Topics in Baryon Spectroscopy and Structure

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Overview

• Introduction, Multiplets, SU(6)xO(3)
• Analysis Tools, Equipment
• Electromagnetic Excitation of the $\Delta(1232)$
• Structure of the Roper and other lower mass resonances.
• “Missing” Resonances
• Exotic Baryons (Pentaquarks)
Why N*’s are important

Nathan Isgur, N*2000 Conference

- Nucleons represent the real world, they must be at the center of any discussion on
  
  “**why the world is the way it is**”

- Nucleons represent the simplest system where
  
  “*the non-abelian character of QCD is manifest*”

  3-gluon vertex

- Nucleons are complex enough to
  
  “**reveal physics hidden from us in mesons**”

  Gell-Mann & Zweig - Quark Model:  3 x 3 x 3 = 10 + 8 + 8 + 1

  O. Greenberg - The Δ++ problem and “color”
An energy excitation spectrum indicates that the proton has a substructure. This was two years later confirmed in elastic ep scattering by Hofstadter.
Total cross sections (PDG2004)

\[ \pi^- p \rightarrow X \]
The $\Delta^{++}(1232)$ leads to "color"

$\pi^+ p \rightarrow \Delta^{++}$ is the largest $\pi N$ cross section, but the $\Delta^{++}$ state is not allowed in CQM w/o color.

O. Greenberg introduces a new quantum number to get asymmetric w.f.

$\Psi_s = \Psi_{\text{flavor}} \Psi_{\text{spin}}$

$\Psi_{\text{as}} = \Psi_{\text{flavor}} \Psi_{\text{spin}} \Psi_{\text{color}}$
Baryon multiplets

Baryons $qqq$

$$3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1$$
Production and decay of $\Omega \rightarrow \Xi \pi$

V.E. Barnes et. al., Phys. Rev. Lett. 8, 204 (1964)

Fig. 2. Photograph and line diagram of event showing decay of $\Omega^-$. 
Baryon Resonances and SU(6) x O(3)

\[ |\text{Baryon}\rangle : \alpha |\text{qqq}\rangle + \beta |\text{qqq}(\bar{q}q)| + \gamma |\text{qqqG}\rangle + .. \]

3 Flavors: \{u,d,s\} → SU(3)

\{qqq\}: \[ 3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1 \]

Quark spin \( s_q = \frac{1}{2} \) → SU(2)

\{q̅q̅q̅\}: \[ 6 \otimes 6 \otimes 6 = 56 \oplus 70 \oplus 20 \]

SU(6) multiplets decompose into flavor multiplets:

\[ 56 = 4^{10} \oplus 2^{8} \]
\[ 70 = 2^{10} \oplus 4^{8} \oplus 2^{8} \oplus 2^{1} \]
\[ 20 = 2^{8} \oplus 4^{1} \]

Baryon spin: \( \vec{J} = \vec{L} + \sum s_i \)

parity: \( P = (-1)^L \)

Lectures by F. Close

O(3)
SU(6)xO(3) Classification of Baryons

Lowest Baryon Supermultiplets
SU(6)xO(3) Symmetry

Particle Data Group
- Green: ****
- Red: ***
- Yellow: **

“Missing”
P_{13}(1870)
Capstick and Roberts

Lowest Baryon Supermultiplets

 Particle Data Group

0
(56,0+)
0\omega

1
(56,0+)
(56,3-)
(70,3-)
(20,3-)

2
(56,2+)
(70,2+)
(70,2-)

3
(56,1-)
(70,1-)
(20,1-)

\Delta(1232)
Roper P_{11}(1440)
D_{13}(1520)
S_{11}(1535)
States with same $I, J^p$ quantum numbers and different total quark spins $S_q = 1/2$ or $S_q = 3/2$, mix with mixing angle $\theta_M$.

$$S_q = 1/2 \quad \quad \quad \quad S_q = 3/2$$

The pure quark states $|N_2, 1/2^-\rangle$ and $|N_4, 1/2^-\rangle$ in $[70,1^-]$ project onto physical states $S_{11}(1535)$ and $S_{11}(1650)$.

$$|S_{11}(1535)\rangle = \cos \theta_1 |N_2, 1/2^-\rangle - \sin \theta_1 |N_4, 1/2^-\rangle$$
$$|S_{11}(1650)\rangle = \sin \theta_1 |N_2, 1/2^-\rangle + \cos \theta_1 |N_4, 1/2^-\rangle$$

$\Theta_1 = 31^\circ$ (measured in hadronic decays).

Notation: $L_{2I,2J}^p$

Similarly for $|N_2, 3/2^-\rangle$ and $|N_4, 3/2^-\rangle$

$$|D_{13}(1520)\rangle = \cos \theta_2 |N_2, 3/2^-\rangle - \sin \theta_2 |N_4, 3/2^-\rangle$$
$$|D_{13}(1700)\rangle = \sin \theta_2 |N_2, 3/2^-\rangle + \cos \theta_2 |N_4, 3/2^-\rangle$$

$\Theta_2 = 6^\circ$

The $|N_4, 5/2^-\rangle$ quark state has no $N_2$ partner, and cannot mix.

$$|D_{15}(1675)\rangle = |N_4, 5/2^-\rangle$$
Analysis Tools
Simple searches for resonances

For a 2-body decay one can search for resonance structures in the invariant mass distribution.

\[ M = (p_p + p_\pi)^2 \]

4-vectors

Rarely can resonances be observed just in mass distributions, e.g. if state is narrow, or if strongly excited. It also gives no information on quantum numbers other than isospin.
Dalitz Plot for 3-body decay (e.g. $p\pi^+\bar{K}^0$)

3-body decay $P, M$  

- Resonance at: $m_{12} = 1.8$ GeV
- Resonance at: $m_{23} = 2.0$ GeV

A narrow resonance at $m_{12} = 2.0$ GeV may appear like a broad enhancement in $m_{23}$ (kinematical reflection).
Dalitz Plot: $\gamma p \rightarrow pK^+K^-$

$E_\gamma = 1.6-3.5$ GeV
Elastic scattering amplitude of spinless particle with momentum $k$ in cms:

$$f(k,\theta) = \frac{1}{k} \sum_l (2l+1)a_l P_l(\cos \theta)$$

$$a_l = \frac{(\eta_l e^{2i\delta_l} - 1)}{2i},$$

$0 \leq \eta_l \leq 1$, $\delta_l$ : phase shift of $l^{th}$ partial wave

For purely elastic scattering: $\eta_l = 1$, (e.g. $\pi N \rightarrow \pi N$)

$$\frac{d\sigma}{d\Omega} = |f(k,\theta)|^2$$

Optical theorem:

$$\sigma_{\text{tot}} = \frac{4\pi}{k} [\text{Im } f(k,0)]$$

Cross section for $l^{th}$ partial wave is bounded:

$$\sigma_l = \frac{4\pi}{k^2(2l+1)} |a_l|^2 \leq \frac{4\pi (2l+1)}{k^2}$$
Argand Diagram

\( a_l \): partial wave amplitude evolving with energy.

