Overview of Spectroscopy Results in Meson Photoproduction with Polarization Observables
Outline

• Motivations

• Helicity amplitudes

• Reactions and results

• PDG then and now
Nucleon resonances

• The nucleon resonance spectrum has many broad overlapping states, making disentangling the spectrum difficult 😞

\[ \gamma p \rightarrow \pi^+ n \]
Resonance Rating System

Nucleon resonances are rated using stars:

* Poor evidence of existence
** Fair evidence of existence
*** Likely evidence of existence, or certain and properties need work
**** Existence is certain and properties well explored

M. Dugger, HADRON, September 2015
### Resonance status for $N^*$ and $\Delta$

<table>
<thead>
<tr>
<th>Particle $J^P$</th>
<th>Status overall $\pi N$ $\gamma N$</th>
<th>Status as seen in —</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$ 1/2$^+$</td>
<td>****</td>
<td></td>
</tr>
<tr>
<td>$N(1440)$ 1/2$^+$</td>
<td>**** **** ****</td>
<td></td>
</tr>
<tr>
<td>$N(1520)$ 3/2$^-$</td>
<td>**** **** ****</td>
<td></td>
</tr>
<tr>
<td>$N(1535)$ 1/2$^-$</td>
<td>**** **** ****</td>
<td></td>
</tr>
<tr>
<td>$N(1650)$ 1/2$^-$</td>
<td>**** **** ****</td>
<td></td>
</tr>
<tr>
<td>$N(1675)$ 5/2$^-$</td>
<td>**** **** ****</td>
<td></td>
</tr>
<tr>
<td>$N(1680)$ 5/2$^+$</td>
<td>**** **** ****</td>
<td></td>
</tr>
<tr>
<td>$N(1685)$ ?</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>$N(1700)$ 3/2$^-$</td>
<td>**** **** ****</td>
<td></td>
</tr>
<tr>
<td>$N(1710)$ 1/2$^+$</td>
<td>**** **** ****</td>
<td></td>
</tr>
<tr>
<td>$N(1720)$ 3/2$^+$</td>
<td>**** **** ****</td>
<td></td>
</tr>
<tr>
<td>$N(1860)$ 5/2$^+$</td>
<td>** **</td>
<td></td>
</tr>
<tr>
<td>$N(1875)$ 3/2$^-$</td>
<td>** ** **</td>
<td></td>
</tr>
<tr>
<td>$N(1880)$ 1/2$^+$</td>
<td>** ** **</td>
<td></td>
</tr>
<tr>
<td>$N(1895)$ 1/2$^-$</td>
<td>** ** **</td>
<td></td>
</tr>
<tr>
<td>$N(1900)$ 3/2$^+$</td>
<td>**** **** ****</td>
<td></td>
</tr>
<tr>
<td>$N(1990)$ 7/2$^+$</td>
<td>** ** **</td>
<td></td>
</tr>
<tr>
<td>$N(2000)$ 5/2$^+$</td>
<td>** ** **</td>
<td></td>
</tr>
<tr>
<td>$N(2040)$ 3/2$^+$</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>$N(2060)$ 5/2$^+$</td>
<td>** ** **</td>
<td></td>
</tr>
<tr>
<td>$N(2100)$ 1/2$^+$</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>$N(2150)$ 3/2$^+$</td>
<td>** ** **</td>
<td></td>
</tr>
<tr>
<td>$N(2190)$ 7/2$^-$</td>
<td>**** **** ****</td>
<td></td>
</tr>
<tr>
<td>$N(2220)$ 9/2$^+$</td>
<td>**** ****</td>
<td></td>
</tr>
<tr>
<td>$N(2250)$ 9/2$^+$</td>
<td>**** ****</td>
<td></td>
</tr>
<tr>
<td>$N(2600)$ 11/2$^-$</td>
<td>**** ****</td>
<td></td>
</tr>
<tr>
<td>$N(2700)$ 13/2$^+$</td>
<td>** **</td>
<td></td>
</tr>
</tbody>
</table>

