target
- Reconstruct both charged and neutral particles over large angular range
- Hermetic detector within solenoid magnetic field
- Meson & Baryon spectroscopy: search for new and exotic states
GlueX Study of $\Xi^-(1820)$

- Use simulated data to study
  \[ \gamma + p \rightarrow K^+ + K^+ + \Xi^-(1820) \]
  \[ \Xi^-(1820) \rightarrow \Lambda + K^- \]

- Final state is 5 charged particles, $K^+$, $K^+$, $K^-$, $p$, $\pi^-$
- Can GlueX reconstruct this?

- Reconstruction efficiency
  - 10 MeV mass resolution
  - Secondary vertex resolution: ~1 cm along beam line (z-direction)

(K. Moriya, priv. comm.)
Baseline equipment

**Forward Detector (FD)**
- TORUS magnet (6 coils)
- HT Cherenkov Counter
- Drift chamber system
- LT Cherenkov Counter
- Forward ToF System
- Pre-shower calorimeter
- E.M. calorimeter

**Central Detector (CD)**
- SOLENOID magnet
- Barrel Silicon Tracker
- Central Time-of-Flight

**Beamline**
- Polarized target (transv.)
- Moller polarimeter
- Photon Tagger

Upgrades to the baseline

**Under construction**
- MicroMegas
- Central Neutron Detector
- Forward Tagger
- RICH detector (1 sector)
- Polarized target (long.)

6/19/14
CLAS12: Very Strange Baryons

Study of the \( \Omega^- \) and \( \Xi^* \) are among the main goals of the CLAS12 spectroscopy program:

- \( \Omega^- \) discovered in 1964: after 50 years, indication on \( J^P \) from Babar and others but full determination not yet achieved
- \( \Xi^* \) spectrum still poorly known: many states missing and spin/parity undetermined

Photoproduction mechanism implies creation of three \( s \) quarks

- Models indicate \( \sigma(\Omega^-) \sim 0.3-2 \text{ nb at } \mathcal{E} \sim 7 \text{ GeV} \)
- Expected production rates in CLAS12:
  - \( \Omega^- \): 90 \text{ /h}
  - \( \Xi^* \): \( \Xi^*(1690)/\Xi^*(1820) \): 0.2/0.9 \text{ k/h}
- \( \Omega^- \): measurement of the cross section and investigation of production mechanisms
- \( \Xi^* \): spin/parity determination, cross section and production mechanism, measurement of doublets mass splitting
Topics not addressed today:

- $\gamma^* K^+$ photoproduction
  - Publication: Cross Sections for the $\gamma p \rightarrow K^{*+}\Lambda$ and $\gamma p \rightarrow K^{*+}\Sigma^0$ Reactions, W. Tang, K. Hicks et al. (CLAS) Phys. Rev. C 87, 065204 (2013).

- $\Xi$ photoproduction
  - g12 group, Goetz, Guo, et al.

- Hypernuclear electroproduction
Summary/Conclusions

- Hyperon photo- and electro-production used to pin down $N^*$ spectrum above 1.6 GeV
- $Y^*$ cross sections compared; $\Lambda(1405)$ “weird”
- Interference effects in $\Lambda(1405)$ line shapes demonstrated
- Direct $J^P$ measurement for $\Lambda(1405)$ made: $\frac{1}{2}^-$
- Cross section scaling demonstrated and strangeness suppression seen
- JLab at 12 GeV with CLAS12 and GlueX will explore $Y^*$ and meson spectra
Supplemental Slides
CLAS Experiment

- Jefferson Lab, Newport News, VA, USA
- Photoproduction:
  - Targets: unpolarized LH$_2$, polarized p and HD
  - Beams: unpolarized, circular, linear, to ~5 GeV
  - Reconstructed $K^+p\pi^- (\pi^0)$ or $K^+\pi^+\pi^- (n)$
  - 20x$10^9$ triggers $\rightarrow$ 1.41x$10^6$ K$\gamma\pi$ events in g11a
- Electroproduction:
  - $Q^2$ from ~0.5 to ~3 (GeV/c)$^2$
  - Rosenbluth and beam-helicity separations
Observables in Pseudoscalar Meson Photoproduction

4 Complex amplitudes: 16 real polarization observables.

Complete measurement from 8 carefully chosen observables.