The amplitude leaves the unitary circle where inelasticity sets in.

\[
a_l = (\eta_l e^{2i\delta_l} - 1)/2i
\]
Breit-Wigner Form

- B-W (non-relativistic) form for an elastic amplitude $a_l$ with a resonance at cm energy $E_R$ and elastic width $\Gamma_{el}$ and total width $\Gamma_{tot}$ is

$$a_l = \frac{\Gamma_{el}/2}{E_R - E - i\Gamma_{tot}/2}$$

- Relativistic form:

$$a_l = \frac{-m\Gamma_{el}}{s - m^2 - im\Gamma_{tot}}$$

- Many other B-W forms exist, dependent of process dynamics.
Electromagnetic Excitation of Baryon Resonances
Why electroexcitation of N*s?

Addresses the question: What are the relevant degrees of freedom at different distance scales?

Spatial resolution $\sim 1/q$

$LQCD$ P.O. Bowman, et al., hep-lat/0209129

$\Rightarrow$ Constituent quark model with fixed quark masses only justified at photon point and low $q$. 
Reach of Current Accelerators

- **LEGS** $\gamma + \bar{p}, \bar{d}$
- **MAMI-B** $\gamma + \bar{p}, \bar{d}$
- **MAMI-C**
- **GRAAL** $\gamma + \bar{p}, \bar{d}$
- **Spring-8**
- **BONN** $\gamma + \bar{p}, \bar{d}$
- **JLAB** $e, \gamma + \bar{p}, \bar{d}$

**Participating Systems**
- $\pi N$
- $\pi \pi N$
- $3\pi N$
- $\eta N$
- $4\pi N$
- $K\Lambda$
- $\omega N$
- $\eta' N$
- $f_0 N$

**Reach**
- $1.0
d- $1.2$
- $1.4$
- $1.6$
- $1.8$
- $2.0$
- $2.2$
- $2.4$

**Partonic States**
- $\Delta$
- 2nd
- 3rd

**Energy (GeV)**
Large Acceptance Detectors for N* Physics.

**CLAS:** (photon and electron reactions)
- Final states with mostly charged particles.
- Operates with electron beams and with energy-tagged photon beams.
- Coverage for photons limited to lab angles < 45°

**Crystal Barrel-ELSA:** (photon reactions)
- CsI crystals with excellent photon detection, e.g. Nπ⁺π⁻, Nπ⁺η

**SAPHIR-ELSA** (photon reactions, detector dismantled)
- Charged particles in final state

**GRAAL** (photon reactions):
- BGO crystals, with excellent photon detection, limited charged particle, polarized laser-backscattered tagged photon

**Crystal Ball – MAMI** (photon reactions)
- Neutral final states with excellent resolution, limited W range

**BES (Beijing)** – N* in e⁺e⁻ collisions.

Not included are setups for more specialized applications.
JLab Site: The 6 GeV CW Electron Accelerator

- $E_{\text{max}} \sim 6$ GeV
- $I_{\text{max}} \sim 200 \ \mu$A
- Duty Factor $\sim 100\%$
- $\sigma_{E/E} \sim 2.5 \times 10^{-5}$
- Beam $P \sim 80\%$
- $E_{\gamma}$(tagged) $\sim 0.8$-5.5 GeV
CEBAF Large Acceptance Spectrometer

Torus magnet
6 superconducting coils

Liquid D₂(H₂)target +
γ start counter; e minitorus

Drift chambers
argon/CO₂ gas, 35,000 cells

Large angle calorimeters
Lead/scintillator, 512 PMTs

Gas Cherenkov counters
e/π separation, 216 PMTs

Time-of-flight counters
plastic scintillators, 684 PMTs

Electromagnetic calorimeters
Lead/scintillator, 1296 PMTs
The CLAS Photon Tagger
Single Event $\gamma d \rightarrow p K^+ K^- X$
Missing Mass Distribution

\[ \gamma p \rightarrow pX \]
Super Photon ring-8 GeV  SPring-8

- Third-generation synchrotron radiation facility
- Circumference: 1436 m
- 8 GeV
- 100 mA
- 62 beamlines
Laser Electron Photon facility at SPring-8

in operation since 2000

Laser Electron Photon at SPring-8

8 GeV → Laser → 3.5 eV

Compton Scattering

e → \gamma → Max 2.4 GeV

SPring-8:
8 GeV electron storage ring
100 mA

8 GeV Electron
Interaction Region
Laser Hutch
Experimental Hutch
Detector
BL33LEP
LEPS detector

- Aerogel Cerenkov (n=1.03)
- Dipole Magnet (0.7 T)
- Start counter
- Liquid Hydrogen Target (50mm thick)
- Silicon Vertex Detector
- MWDC 1
- MWDC 2
- MWDC 3
- TOF wall

\[ \gamma \]
The GRAAL Experiment
The Crystal Barrel @ ELSA

\[ \gamma \gamma \text{ invariant mass} \]

\[ \pi^0 \]

\[ \eta \]

\(-2.6\ \text{million}\ \pi^0 \rightarrow 2\ \gamma\)
Electromagnetic Excitation of N*’s

Primary Goals

• Extract photocoupling amplitudes for known $\Delta, N^*$ resonances
  – Partial wave and isospin decomposition of hadronic decay
  – Assume EM and strong interaction vertices factorize
  – Helicity amplitudes $A_{3/2}, A_{1/2}, S_{1/2}$ and their $Q^2$ dependence
  – Study quark wave function and symmetries
  – Quark models: relativity, gluons vs. mesons.