26 $N^*$ states:
- 10 with ****
- 5 with ***
- 8 with **
- 3 with *

### Nucleon $\Delta$ states:

<table>
<thead>
<tr>
<th>Particle $J^P$</th>
<th>Status overall $\pi N$ $\gamma N$</th>
<th>Status as seen in —</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta(1232)$ 3/2$^+$</td>
<td>**** **** ****</td>
<td>F</td>
</tr>
<tr>
<td>$\Delta(1600)$ 3/2$^+$</td>
<td>**** **** ****</td>
<td>o</td>
</tr>
<tr>
<td>$\Delta(1620)$ 1/2$^-$</td>
<td>**** **** ****</td>
<td>r</td>
</tr>
<tr>
<td>$\Delta(1700)$ 3/2$^-$</td>
<td>**** **** ****</td>
<td>b</td>
</tr>
<tr>
<td>$\Delta(1750)$ 1/2$^+$</td>
<td>* * i</td>
<td></td>
</tr>
<tr>
<td>$\Delta(1900)$ 1/2$^-$</td>
<td>** ** d</td>
<td></td>
</tr>
<tr>
<td>$\Delta(1905)$ 5/2$^+$</td>
<td>**** **** ****</td>
<td>d</td>
</tr>
<tr>
<td>$\Delta(1910)$ 1/2$^+$</td>
<td>**** **** ****</td>
<td>e</td>
</tr>
<tr>
<td>$\Delta(1920)$ 3/2$^+$</td>
<td>**** **** ****</td>
<td>n</td>
</tr>
<tr>
<td>$\Delta(1930)$ 5/2$^-$</td>
<td>**** **** ****</td>
<td></td>
</tr>
<tr>
<td>$\Delta(1940)$ 3/2$^-$</td>
<td>** * e</td>
<td>F</td>
</tr>
<tr>
<td>$\Delta(1950)$ 7/2$^+$</td>
<td>**** **** ****</td>
<td>(seen in $\Delta\eta$)</td>
</tr>
<tr>
<td>$\Delta(2000)$ 5/2$^+$</td>
<td>**** **** ****</td>
<td>o</td>
</tr>
<tr>
<td>$\Delta(2150)$ 1/2$^+$</td>
<td>* * b</td>
<td></td>
</tr>
<tr>
<td>$\Delta(2200)$ 7/2$^-$</td>
<td>* * *</td>
<td>i</td>
</tr>
<tr>
<td>$\Delta(2300)$ 9/2$^+$</td>
<td>** d</td>
<td>d</td>
</tr>
<tr>
<td>$\Delta(2350)$ 5/2$^-$</td>
<td>* * d</td>
<td></td>
</tr>
<tr>
<td>$\Delta(2390)$ 7/2$^+$</td>
<td>* * e</td>
<td></td>
</tr>
<tr>
<td>$\Delta(2400)$ 9/2$^-$</td>
<td>* * n</td>
<td></td>
</tr>
<tr>
<td>$\Delta(2420)$ 11/2$^+$</td>
<td>**** **** ****</td>
<td></td>
</tr>
<tr>
<td>$\Delta(2750)$ 13/2$^+$</td>
<td>* * b</td>
<td></td>
</tr>
<tr>
<td>$\Delta(2950)$ 15/2$^+$</td>
<td>** * b</td>
<td></td>
</tr>
</tbody>
</table>

22 $\Delta$ states:
- 7 with ****
- 3 with ***
- 7 with **
- 5 with *

- Nearly half the states have only fair or poor evidence!
- Most states need more work to learn details
- Are there missing states?

M. Dugger, HADRON, September 2015
Resonances

• Masses, widths, and coupling constants not well known for many resonances

• Many models: quark model, Goldstone-boson exchange, diquark and collective models, instanton-induced interactions, flux-tube models, lattice QCD…

• Big Puzzle: Most models predict more resonance states than observed
Brief look at the non-relativistic quark model

- Harmonic oscillator states
- Non-harmonic perturbation
- Spin-spin hyperfine interaction including tensor part

\[ H_{hyp}^{ij} = \frac{2\alpha_s}{3m_im_j} \left\{ \frac{8\pi}{3} \vec{S}_i \cdot \vec{S}_j \delta^3(r_{ij}) \right\} + \frac{1}{r_{ij}^3} \left[ \frac{3(S_i \cdot r_{ij})(S_j \cdot r_{ij})}{r_{ij}^2} - \vec{S}_i \cdot \vec{S}_j \right] \]