\( \pi N \) has large cross section but in \( KY \) recoil is self-analysing

\[ \begin{array}{|c|c|c|c|}
\hline
\text{Symbol} & \text{Transversity representation} & \text{Experiment required} & \text{Type} \\
\hline
\frac{d\sigma}{dt} & |b_1|^2 + |b_2|^2 & \{ \pm \pi \}, \pm y & S \\
\Sigma \frac{d\sigma}{dt} & |b_1|^2 - |b_2|^2 - |b_3|^2 + |b_4|^2 & \{ \pm \pi \}, \pm y & \text{BP} \\
T \frac{d\sigma}{dt} & |b_1|^2 + |b_2|^2 - |b_3|^2 + |b_4|^2 & \{ \pm \pi \}, \pm y & \text{BP} \\
\frac{Pd\sigma}{dt} & |b_1|^2 - |b_2|^2 - |b_3|^2 - |b_4|^2 & \{ \pm \pi \}, \pm y & \text{BP} \\
G \frac{d\sigma}{dt} & 2 \text{Im}(b_1 b_3^* + b_2 b_4^*) & \{L(\pm \frac{1}{2} \pi), \pm z\} & \text{BT} \\
H \frac{d\sigma}{dt} & -2 \text{Re}(b_1 b_3^* - b_2 b_4^*) & \{L(\pm \frac{1}{2} \pi), \pm x\} & \text{BT} \\
E \frac{d\sigma}{dt} & -2 \text{Re}(b_1 b_3^* + b_2 b_4^*) & \{C; \pm x\} & \text{BP} \\
F \frac{d\sigma}{dt} & 2 \text{Im}(b_1 b_3^* - b_2 b_4^*) & \{C; \pm x\} & \text{BP} \\
O_x \frac{d\sigma}{dt} & -2 \text{Re}(b_1 b_3^* - b_2 b_4^*) & \{L(\pm \frac{1}{4} \pi), \pm x'\} & \text{BP} \\
O_x \frac{d\sigma}{dt} & -2 \text{Im}(b_1 b_3^* + b_2 b_4^*) & \{L(\pm \frac{1}{4} \pi), \pm z'\} & \text{BP} \\
C_x \frac{d\sigma}{dt} & 2 \text{Im}(b_1 b_3^* - b_2 b_4^*) & \{C; \pm x\} & \text{BP} \\
C_x \frac{d\sigma}{dt} & -2 \text{Re}(b_1 b_3^* + b_2 b_4^*) & \{C; \pm z\} & \text{BP} \\
T_x \frac{d\sigma}{dt} & 2 \text{Re}(b_1 b_3^* - b_2 b_4^*) & \{\pm x; \pm x'\} & \text{TR} \\
T_x \frac{d\sigma}{dt} & 2 \text{Im}(b_1 b_3^* - b_2 b_4^*) & \{\pm x; \pm z'\} & \text{TR} \\
L_x \frac{d\sigma}{dt} & 2 \text{Im}(b_1 b_3^* + b_2 b_4^*) & \{\pm z; \pm x'\} & \text{TR} \\
L_x \frac{d\sigma}{dt} & 2 \text{Re}(b_1 b_3^* + b_2 b_4^*) & \{\pm z; \pm z'\} & \text{TR} \\
\hline
\end{array} \]

Excited $Y^*$ cross sections measured at CLAS
- $\Sigma^0(1385)$ ($J^P = 3/2^+$) in $\Lambda\pi^0$ channel
- $\Lambda(1405)$ ($J^P = 1/2^-$) in 3 $\Sigma\pi$ channels
- $\Lambda(1520)$ ($J^P = 3/2^-$) in 3 $\Sigma\pi$ channels

Isospin interference in $\Lambda(1405)$: line shapes

Spin & parity $J^P$ of the $\Lambda(1405)$

First Electro-production of $\Lambda(1405)$

$K^*Y$ production
\[ \gamma p \rightarrow K^+ \Lambda : \text{beam asymmetry } \Sigma \]

The trends are consistent: \( \Sigma \) is smooth and featureless at all energies and angles.

GRAAL threshold range, \( E_\gamma < 1.5 \text{ GeV} \)

LEPS 1.5 < \( E_\gamma \) < 2.4 GeV

**Fig. 14.** Angular distributions of the beam asymmetries \( \Sigma \) for \( \gamma p \rightarrow K^+ \Lambda \) and \( \gamma \)-ray energies ranging from 1 to 15 GeV. Data are compared with the new solutions of the BCC (solid line), SAPOC (dashed line) and GRF (dotted line).

$\gamma Y^* \to K^+ \Lambda$ Beam-Recoil $O_x$ and $O_z$

Fig. 9. Angular distributions of the beam-recoil observable $O_x$ for photon energies $E_\gamma$ ranging from 980 MeV to 1466 MeV. Error bars represent the quadratic sum of statistical and systematic errors. Data are compared with the predictions of the BG (solid line) and RPR (dashed line) models.

GRAAL data: fair agreement with BoGa and RPR models
$\gamma K^+ p \rightarrow K^+ \Lambda :$ helicity asymmetry E

![Helicity asymmetry plots for different energies](image-url)
The combination of all of these measurements on proton and neutron targets represents an extremely powerful tool in the search for new baryon states.