• Identify missing resonances expected from SU(6)xO(3)
  – More selective hadronic decays: $2\pi, \eta, \rho, \omega, K\Lambda$
Inclusive Electron Scattering

\[ p(e,e')X \]

Inclusive scattering \( ep \rightarrow eX \)

- \( p(e,e')X \)
- \( E=4\text{GeV} \)
- N(1520)
- N(1680)
- deep inelastic
- N(940)
- \( \Delta(1232) \)
- missing states

\[ Q^2(\text{GeV}^2) \]

\[ W(\text{GeV}) \]

- elastic \( ep \)
- known resonances
- missing resonances
- deep inelastic
W-Dependence of Selected Channels at 4 GeV

- $p(e,e')X$ (trigger)
- $p(e,e'p)\pi^0$
- $p(e,e'\pi^+)n$
- $p(e,e'p\pi^+)\pi^-$
- $p(e,e'p\pi^+)X$
NΔ(1232) Transition
N-Δ(1232) Quadrupole Transition

SU(6): \( E_{1+} = S_{1+} = 0 \)

(A. Buchmann, E. Henley, 2000)
NΔ - Quadrupole transition in SQT

Magnetic single quark Transition.

Coulomb single quark transition.
Pion Electroproduction Structure Functions

\[
\frac{d^2 \sigma}{d \Omega_\pi^*} = \frac{p_\pi^*}{k_\gamma} \left( \sigma_T + \varepsilon_L \sigma_L + \varepsilon \sigma_{TT} \sin^2 \theta_\pi^* \cos 2\phi_\pi^* + \sqrt{2 \varepsilon_L (\varepsilon + 1)} \sigma_{LT} \sin \theta_\pi^* \cos \phi_\pi^* \right)
\]

- Longitudinal sensitivity w/o Rosenbluth separation.
- Measurement requires out-of-plane detection of hadronic decay.
- Structure functions extracted from fits to \( \phi^* \) distributions for each \((Q^2, W, \cos \theta^*)\) point.
- LT and TT interference sensitive to weak quadrupole and longitudinal multipoles.
The Power of Interference I

- Unpolarized structure function

$$\sigma_{LT} \sim Re(L \ast T)$$
$$= Re(L)Re(T) + Im(L)Im(T)$$

- Amplify small resonance multipole by an interfering larger resonance multipole
Truncated Multipole Expansion in $\Delta(1232)$ Region

- $s$, $p$ waves only, $J_{\text{max}} = 3/2$, $M_{1+}$ dominance, i.e. retain only terms containing $M_{1+}$

\[
\frac{d\sigma}{d\Omega} \approx \frac{|\vec{p}_\pi W|}{K M} \left\{ \frac{5}{2} |M_{1+}|^2 - 3 \text{Re}(M_{1+}E_{1+}^*) + \text{Re}(M_{1+}M_{1-}^*) \right. \\
+ 2 \cos \theta \text{Re}(E_{0+}M_{1+}^*) \\
+ \cos^2 \theta \left[ -\frac{3}{2} |M_{1+}|^2 + 9 \text{Re}(M_{1+}E_{1+}^*) - 3 \text{Re}(M_{1-}M_{1+}^*) \right] \\
+ \epsilon \sin^2 \theta \cos 2\phi \left[ -\frac{3}{2} |M_{1+}|^2 - 3 \text{Re}(M_{1+}E_{1+}^*) \right] \\
- \sqrt{2}\epsilon_L(\epsilon + 1) \sin \theta \cos \phi \left[ \text{Re}(S_{0+}M_{1+}^*) + 6 \cos \theta \text{Re}(S_{1+}M_{1+}^*) \right] \right\} ,
\]

- 6 unknown terms remain, which can be determined uniquely by measuring the azimuthal and polar angle dependence of the cross section.
N* program – NΔ(1232) transition
Structure Functions - Invariant Mass W

![Graph showing invariant mass W with various plots for different cosine values.](image-url)
Structure Functions - \( \cos \theta^* \)

\[ |M_{1+}|^2 (1 - 3/5 \cos^2 \theta) \]

\[ -|M_{1+}|^2 - 2 \text{Re}(M_{1+} E_{1+} \ast) \]

\[ A + 6 \cos \theta \text{Re}(M_{1+} S_{1+} \ast) \]
Legendre Expansion of Structure Functions

\[ \sigma_T + \epsilon_L \sigma_L = A_0 + A_1 P_1 + A_2 P_2 \]
\[ \sigma_{TT} = C_0 \]
\[ \sigma_{LT} = D_0 + D_1 P_1 \]

(M$_{1+}$ dominance)

Resonant Multipoles

\[ |M_{1+}|^2 = A_0 / 2 \]
\[ \text{Re}(E_{1+} M_{1+}^*) = \left( A_2 - 2C_0 / 3 \right) / 8 \]
\[ \text{Re}(S_{1+} M_{1+}^*) = D_1 / 6 \]

Non-Resonant Multipoles

\[ \text{Re}(E_{0+} M_{1+}^*) = A_1 / 2 \]
\[ \text{Re}(S_{0+} M_{1+}^*) = D_0 \]
\[ \text{Re}(M_{1-} M_{1+}^*) = -\left( A_2 + 2 \left( A_0 + C_0 \right) \right) / 8 \]
Electroproduction of $\Delta(1232)$

Recent quark models still fall short at low $Q^2$

Missing $\bar{q}q$ strength?

Sea quarks?

$\text{Im}(M_{1+}) \Rightarrow G^*_M$
Multipole Ratios $R_{EM}$, $R_{SM}$ before 1999

- Data could not determine sign or $Q^2$ dependence.
Multipole Ratios $R_{EM}$, $R_{SM}$ in 2002

- Sign? < 0 !
- $Q^2$ dependence
  - Slope < 0 !

- No trend towards zero crossing and pQCD behavior is observed for $Q^2$ up to 4 GeV$^2$. 
Deviation from spherical symmetry of the $\Delta(1232)$ in LQCD (unquenched).

Dynamical models attribute the deformation to contributions of the pion cloud at low $Q^2$. 

\( R_{EM}, R_{SM} \) in 2004
What does empirical $E_{1+}/M_{1+}$ ratio measure?