- Spin-spin interaction
- Tensor interaction

M. Dugger, HADRON, September 2015
Brief look at the non-relativistic quark model

Oscillator state: $N = 1$; $S = 1/2, 3/2$; negative parity; $P$ wave

Oscillator +
spin-spin interaction

Oscillator +
spin-spin + tensor interaction

Notation: $X^{2S+1}L_{\pi}JP$, where $\pi$ is permutation symmetry
Example: Lattice QCD results for $N^*$ resonances

- Noticeable change as the $\pi$ mass becomes more realistic

- Number of low-lying states (boxed regions) remains the same for the two $\pi$-masses, and is the same as the non-relativistic quark model

Low-lying Resonance States

Lattice QCD is consistent with non-relativistic quark model for number of low-lying states.
More than resonances

• Born term: nucleon propagator

• $t$-channel: vector meson propagator

- The meson-NN coupling can be extracted from the Born term

- The $\rho^0$, $\omega$, and $\varphi$ have same quantum numbers as the photon $\rightarrow$ Vector Meson Dominance
Outline

- Motivations
- Helicity amplitudes
- Reactions and results
- PDG then and now
Helicity amplitudes for $\gamma + p \rightarrow p + \text{pseudoscalar}$

- 8 helicity states: 4 initial, 2 final $\rightarrow 4 \cdot 2 = 8$
- Amplitudes are complex but parity symmetry reduces independent numbers to 8
- Overall phase unobservable $\rightarrow$ 7 independent numbers

- **HOWEVER**, not all possible observables are linearly independent and it turns out that there must be a minimum of 8 observables / experiments

\[
A = \begin{bmatrix}
A_{11} & A_{12} \\
A_{21} & A_{22}
\end{bmatrix}
\]

Initial helicity

- helicity +1 photons ($\varepsilon_+$):
  \[
  A_{\varepsilon_+} = \frac{1}{2} \begin{bmatrix}
  \frac{3}{2} & \frac{1}{2} \\
  H_1 & H_2
\end{bmatrix}
  \]
- helicity -1 photons ($\varepsilon_-$):
  \[
  A_{\varepsilon_-} = \frac{1}{2} \begin{bmatrix}
  \frac{-1}{2} & \frac{-3}{2} \\
  -H_2 & H_1
\end{bmatrix}
  \]

Parity symmetry $\rightarrow$

- $A_{-\mu,-\lambda} = -e^{(\lambda-\mu)\pi} A_{\mu,\lambda}$

M. Dugger, HADRON, September 2015
The alphabet soup of observables for pseudo-scalar photoproduction

- Most experiments are done with photon and/or target polarization

<table>
<thead>
<tr>
<th>Photon</th>
<th>Target</th>
<th>Recoil</th>
<th>Target + Recoil</th>
</tr>
</thead>
<tbody>
<tr>
<td>unpolarized</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>linear pol.</td>
<td>H (-P)</td>
<td>(-T)</td>
<td>(-L_x')</td>
</tr>
<tr>
<td>circular pol.</td>
<td>F 0</td>
<td>-E</td>
<td>(-L_z')</td>
</tr>
</tbody>
</table>

- Hyperons are “self analyzing” and allow for recoil polarization measurements without using recoil polarimeter 😊
# Helicity amplitudes and observables for single pseudoscalar photoproduction