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Source: V. D. Burkert
$\gamma^{*} \rightarrow K^+ \Sigma^0$ Structure Functions

\[ E = 5.5 \text{ GeV}, \ W: \text{thr} - 2.6 \text{ GeV}, \ Q^2 = 1.80, 2.60, 3.45 \text{ GeV}^2 \]

[Carman et al., PR C 87, 025204 (2013)]
Recoil Polarization $\vec{e}p \rightarrow e'K^+\Lambda$

$\langle Q^2 \rangle \sim 1.9 \text{ GeV}^2$

[Gabrielyan et al., PR C 90, 035202 (2014)]

Kaon-Maid    Maxwell    RPR-2007

RPR-2011 (solid-full, dash-NR)

[G McCracken et al., PR C 81, 025201 (2010)]
Transfer Polarization $\gamma K^+ \rightarrow e^' K^+ \Lambda$

$W = 1.753$ GeV, $Q^2 = 2.61$ GeV$^2$

$W = 1.985$ GeV, $Q^2 = 2.56$ GeV$^2$

$W = 2.314$ GeV, $Q^2 = 2.41$ GeV$^2$

Data not included in fits

Rule out $P_{11}(1900)$ assignment

$D_{13}(1900)$ not ruled out via $P'$ data but with S.F. data

5.754 GeV
Summed over $Q^2, \Phi$

Isobar Model - Mart
Regge Model - GLV
RPR w $P_{11}(1900)$ - Ghent
RPR w $D_{13}(1900)$ - Ghent

RPR background + $S_{11}(1650)$, $P_{11}(1710)$, $P_{13}(1720)$, $P_{13}(1900)$

[Carman et al., PRC 79, 065205 (2009)]
N* Baryons: Seen & “Missing”

- Relativized CQM
  - Classify oscillator-model states by $I, J, P$

- Consistent with observation of a “missing” N* state in $K^+\Lambda$

- PDG2013 now lists the “**” N(2150) $3/2^− D_{13}$

Events in $K^+\Sigma^+\pi^-$ Final State

K* overlap must be subtracted in some W bins

2.550 < W < 2.650
counts: 47,790
Yields for $\Sigma^0(1385)$

- Use the dominant $\Lambda\pi^0$ decay mode (88%)
- Select $\Lambda$ in $p\pi^-$ invariant mass;
- Select $\pi^0$ via $K^+\Lambda$ missing mass
- Fit to $\Lambda\pi^0$ channel
- Remove other channels ($K^*\Sigma$) by incoherent fits with Monte Carlo templates

$\Sigma^0(1385)$ in one energy and angle bin
Yields for $\Lambda(1405)$ & $\Lambda(1520)$

- Reconstruct and select ground state $\Sigma^\pm$ states
- Remove $\Sigma^0(1385) \rightarrow \Sigma^\pm \pi^\mp$ (6% each) by scaling down contribution from dominant $\Lambda\pi$ channel
- Separate other channels ($K^*\Sigma$, $K^+Y^*$) by incoherent fits with Monte Carlo templates and Breit-Wigner functions

Fit to $\Sigma^+\pi^-$ channel

Total fit result
Iterated $\Lambda(1405)$ line shape
Differential $\Lambda(1520)$ Cross Section

$\gamma + p \rightarrow K^+ + \Lambda(1520)$

- Good agreement among $\Sigma\pi$ decay modes
- Corrected with 42% branching fraction to $\Sigma\pi$

Agreement between $\Sigma^+\pi^-$ decay modes: tests acceptance consistency

Agreement among $\Sigma^+\pi^-, \Sigma^0\pi^0, \Sigma^-\pi^+$ decay modes: tests acceptance consistency
\[ \gamma + p \rightarrow K^+ + \Lambda(1405) \]

- **Blue**: measured;  **Red**: extrapolated total

- **Model**: \( s \)-channel Born term dominant; \( K^* \) exchange for 3 values of \( g_{K^*N\Lambda^*} \)

---

\( \gamma K^+ \) Direct Y* Cross Section Comparison

- \( \gamma + p \rightarrow K^+ + Y^* \)
  - Sum \( \Lambda(1405) \) channels
  - Apply branching fractions for \( \Lambda(1520), \Sigma(1385) \)

- All three hyperons have
  - Strong forward peaking
  - Similar \( t \)-slopes
  - Back-angle rises
  - Similar-size cross sections

\( d\sigma_{K^+}^{c.m.} / d\cos\theta_{K^+} \)

\( 2.45 < W < 2.55 \)
Example at $W=2.40$ GeV

$\gamma \vec{K}^+ \to \pi^+ \pi^- \pi^0$

$I=0$ contribution with $\vec{K}N$ threshold break

$I=1$ contributions

$W = 2.40$ GeV