Deformation of $N, \Delta$ quark core?

Shape of pion cloud?

Answer will depend on wavelength of probe. With increasing resolution, we are mapping out the shape of the $\Delta$ vs. the distance scale.
The nature of the Roper $P_{11}(1440)$, $S_{11}(1535)$, $D_{13}(1520)$
SU(6)xO(3) Classification of Baryons

Lowest Baryon Supermultiplets
SU(6)xO(3) Symmetry

Particle Data Group

- ****
- ***
- **

SU(6) x O(3) Symmetry

<table>
<thead>
<tr>
<th>Mass</th>
<th>1/2</th>
<th>3/2</th>
<th>5/2</th>
<th>7/2</th>
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<tr>
<td>(1135 MeV)</td>
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<td>(1545 MeV)</td>
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<td>(1839 MeV)</td>
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<tr>
<td>(2130 MeV)</td>
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</table>

D_{13}(1520)
S_{11}(1535)
Roper P_{11}(1440)
What are the issues?

\textbf{P}_{11}(1440): Poorly understood in nrCQMs

Alternative models:

- Light front kinematics (relativity)
- Hybrid baryon with gluonic excitation \( |q^3G> \)
- Quark core with large meson cloud \( |q^3m> \)
- Nucleon-sigma molecule \( |Nm> \)
- Dynamically generated resonance

\textbf{S}_{11}(1535): Hard form factor

Not a quark resonance, but \( \bar{K}\Sigma \) dynamical system?

\textbf{D}_{13}(1520): Change of helicity structure with increasing \( Q^2 \) from \( \lambda=3/2 \) dominance to \( \lambda=1/2 \) dominance, predicted in nrCQMs, pQCD.

\[
\text{CQM: } \left. \frac{A^{D_{13}}_{1/2}}{A^{D_{13}}_{3/2}} \right| = \left. \frac{-1}{\sqrt{3}} \left( \frac{Q^2}{\alpha^2} - 1 \right) \right|
\]
Photocoupling Amplitudes of the $P_{11}(1440)$

(status of 2003, data are from the 1970’s & 80’s, $p\pi^0$ cross sections only)

The failure of CQMs to describe the photocoupling amplitudes led to the development of the hybrid model $|q^3G>$ . In non-rel. approximation $A_{1/2}(Q^2)$, $S_{1/2}(Q^2)$ behave like the $\Delta(1232)$ amplitudes.
Lattice calculations of $P_{11}(1440)$, $S_{11}(1535)$

Masses of both states well reproduced in quenched LQCD with 3 valence quarks.

F. Lee, N*2004

=> Christine Davies
Resonance analyses above the Delta.

- Above the $\Delta(1232)$ many multipoles can contribute.

- Resonance parameters are extracted in somewhat model-dependent fashion with approaches such as Unitary Isobar Models and Dispersion Relations, tuned to previous data.

- Parameterizations incorporate theoretical constraints such as known Born terms, unitarized amplitudes, and different isospin channels.

A detailed discussion of analyses approaches is given in:

Global Analysis of Nucleon Resonances

- Based on **Unitary Isobar Model**.
- Includes all resonances seen in photoproduction PWA
- Breit-Wigner resonant amplitudes:

\[
A_{l\pm}(W) = a_{l\pm} \left( \frac{q_r}{k} \frac{k_r}{q} \frac{\Gamma_\pi}{\eta_\pi} \frac{\Gamma_\gamma}{\Gamma} \right)^{1/2} \times \frac{M\Gamma}{M^2 - W^2 - iM\Gamma_{total}}
\]

- Fixed background from nucleon pole diagrams, \(t\)-channel pion, \(\rho\)- and \(\omega\)-meson exchange.
- Regge behavior for \(W^2 > 2.5 \text{ GeV}^2\) with a smooth transition from UIM to Regge background:

\[
B_{tot} = B_{born} \frac{1}{1 + (W - W_0)^2} + B_{regge} \frac{(W - W_0)^2}{1 + (W - W_0)^2}
\]

- Phase modifications to resonant \(P_{33}\) amplitudes to satisfy Watson’s theorem below 2-pion threshold.
Dispersion Relations

- Causality, analyticity constrain real and imaginary amplitudes:

\[ \text{Re } B_i^{(\pm,0)}(s,t,Q^2) = \text{Born} + \frac{P}{\pi} \int_{\text{thr}}^{\infty} \text{Im } B_i^{(\pm,0)}(s',t,Q^2) \left( \frac{1}{s' - s} \pm \frac{1}{s' - u} \right) ds' \]

- Born term is nucleon pole in s- and u-channels and meson-exchange in t-channel.

- Dispersion integrals summed over 3 energy regions:

\[
\int_{\text{thr}}^{\infty} ds' = \int_{\text{thr}}^{2.2\text{GeV}^2} ds' + \int_{2.2\text{GeV}^2}^{3\text{GeV}^2} ds' + \int_{3\text{GeV}^2}^{\infty} ds'
\]

- Integrals over resonance region saturated by known resonances (Breit-Wigner). P_{33}(1232) amplitudes found by solving integral equations.

- Integrals over high energy region are calculated through π,ρ,ω,b₁,a₁ Regge poles. However, these contributions were found negligible in Regions 1 and 2.

- For η channel, contributions of Roper P_{11}(1440) and S_{11}(1535) to unphysical region s<\((m_\eta + m_N)^2\) of dispersion integral included.
Isospin Amplitudes

• Nucleon resonances are eigenstates of isospin, with $I = 1/2, 3/2$.
• Final states in electromagnetic meson production are not eigenstates of isospin.
• The photon transfers $\Delta I = 0, 1$ resulting in 3 isospin amplitudes for $\pi$ production:
  - $T^s$: Isoscalar, $I_{mN} = 1/2$
  - $T_1^v$: Isovector, $I_{mN} = 1/2$
  - $T_3^v$: Isovector, $I_{mN} = 3/2$

For $\pi$ production from proton target:

\[
\langle \pi^+ n | T | \gamma \nu p \rangle = \sqrt{\frac{1}{3}} T_3^v - \sqrt{\frac{2}{3}} (T_1^v - T^s),
\]

\[
\langle \pi^0 p | T | \gamma \nu p \rangle = \sqrt{\frac{2}{3}} T_3^v + \sqrt{\frac{1}{3}} (T_1^v - T^s),
\]

Examples: $P_{33} (1232)$, $I = 3/2$ => $T_3^v$ contributes => $(\pi^+ n/\pi^0 p)^2 = 1/2$

$P_{11} (1440)$, $I = 1/2$ => $T^s, T_1^v$ contribute => $(\pi^+ n/\pi^0 p)^2 = 2$

$\Rightarrow$ Need both channels to separate $\Delta$ and $N^*$ states
The Roper $P_{11}(1440)$ as a gluonic partner of the nucleon?