<table>
<thead>
<tr>
<th>Spin observable</th>
<th>Helicity representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{\Omega}^1 = \mathcal{I}(\theta)$</td>
<td>$\frac{1}{2}(</td>
</tr>
<tr>
<td>$\tilde{\Omega}^4 = \tilde{\Sigma}$</td>
<td>Re($-H_1H_4^* + H_2H_3^*$)</td>
</tr>
<tr>
<td>$\tilde{\Omega}^{10} = -\tilde{T}$</td>
<td>Im($H_1H_2^* + H_3H_4^*$)</td>
</tr>
<tr>
<td>$\tilde{\Omega}^{12} = \tilde{P}$</td>
<td>Im($-H_1H_3^* - H_2H_4^*$)</td>
</tr>
<tr>
<td>$\tilde{\Omega}^3 = \tilde{G}$</td>
<td>Im($H_1H_4^* - H_3H_2^*$)</td>
</tr>
<tr>
<td>$\tilde{\Omega}^5 = \tilde{H}$</td>
<td>Im($-H_2H_4^* + H_1H_3^*$)</td>
</tr>
<tr>
<td>$\tilde{\Omega}^9 = \tilde{E}$</td>
<td>$\frac{1}{2}(</td>
</tr>
<tr>
<td>$\tilde{\Omega}^{11} = \tilde{F}$</td>
<td>Re($-H_2H_1^* - H_4H_3^*$)</td>
</tr>
<tr>
<td>$\tilde{\Omega}^{14} = \tilde{O}_x$</td>
<td>Im($-H_2H_1^* + H_4H_3^*$)</td>
</tr>
<tr>
<td>$\tilde{\Omega}^7 = -\tilde{O}_z$</td>
<td>Im($H_1H_4^* - H_2H_3^*$)</td>
</tr>
<tr>
<td>$\tilde{\Omega}^{16} = -\tilde{C}_x$</td>
<td>Re($H_2H_4^* + H_1H_3^*$)</td>
</tr>
<tr>
<td>$\tilde{\Omega}^2 = -\tilde{C}_z$</td>
<td>$\frac{1}{2}(</td>
</tr>
</tbody>
</table>

**Double polarization observables**

- Need **at least 4** of the double observables from at least 2 groups for a “complete experiment”
- $\pi^0 p$, $\pi^+ n$, and $\eta p$ will be nearly complete
- $K^+ \Lambda$ will be complete!
Finding missing resonances requires lots of different observables. *Cross sections are not enough!*
Outline

• Motivations
• Helicity amplitudes
• Reactions and results
• Conclusions
### Status of CLAS meson photoproduction

| | σ | Σ | T | P | E | F | G | H | Tₓ | Tᶻ | Lₓ | Lᶻ | Oₓ | Oᶻ | Cₓ | Cᶻ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Proton target** | | | | | | | | | | | | | | | |
| ρπ⁰ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | | | | | | | | |
| np⁺ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | | | | | | | | | |
| η | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | | | | | | | | |
| η’ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | | | | | | | | |
| K⁺Λ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | | | | |
| K⁺Σ⁰ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | | | | |
| K⁰Σ⁺ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | | | | |
| **“Neutron” target** | | | | | | | | | | | | | | | |
| ρπ⁻ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | | | | | | | | | |
| K⁺Σ⁻ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | | | | | | | | | | |
| K⁰Λ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | | | | |
| K⁰Σ⁰ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | ✔️ | | | | |

- ✔️ - published
- ✔️ - acquired

Not shown in table: ω, ρ and multi-meson observables

- See Priyashree Roy, Thursday at 11:05 (session 2) for ω and ρ CLAS results
Polarization observables from the proton CBELSA/TAPS

Data from first round of double polarization measurements
Data

- There are several labs performing polarization measurements
- There are too many reactions and observables for me to do justice to the work that has been performed
- I will just show some examples of reactions specific features along with samples of data

Talks at HADRON that include polarization observables:
- Helicity Asymmetry Measurements for \( \pi^0 \) photoproduction on the CLAS Frozen Spin Target: Igor Strakovsky, Thursday at 9:35 (session 1)
- Polarization Observables in Vector Meson Production decaying to Multi-pion-Final States using a Transversely Polarized Target and Polarized Photons at CLAS, Priyashree Roy, Thursday at 11:05 (session 2)
- Baryon Spectroscopy – Recent Results from the CBELSA/TAPS Experiment, Jan Hartmann, Thursday at 11:45 (session 2)
- Polarization Observables in \( \eta \) and \( \pi \) Production using a Polarized Target with the Crystal Ball/TAPS at MAMI, Natalie Walford, Thursday at 12:05 (session 2)
- Baryon spectroscopy from JLab, David Ireland, Thursday at 3:10 (plenary session)
Isospin combinations for reactions involving $\pi^0$ and $\pi^+$

- Differing isospin compositions for $N^*$ and $\Delta^+$ for the $\pi^0$ $p$ and $\pi^+$ $n$ final states

- The $\pi^0$ $p$ and $\pi^+$ $n$ final states can help distinguish between the $\Delta$ and $N^*$

\[
\begin{align*}
\Delta^+ & : \pi^0 + p : \sqrt{2/3} |I = \frac{3}{2}, I_3 = \frac{1}{2}\rangle - \sqrt{1/3} |I = \frac{1}{2}, I_3 = \frac{1}{2}\rangle \\
N^* & : \pi^+ + n : \sqrt{1/3} |I = \frac{3}{2}, I_3 = \frac{1}{2}\rangle + \sqrt{2/3} |I = \frac{1}{2}, I_3 = \frac{1}{2}\rangle
\end{align*}
\]
Isospin photo-couplings