Because gluonic baryons do not have “exotic” quantum numbers they must be distinguished from ordinary baryons in different ways.

“... electromagnetic transition form factors are a powerful tool in distinguishing regular $|q^3>$ states from $|q^3G>$ states.”

“… more complete data are needed to study the apparently strong $Q^2$ dependence of $A_{1/2}$ at small $Q^2$, and to establish more accurate values for the longitudinal coupling.”

Fit Summary

# data points: 15,447, $E_e = 1.515, 1.645$ GeV

<table>
<thead>
<tr>
<th>Observable</th>
<th>$Q^2$</th>
<th>Data points</th>
<th>$\chi^2/\text{data UIM}$</th>
<th>$\chi^2/\text{data DR}$</th>
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<td>$\frac{d\sigma}{d\Omega}(\pi^0)$</td>
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<td>$A_{LT'}(\pi^0)$</td>
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<td>0.65</td>
<td>812</td>
<td>1.18</td>
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<tr>
<td>$\frac{d\sigma}{d\Omega}(\eta)$</td>
<td>0.375</td>
<td>172</td>
<td>1.32</td>
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<tr>
<td></td>
<td>0.750</td>
<td>412</td>
<td>1.42</td>
<td>1.45</td>
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</table>
Fits for $e\nu \rightarrow e\nu \pi^+$

$$\frac{d^2\sigma}{d\Omega_\pi} = \frac{p^*_\pi}{k_\gamma} (\sigma_T + \varepsilon_L \sigma_L + \varepsilon \sigma_{TT} \sin^2 \theta^*_\pi \cos 2\phi^*_\pi + \sqrt{2}\varepsilon_L (\varepsilon + 1) \sigma_{LT} \sin \theta^*_\pi \cos \phi^*_\pi)$$

$Q^2 = 0.40 \ (GeV/c)^2$, $W = 1.510 \ (GeV/c)^2$ $\Delta Q^2 = 0.100 \ (GeV/c)^2$, $\Delta W = 0.020 \ (GeV/c)^2$
Fits to Structure Functions \( ep \rightarrow en\pi^+ \)

\[ Q^2 = 0.4 \text{ GeV}^2 \]
UIM Fits for $\bar{e}p \rightarrow e\nu n\pi^+$

**Polarized beam**  \[ \pm h\sqrt{2\varepsilon_L (1 - \varepsilon)} \sigma'_{LT} \sin\theta^*_\pi \sin\phi^*_\pi \]

Beam helicity

\[ A_e = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \]

**$Q^2 = 0.40 \ (GeV/c)^2$, $W = 1.500 \ (GeV/c)^2$, $\Delta Q^2 = 0.100 \ (GeV/c)^2$, $\Delta W = 0.040 \ (GeV/c)^2$**

**$A_e$ vs. $\cos \theta^*$**
UIM vs DR Fits for $ep \rightarrow en\pi^+$

$Q^2 = 0.4 \text{ GeV}^2$

$W = 1.53 \text{ GeV}$
Power of Interference II

• Unpolarized structure function

\[ \sigma_{LT} \sim Re(L \ast T) \]
\[ = Re(L)Re(T) + Im(L)Im(T) \]

– Amplify small resonance multipole by an interfering larger resonance multipole

• Polarized structure function

\[ \sigma_{LT'} \sim Im(L \ast T) \]
\[ = Re(L)Im(T) + Im(L)Re(T) \]

– Amplify resonance multipole by a large background amplitude
Sensitivity to $P_{11}(1440)$

Polarized structure functions are sensitive to imaginary part of $P_{11}(1440)$ through interference with real Born background.
Meson contribution or relativity are needed to describe data.
Roper $P_{11}(1440)$ - Electrocoupling amplitudes

Meson contribution or relativity are needed to describe data.
Comments on the Roper results

- LQCD shows a **3-quark component**. Does it exclude a meson-nucleon resonance?

- Roper resonance transition formfactors **not described in non-relativistic CQM**. If relativity (LC) is included the description is improved.

- Best description in model with **large meson cloud**.

- **Gluonic excitation**, i.e. a hybrid baryon, seems ruled out due to strong longitudinal coupling.

- Other models need to predict transition form factors as a sensitive test of internal structure.
The $S_{11}(1535)$ – an isolated resonance

$S_{11} \rightarrow \eta \ (\sim 55\%)$
The $S_{11}(1535)$ – an isolated resonance

Use same approximation as for the $\Delta(1232)$.

\[
\frac{d\sigma_T}{d\Omega^*_\eta} + \epsilon \frac{d\sigma_L}{d\Omega^*_\eta} = \sum_{\ell=0}^{\infty} A_{\ell} P_{\ell} (\cos \theta^*_\eta)
\]
\[
\sqrt{2\epsilon(\epsilon + 1)} \frac{d\sigma_{LT}}{d\Omega^*_\eta} = \sum_{\ell=1}^{\infty} B_{\ell} P'_{\ell} (\cos \theta^*_\eta)
\]
\[
\epsilon \frac{d\sigma_{TT}}{d\Omega^*_\eta} = \sum_{\ell=2}^{\infty} C_{\ell} P''_{\ell} (\cos \theta^*_\eta)
\]

For $l_{\text{max}} = 2$

There is no interference between the resonant multipoles $E_{0+}$ and $S_{0+}$ in this approximation. Assume $S_{0+}$ is small, use resonance approximation to extract $|E_{0+}| \Rightarrow A_{1/2}$. 
S\(_{11}(1535)\) - Electrocoupling amplitudes

UIM/DR - Analysis of CLAS data

\(\Delta\) GWU (\(\pi\))
- p\(\pi^0\), n\(\pi^+\)
- p\(\eta\)
○ PDG

\(\triangleleft\) hypCP Giannini
- rCQM
- nrCQM Capstick, Keister
- rCQM - Warns

\(\pi/\eta\) discrepancy

no \(\pi/\eta\) discrepancy

no model comes close

\(\tau_{1/2}(10^3\text{GeV}^{-1/2})\)

\(Q^2 (\text{GeV}^2)\)
Measuring the small $D_{13} \rightarrow p\eta$ and $F_{15} \rightarrow p\eta$ branching ratios with linearly polarized photons, $\Sigma_{\gamma}$ (real) or $\sigma_{TT}$ (virtual).

The $D_{13}$ is known to have a very small coupling to $p\eta$. But how small is it?

The beam asymmetry can be expressed in terms of multipoles:

$$\Sigma_{\gamma} \approx 3 \sin^2 \theta \text{Re}[E_{0+}^*(E_{2-} + M_{2-})]/|E_{0+}|^2$$

The $E_{0+}$ multipole is known from the $S_{11}$ resonance analysis described earlier, and the $\eta$ - multipoles $E_{2-} + M_{2-}$ of the $D_{13}$ can be determined. The angular distributions show a $\sin^2 \theta$ dependence.

The $F_{15}$ b.r. can be determined by fitting the distortion from the $\sin^2 \theta$ distribution at the $F_{15}$ mass.
D_{13}(1520) – Electrocoupling amplitudes

CQM prediction:

\[
\frac{A_{1/2}^{D_{13}}}{A_{3/2}^{D_{13}}} = -\frac{1}{\sqrt{3}} \left( \frac{Q^2}{\alpha^2} - 1 \right)
\]

A_{1/2} dominance at high Q^2.

A_{1/2}/A_{3/2} \sim Q^2

at large Q^2, consistent with pQCD prediction.

PDG average

UIM/DR - Analysis of CLAS data

p\pi^0, n\pi^+
Single Quark Transition Model

(F. Close, Quarks and Partons)

Basic process: \( \gamma q \rightarrow q \)

In a frame where the process is collinear:

\( \gamma \) \( q \rightarrow q \)

\[ z' \]

quark spin flipped along \( z' \)

\[ \downarrow \text{boost} \]

\( N^* \) \( \rightarrow \) \( N \)

\[ z \]

\( z \neq z' \)

\( \gamma q \rightarrow q \) not collinear along \( z \) => \( \sigma_z \) and \( L_z \) can be flipped
Single Quark Transition Model

EM transitions between all members of two SU(6)xO(3) multiplets expressed as 4 reduced matrix elements A,B,C,D.

\[ J^+ = A L^+ + B \sigma^+ L_z + C \sigma_z L^+ + D \sigma^- L^+ L^+ \]

\[ \Delta L_z = 1 \quad \Delta S_z = 1 \quad \Delta L_z = 1 \quad \Delta S_z = 1 \]

\[ \Delta L_z = 2 \quad \Delta S_z = 1 \]

Example: \[ [56, 0^+] \rightarrow [70, 1^-] \quad (D=0) \]

Fit A,B,C to D_{13}(1535) and S_{11}(1520)

A_{3/2}, A_{1/2} \rightarrow \text{SU(6) Clebsch-Gordon} \rightarrow A,B,C,D

Predicts 16 amplitudes of same supermultiplet
Single Quark Transition Model

Photocoupling amplitudes $\leftrightarrow$ SQTM amplitudes
(C-G coefficients and mixing angles)

<table>
<thead>
<tr>
<th>State</th>
<th>Proton target</th>
<th>Neutron target</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{11}(1535)$</td>
<td>$A_{1/2}^+ = \frac{1}{8}(A + B - C) \cos \theta$</td>
<td>$A_{1/2}^\circ = -\frac{1}{8}(A + \frac{1}{6}B - \frac{1}{3}C)$</td>
</tr>
<tr>
<td>$D_{13}(1520)$</td>
<td>$A_{1/2}^+ = \frac{1}{6\sqrt{2}}(A - 2B - C)$</td>
<td>$A_{1/2}^\circ = -\frac{1}{18\sqrt{2}}(3A - 2B - C)$</td>
</tr>
<tr>
<td>$A_{3/2}^+ = \frac{1}{2\sqrt{6}}(A + C)$</td>
<td>$A_{3/2}^\circ = \frac{1}{6\sqrt{6}}(3A - C)$</td>
<td></td>
</tr>
<tr>
<td>$S_{11}(1650)$</td>
<td>$A_{1/2}^+ = \frac{1}{6}(A + B - C) \sin \theta$</td>
<td>$A_{1/2}^\circ = \frac{1}{18}(B - C)$</td>
</tr>
<tr>
<td>$D_{13}(1700)$</td>
<td>$A_{1/2}^+ = 0$</td>
<td>$A_{1/2}^\circ = \frac{1}{18\sqrt{5}}(B - 4C)$</td>
</tr>
<tr>
<td>$A_{3/2}^+ = 0$</td>
<td>$A_{3/2}^\circ = \frac{1}{6\sqrt{15}}(3B - 2C)$</td>
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</tr>
<tr>
<td>$D_{15}(1675)$</td>
<td>$A_{1/2}^+ = 0$</td>
<td>$A_{1/2}^\circ = -\frac{1}{6\sqrt{5}}(B + C)$</td>
</tr>
<tr>
<td>$A_{3/2}^+ = 0$</td>
<td>$A_{3/2}^\circ = -\frac{1}{8} \sqrt{\frac{2}{5}}(B + C)$</td>
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</tr>
<tr>
<td>$D_{33}(1700)$</td>
<td>$A_{1/2}^+ = \frac{1}{6\sqrt{2}}(A - 2B - C)$</td>
<td>same</td>
</tr>
<tr>
<td>$A_{3/2}^+ = \frac{1}{2\sqrt{6}}(A + C)$</td>
<td>same</td>
<td></td>
</tr>
<tr>
<td>$S_{31}(1620)$</td>
<td>$A_{1/2}^+ = \frac{1}{18}(3A - B + C)$</td>
<td>same</td>
</tr>
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</table>
Single Quark Transition Model Predictions for \([56,0^+] \rightarrow [70,1^-]\) Transitions
Single Quark Transition Model Predictions for $[56,0^+] \rightarrow [70,1^-]$ Transitions

Neutron

\[ A_{1/2} = A_{3/2} = 0 \text{ for } D_{15}(1675) \text{ on protons} \]
Searching for New Baryon States
“Missing” Baryon States

Quark models with underlying SU(6)xO(3) symmetry predict many states, not observed in either hadronic experiments or in meson photo- and electro-production.