- Using both proton and neutron targets allows decomposition of iso-singlet and iso-vector photo-couplings $C^0$, $C^1$

Example:

\[ \gamma p \rightarrow n\pi^+ : \quad \pm \sqrt{\frac{2}{3}} \left[ C^0 \bigotimes \sqrt{\frac{1}{3}} C^1 \right] N^* + \frac{\sqrt{2}}{3} C\Delta^* \]

\[ \gamma n \rightarrow p\pi^- : \quad \mp \sqrt{\frac{2}{3}} \left[ C^0 \bigoplus \sqrt{\frac{1}{3}} C^1 \right] N^* + \frac{\sqrt{2}}{3} C\Delta^* \]
Preliminary results

CLAS results agree well with previous data
$F$ for $\gamma p \rightarrow n \pi^+$

- Early stage results
- Predictions get much worse at higher energies
- SAID13 are predictions based on preliminary fits to CLAS pion $\Sigma$ measurements
$E$ for $\gamma p \rightarrow p \pi^0$

- ELSA results

Black solid: BnGa fit
Black dashed: BnGa previous to fit
Blue solid: MAID
Red solid: SAID (CM12)
Red dashed: SAID (SN11)

- See Igor Strakovsky, Thursday at 9:35 (session 1) for CLAS results and more about this observable

M. Gottschall et al., PRL 112, 012003 (2014)
S. Strauch, CLAS Collaboration, submitted to PRC

- Models needed data to obtain reasonable agreement

> Blue short dash: Julich (14E)
> Blue long dash: Julich (14 prediction)
> Green solid: SAID (st14E)
> Green dash-dotted: SAID (st14 prediction)

• See Dave Ireland, Thursday at 3:10 (plenary session) for more CLAS π observables
$E$ for $\gamma n \rightarrow \pi p$

- Preliminary CLAS results (Tsuneo Kageya)
- Deuteron target: HD-ICE
  - Red: SAID prediction
  - Blue: BnGa prediction
G for $\gamma p \rightarrow p \pi^0$

- ELSA results
  - Blue dotted: MAID
  - Red dashed: SAID
  - Black solid: BnGa

- Discrepancies between the different model predictions can be traced to the $E_{0^+}$ and $E_{2^-}$ multipoles

A. Thiel et al., PRL 109, 102001 (2012)

- See Jan Hartmann’s talk (Thursday session 2) for more CBELSA/TAPS results
“Isospin filters”

• The $\eta p$, and $\omega p$ systems have isospin $\frac{1}{2}$ and limit one-step excited states of the proton to be isospin $\frac{1}{2}$. Final states like $\eta p$, $\omega p$ act as isospin filters to the resonance spectrum.

\[ \gamma p \rightarrow \pi^+ n \]

\[ \gamma p \rightarrow \eta p \]
$T$ and $F$ for $\eta$ photoproduction

C.X. Akondi et al., PRL 113, 102001 (2014)

- See Natalie Walford, Thursday at 12:05 (session 2) for more about MAMI results and these observables

- Model predictions do not reproduce results of the data
- CLAS results coming soon

Black circles: MAMI
Pink triangles: Bonn

Red dashed: MAID
Green long dashed: Gissen
Black dash dotted: BG2011-02
Blue dotted: SAID GE09
Black: Legendre fits
E-observable for $\eta$ photoproduction on proton

- Cross section for $\gamma n \rightarrow \eta n$ shows strong enhancement in narrow region around $W = 1685$ MeV not seen in cross sections of $\gamma p \rightarrow \eta p$

- Looking for structure near $W = 1685$ MeV in other observables for the $\gamma p \rightarrow \eta p$ reaction

Hint of structure at $W = 1685$ MeV but not conclusive evidence of narrow resonance

I. Senderovich, CLAS Collaboration, submitted to PRL
The $\eta'$ isosinglet

- The $\eta'$ is the only isosinglet pseudoscalar meson. This property can be used to indirectly probe gluonic coupling to the proton.