Possible solutions:

1. States don’t exist, e.g. di-quark model predicts fewer states, with different underlying symmetry group

2. States exist but have not been found.

Possible reason: they decouple from $\pi N$-channel.

Model expectations: Hadronic couplings to $N\pi\pi (\Delta\pi, N\rho)$ much larger, while photocouplings are more comparable to those for observed states.

Other channels sensitive to “missing” states are: K$\Lambda$, K$\Sigma$, p$\omega$
<table>
<thead>
<tr>
<th>$L_{2I,2J}$ (Mass)</th>
<th>Multiplet</th>
<th>Status</th>
<th>$L_{2I,2J}$ (Mass)</th>
<th>Multiplet</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{1,1}$ (938)</td>
<td>(56,0$^+$)</td>
<td>***</td>
<td>$P_{3,3}$ (1232)</td>
<td>(56,0$^+$)</td>
<td>***</td>
</tr>
<tr>
<td>$S_{1,1}$ (1535)</td>
<td>(70,1$^-$)</td>
<td>***</td>
<td>$S_{3,1}$ (1620)</td>
<td>(70,1$^-$)</td>
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<tr>
<td>$S_{1,1}$ (1650)</td>
<td>(70,1$^-$)</td>
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</tr>
<tr>
<td>$D_{1,5}$ (1520)</td>
<td>(70,1$^-$)</td>
<td>***</td>
<td>$D_{3,3}$ (1700)</td>
<td>(70,1$^-$)</td>
<td>***</td>
</tr>
<tr>
<td>$D_{1,5}$ (1700)</td>
<td>(70,1$^-$)</td>
<td>***</td>
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</tr>
<tr>
<td>$D_{1,6}$ (1675)</td>
<td>(70,1$^-$)</td>
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</tr>
<tr>
<td>$P_{1,1}$ (1440)</td>
<td>(56,0$^+$)</td>
<td>***</td>
<td>$P_{3,1}$ (1875)</td>
<td>(56,2$^+$)</td>
<td>***</td>
</tr>
<tr>
<td>$P_{1,1}$ (1710)</td>
<td>(70,0$^+$)</td>
<td>***</td>
<td>$P_{3,1}$ (1835)</td>
<td>(70,0$^+$)</td>
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</tr>
<tr>
<td>$P_{1,1}$ (1880)</td>
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<tr>
<td>$P_{1,1}$ (1975)</td>
<td>(20,1$^+$)</td>
<td>***</td>
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<td>$P_{1,3}$ (1720)</td>
<td>(56,2$^+$)</td>
<td>***</td>
<td>$P_{3,3}$ (1600)</td>
<td>(56,0$^+$)</td>
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<td>$P_{1,3}$ (1870)</td>
<td>(70,0$^+$)</td>
<td>*</td>
<td>$P_{3,3}$ (1980)</td>
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<td>$P_{3,3}$ (1985)</td>
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<td>$P_{1,3}$ (1950)</td>
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<td>*</td>
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<tr>
<td>$P_{1,3}$ (2030)</td>
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<td>*</td>
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<td>$F_{1,5}$ (1680)</td>
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<td>***</td>
<td>$F_{3,6}$ (1905)</td>
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<td>$F_{1,5}$ (2000)</td>
<td>(70,2$^+$)</td>
<td>*</td>
<td>$F_{3,6}$ (2000)</td>
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<td>$F_{1,5}$ (1995)</td>
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<td>(P_{33}(1232))</td>
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<td>(S_{11}(1535))</td>
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<td>(P_{35}(1600))</td>
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<td>((70,2^+))</td>
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</tbody>
</table>
Evidence for new baryon states?

- Is the $P_{33}(1600)$ really there?

- One more $3/2^+(1720)$ state?

- A new $N^*(2000)$?

- New resonances in $p\omega$, $K\Lambda$?
Search for Baryon States in $\gamma p \rightarrow p\pi^+\pi^-$

Two methods:

- **Isobar models** (similar approach as in single pion analysis):
  - energy-dependences of amplitudes are parameterized.
  - fits to one-dimensional projections.

- **Event-by event analysis**:
  - fit partial-wave content independently for every energy bin.
  - makes maximum use of all correlations in the multi-dimensional phase space.
  - ambiguities can give multiple solutions.
  
  - A variation of this method uses energy-dependent partial waves in isobar formulation.
Search for Baryon States in $\gamma p \rightarrow p\pi^+\pi^-$

JLab-MSU Dynamical Isobar Model

Residual production mechanism
SU(6)xO(3) Classification of Baryons

Particle Data Group

SU(6)xO(3) Symmetry

Lowest Baryon Supermultiplets

Mass

Particle Data Group

SU(6)xO(3) Symmetry

Lowest Baryon Supermultiplets

3

2

1

0

L_{3q}

N

P_{33}(1600)
Evidence for $P_{33}(1600)$ *** state

$\gamma p \rightarrow p\pi^+\pi^-$

Fit to high statistics photoproduction data requires inclusion of $P_{33}(1600)$ state.

Sample data $W=1.59$ GeV

- **no** $P_{33}(1600)$
- **with** $P_{33}(1600)$
# $P_{33}(1600)$ state parameters

<table>
<thead>
<tr>
<th></th>
<th>this analysis</th>
<th>world</th>
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<tbody>
<tr>
<td><strong>Mass, MeV</strong></td>
<td>1686 ± 10</td>
<td>1550 - 1700 PDG</td>
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<td></td>
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<td>1687 ± 44</td>
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<tr>
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<td>Dytman</td>
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<td></td>
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<td>1706 ± 10</td>
</tr>
<tr>
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<td>Manley</td>
</tr>
<tr>
<td><strong>Total decay width, MeV</strong></td>
<td>338 ± 100</td>
<td>250 - 450 PDG</td>
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<td>493 ± 75</td>
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<td>430 ± 75</td>
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<td>Manley</td>
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<tr>
<td><strong>BF (πΔ), %</strong></td>
<td>65 ± 6</td>
<td>40 -70 PDG</td>
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<tr>
<td></td>
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<td>59 ± 10</td>
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<td>Dytman</td>
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<td>67 ± 5</td>
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<td>Manley</td>
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<tr>
<td><strong>$A_{1/2}$</strong></td>
<td>-30 ± 10</td>
<td>- 29 ± 20 PDG</td>
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<tr>
<td><strong>$A_{3/2}$</strong></td>
<td>-17 ± 10</td>
<td>-19 ± 20 PDG</td>
</tr>
</tbody>
</table>

$A_{1/2}, A_{3/2}$ [GeV^{-1/2}*100]
A new $3/2^+(1720)$ baryon state?