**Flavor-singlet Goldberger-Treiman relation**

$$2m_N G_A(0) = F g_{\eta'NN} - \frac{F^2 m_{\eta'}^2}{N_F} g_{GNN}(0)$$

- $m_N$ = mass of nucleon
- $G_A(0)$ = nucleon flavor-singlet axial charge
- $F^\prime$ = invariant decay constant (reduces to $F_\pi$ if $U_A(1)$ anomaly were turned off)

- $N_F$ = Number of flavors
- $g_{\eta'NN}$ = $\eta'$-nucleon-nucleon coupling constant
- $g_{GNN}$ = gluon-nucleon-nucleon coupling constant

$G_A(0) = 0.213 \pm 0.138$

Taking $F = F_\pi$ and $N_F = 3$ allows a rough calculation of $g_{GNN}$ given $g_{\eta'NN}$.
Beam asymmetry for $\gamma p \rightarrow \eta' p$

- Predictions do not match the data
- CLAS data coming soon

- GRAAL data: P. Levi Sandri et al., arXiv: 1407.6991v2

Photoproduction of $\pi \pi \ p$ states

- 64 observables
- 28 independent relations related to helicity amplitude magnitudes
- 21 independent relations related to helicity amplitude phases
- Results in 15 independent numbers

Good for discovering resonances that decay into other resonances!
A small sample of $I^s$ for $\gamma p \rightarrow p \pi^0 \pi^0$

- $\sigma = \sigma_0 \{1 + P_\gamma [I^s \sin(\phi) + I^c \cos(\phi)]\}$
- CBELSA/TAPS data
- Much more data than shown
- $I^c$ not shown
- Black: BnGa full fit
- Green: BnGa without N(1900)3/2+

Clear evidence for intermediate states:
- $\Delta(1232)\pi$
- $N(1520)3/2^- \pi$
- $N(1680)5/2^+ \pi$
- $Nf_0(980)$

$N(1900)^{J^P} \rightarrow N(1520)^{3/2^-} \pi^0$

$J^P$

$3/2^+$

$3/2^-$

$5/2^-$

$5/2^+$

$7/2^+$

Best fit

- Data from region II


• See Jan Hartmann’s talk (Thursday session 2) for more CBELSA/TAPS results

M. Dugger, HADRON, September 2015
Interpretation of the $\rho \pi^0 \pi^0$ data using $\rho \lambda$ oscillators

- If $L=2$ with both $\rho$ and $\lambda$ oscillators excited, then there must be an intermediate state.
- Resonances where only one oscillator is excited have a much reduced chance to decay into an intermediate resonance.
- High mass resonances should have a three-particle component that excludes a simple quark-diquark picture of baryon resonances.

$\rho = (x_1 - x_2)/\sqrt{2}$ Antisymmetric under $1 \leftrightarrow 2$

$\lambda = (x_1 + x_2 - 2x_3)/\sqrt{6}$ Symmetric under $1 \leftrightarrow 2$

Self-analyzing reaction $K^+ Y$ (hyperon)

- The weak decay of the hyperon allows the extraction of the hyperon polarization by looking at the decay distribution of the baryon in the hyperon center of mass system:

\[
I(\cos \theta) = \frac{1}{2} \left( 1 + \alpha P_Y \cos \theta \right)
\]

where $I$ is the decay distribution of the baryon, $\alpha$ is the weak decay asymmetry ($\alpha_A = 0.642$ and $\alpha_{\Sigma_0} = -\frac{1}{3} \alpha_A$), and $P_Y$ is the hyperon polarization.

- We can obtain recoil polarization information without a recoil polarimeter and the reaction is said to be “self-analyzing”
The alphabet soup of observables for pseudo-scalar photoproduction

- Most experiments are done with photon and/or target polarization

<table>
<thead>
<tr>
<th></th>
<th>Photon</th>
<th>Target</th>
<th>Recoil</th>
<th>Target + Recoil</th>
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<td>$x$</td>
<td>$y$</td>
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<td>$y'$</td>
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<tr>
<td>$\sigma_0$</td>
<td>0</td>
<td>$T$</td>
<td>$z$</td>
<td>$z'$</td>
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<td>linear pol.</td>
<td>$-\Sigma$</td>
<td>$H$</td>
<td>$-P$</td>
<td>$-P$</td>
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<tr>
<td>circular pol.</td>
<td>0</td>
<td>$F$</td>
<td>$-G$</td>
<td>$-G$</td>
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</table>

- Hyperons are “self analyzing” and allow for recoil polarization measurements without using recoil polarimeter 😊
Observables $C_x$ and $C_z$ for $\gamma p \rightarrow K^+ \Lambda$

Without $P_{13}(1900)$

With $P_{13}(1900)$

- Open circles: $C_z$
- Filled circles: $C_x$

- Inclusion of $P_{13}(1900)$ helped improve fit

- Data: R. Bradford et al., CLAS Collaboration, PRC 75, 035205 (2007)
Spin and parity of the $\Lambda(1405)$

- Reaction: $\gamma p \rightarrow K^+ \Lambda(1405)$ where $\Lambda(1405) \rightarrow \Sigma^+ \pi^-$
- $2.55 < W < 2.85$ GeV and $0.6 < \cos(\theta_{c.m.}^{K^+}) < 0.9$
- Polarization = 0.45
- Decay distribution consistent with $J = 1/2$

$Q$ is the polarization transfer:
- Odd: independent of $\theta_{\Sigma}$
- Even: dependent on $\theta_{\Sigma}$
$T$ observable for $\gamma p \rightarrow K^+ \Lambda$

Data:
- **Red**: CLAS (preliminary from Natalie Walford)
- **Black**: Bonn78
- **Green**: GRAAL09

Models:
- **Red**: RPR-Ghent
- **Blue**: MAID
- **Purple** dashed: BnGa

- GRAAL and CLAS data agree fairly well
- More observables for this reaction and $K^+ \Sigma^0$ coming soon 😊

- See Dave Ireland, Thursday at 3:10 (plenary session) for more CLAS hyperon observables
New experiment coming online: BGO-OD at ELSA

- Energy tagged bremsstrahlung photon beam up to 3 GeV
- BGO calorimeter (central region) & Forward Spectrometer combination
- High momentum resolution, excellent charged and neutral particle ID

Example of recent commissioning data (preliminary calibrations)

\[ E_{e^-} = 2.9 \text{ GeV}, \text{ linearly polarised beam} \]

Neutral meson reconstruction in the BGO

Fit to \( x^2 \) peak
Mean = 137 MeV
\( \sigma = 15 \text{ MeV} \)

Fit to \( \eta \) peak
Mean = 528 MeV
\( \sigma = 31 \text{ MeV} \)

Charged particle ID in the Forward Spec.

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PDG: then and now

Since 2010:

- Eight resonance states have been added:
  - $N(1685)$?
  - $N(1860)5/2^+$
  - $N(1875)3/2^-$
  - $N(1880)1/2^+$
  - $N(1895)1/2^-$
  - $N(2040)3/2^+$
  - $N(2060)5/2^-$
  - $N(2120)3/2^-$

- Three resonance states have been removed:
  - $N(2080)D_{13}$
  - $N(2090)S_{11}$
  - $N(2200)D_{15}$

- The $N(1900)3/2^+$ has been upgraded from ** to ***
- The $\Delta(1940)3/2^-$ has been upgraded from * to **
Thanks for your time 😊
Title
Temporary
Linking experiment and theories

- **Experiment**
  - cross sections
  - spin observables

- **Amplitude analysis**
  - multipole amplitudes
  - phase shifts

- **Baryon models**
  - LQCD
  - quark models
  - etc...

- **Reaction model**
  - effective Lagrangians
  - isobars
  - etc...
Circular beam polarization

• Circular photon beam from longitudinally-polarized electrons

• Incident electron beam polarization $> 85$

\[ P_\gamma = P_e \cdot \frac{4k - k^2}{4 - 4k + 3k^2} \]

Linearly polarized photons

- Coherent bremsstrahlung from 50-μ oriented diamond

- Two linear polarization states (vertical & horizontal)

- Analytical QED coherent bremsstrahlung calculation fit to actual spectrum (Livingston/Glasgow)

- Vertical 1.3 GeV edge shown
The FroST target and its components:
A: Primary heat exchanger
B: 1 K heat shield
C: Holding coil
D: 20 K heat shield
E: Outer vacuum can (Rohacell extension)
F: CH2 target
G: Carbon target
H: Butanol target
J: Target insert
K: Mixing chamber
L: Microwave waveguide
M: Kapton coldseal

Performance Specs:
Base Temp: 28 mK w/o beam, 30 mK with
Cooling Power: 800 μW @ 50 mK, 10 mW @ 100 mK, and 60 mW @ 300 mK
Polarization: +82%, -90%
1/e Relaxation Time: 2800 hours (+Pol), 1600 hours (-Pol)
  Roughly 1% polarization loss per day.

Butanol composition: C₄H₉OH
C and O are even-even nuclei → No polarization of the bound nucleons

Carbon target used to represent bound nucleon contribution of butanol
Performance: target polarization

- Frozen spin butanol ($C_4H_9OH$)
- $P_z \approx 80\%$
- Target depolarization: $\tau \approx 100$ days

- For g9a (longitudinal orientation) 10% of allocated time was used polarizing target
- For g9b (transverse orientation) 5% of allocated time was used polarizing target
HDICE target

- Deuteron+Hydrogen target
- Neutron and proton polarization possible

D polarization during g14/E06-101

A.M. Sandorfi

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Look at the matrix element:

\[ \langle N(p')|J_5^\mu|N(p)\rangle = \bar{u}(p')[\gamma^\mu\gamma^5F(q^2) + q^\mu\gamma^5G(q^2)]\mu(p) \]

Approximate the axial current as being conserved: \( \partial_\mu J_5^\mu = 0 \)

Obtain \( 2m_N F(q^2) = q^2 G(q^2) \)

Take as \( q \to 0 \): \( G(q^2) \to f_\pi (1/q^2) g_{\pi NN} \), where \( f_\pi \) is the pion decay constant and \( m_\pi = 0 \)

Goldberger-Treiman: \( 2m_N F(0) = f_\pi g_{\pi NN} \), Note: \( F(0) \) is the isotriplet axial-vector form factor at \( q^2 = 0 \)

Do the same calculation for the flavor singlet axial current to get:
\( 2m_N G_A(0) = f g_{\eta_0 NN} \), where \( \eta_0 \) is the unphysical flavor singlet goldstone boson
Why do baryon spectroscopy?

Atomic spectroscopy:
\[ H + \gamma \rightarrow H^* \rightarrow H + \gamma \]

Continuous spectrum

Absorption spectrum

Intensity vs. wavelength

Emission spectrum

Ne + H

350nm to 700nm

Intensity vs. wavelength

Quantum mechanics for
\[ H^* \rightarrow H + \gamma \]
reproduces the observed spectrum

Baryon models must also be tested experimentally
pi0 beam asymmetry
\[ \gamma p \rightarrow p \pi^\pm \pi^- \]

The differential cross section for $\gamma p \rightarrow p \pi^\pm \pi^-$

(without measuring the polarization of the recoiling nucleon)

\[
\frac{d\sigma}{d\chi_i} = \sigma_0 \left\{ (1 + \vec{\Lambda}_i \cdot \vec{P}) + \delta_\odot (I^\odot + \vec{\Lambda}_i \cdot \vec{P}^\odot) \right. \\
+ \left. \delta_\downarrow [ \sin 2\beta (I^s + \vec{\Lambda}_i \cdot \vec{P}^s) + \cos 2\beta (I^c + \vec{\Lambda}_i \cdot \vec{P}^c) ] \right\}
\]

- $\sigma_0$: The unpolarized cross section
- $\beta$: The angle between the direction of polarization and the x-axis
- $\delta_\odot, \delta_\downarrow$: The degree of polarization of the photon beam $\Rightarrow \delta_\odot$, and $\delta_\downarrow$
- $\vec{\Lambda}_i$: The polarization of the initial nucleon $\Rightarrow (\Lambda_x, \Lambda_y, \Lambda_z)$
- $I^\odot, I^s, I^c$: The observable arising from use of polarized photons $\Rightarrow I^\odot, I^s, I^c$
- $\vec{P}$: The polarization observable $\Rightarrow (P_x, P_y, P_z) (P_x^\odot, P_y^\odot, P_z^\odot) (P_x^s, P_y^s, P_z^s) (P_x^c, P_y^c, P_z^c)$

15 Observables

Linear beam and unpolarized target: $\Lambda_i = \delta_\odot = 0$
Conclusion
Title