- **JLab-MSU Dynamical Model Analysis**
  - Contributions from conventional states only
  - Fit with new $3/2^+(1720)$ state

M.Ripani et. al.

Difference between curves due to signal from possible $3/2^+(1720)$ state
Photo- and electroproduction comparison

$p\pi^+\pi^-$

**Electroproduction**

**Photoproduction**

\[
Q^2 = 0, Q^2 = 0.65 \text{ GeV}^2, Q^2 = 0.95 \text{ GeV}^2, Q^2 = 1.30 \text{ GeV}^2
\]

\[
W(\text{GeV})
\]

\[
\sigma \text{ (integ, mb)}
\]
Photoexcitation of $P_{13}(1720)$ in $p\pi^+\pi^-$

$P_{13}(1720)$ state shows stronger presence in $\gamma p$ data.

PDG photocouplings

Enhanced photocouplings fitted to the CLAS data
Total $\gamma p \rightarrow p\pi^+\pi^-$ cross-section off protons.

- Hadronic couplings and mass derived from the fit of virtual photon data, and $3/2^+(1720)$ photocouplings fitted to the real photon data.

- Signal from $3/2^+(1720)$ state present, but masked by large background and destructive $N^*/$background interference.
Parameters derived from combined analysis

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass, MeV</td>
<td>1722</td>
<td>92</td>
<td>50</td>
<td>11</td>
</tr>
<tr>
<td>Total width, MeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BF($\pi\Delta$), %</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BF($\rho P$), %</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

PDG P13(1720)

1650-1750

100-200

not observed

70 – 85
The first mass peak is due to the $P_{11}(1440)$ and $D_{13}(1520)$, while the second peak was concluded to be due to the $P_{11}(1710)$. A large photocoupling for that state is needed to fit the data. This is not supported by single pion analysis which finds a small photocoupling for the $P_{11}(1710)$. Also, the diff. cross sections are not well reproduced by the fit (compared with analysis of $p\pi^+\pi^-$).
Partial Wave Analysis - another way of analyzing complex final states.
Partial Wave Formalism for $\gamma p \rightarrow p\pi^+\pi^-$

- Transition matrix:

$$T_{fi} = \langle p\pi^+\pi^-; \tau_f | T | \gamma p; E \rangle$$

$$= \sum_{\alpha} \langle p\pi^+\pi^-; \tau_f | \alpha \rangle \langle \alpha | T_{\alpha i} | \gamma p; E \rangle$$

$$= \sum_{\alpha} \psi^{(\alpha)}(\tau_f) V^{(\alpha)}(E)$$

$$|\alpha> = |J^P M,\text{isobar},l,s,\lambda_f>$$

- Decay amplitude $\psi^{(\alpha)}(\tau_f)$ calculated using isobar model:

E.g. $J^P = 3/2^+, M = +1/2 \rightarrow \Delta^{++}\pi^- \ (l=1), \lambda_f = +1/2$

- Production amplitude $V^{(\alpha)}(E)$ is fitted in unbinned maximum likelihood procedure. Assume $V^{(\alpha)}(E)$ is independent of $E$ in small energy range. No assumptions are made on intermediate resonances, only on quantum numbers.
Sum over intermediate states

\[ \gamma \rightarrow \pi^+ \pi^- + \sum J^{pM} \delta N^* L + \rho,\sigma + \rho,\sigma + \Delta, N \]
Partial Wave Decomposition of $T_{fi}$

For a *small* range of incident energies near $E$...

\[ T_{fi} = \langle p\pi^+\pi^-; \tau_f | T | \gamma p; E \rangle \]
\[ = \sum_\alpha \langle p\pi^+\pi^-; \tau_f | \alpha \rangle \langle \alpha | T_{\alpha i} | \gamma p; E \rangle \]
\[ = \sum_\alpha \psi_\alpha(\tau_f)V_\alpha(E) \]

- $|\alpha\rangle = |J^P M, \text{isobar}, \ell, s, \lambda_f\rangle$

- *Calculate* decay amplitude $\psi_\alpha(\tau_f)$ using isobar model

E.g. $\frac{3}{2}^+ (M = +\frac{1}{2}) \rightarrow \Delta^{++}\pi^- (\ell = 1), \lambda_f = +\frac{1}{2}$

- *Fit* production amplitude $V_\alpha(E)$ using unbinned extended maximum likelihood

Note: Assume $V_\alpha(E)$ doesn’t vary within this energy range
  (“Energy independent”)
<table>
<thead>
<tr>
<th>$J^P$</th>
<th>$M$</th>
<th>Isobars</th>
<th># of waves</th>
<th>Motivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1^+\over2$</td>
<td>$1/2$</td>
<td>$\Delta\pi$</td>
<td>2</td>
<td>$P_{11}(1440)$, $P_{11}(1710)$</td>
</tr>
<tr>
<td>$1^-\over2$</td>
<td>$1/2$</td>
<td>$\Delta\pi$</td>
<td>2</td>
<td>$S_{11}(1535)$, $S_{11}(1650)$</td>
</tr>
<tr>
<td>$1^-\over2$</td>
<td>$1/2$</td>
<td>$(p\rho)_{(s=1/2;\ell=0)}$</td>
<td>1</td>
<td>$S_{31}(1620)$</td>
</tr>
<tr>
<td>$3^+\over2$</td>
<td>$1/2, 3/2$</td>
<td>$(\Delta\pi)_{(\ell=1)}$</td>
<td>4</td>
<td>$P_{13}(1720)$, $P_{33}(1600)$</td>
</tr>
<tr>
<td>$3^-\over2$</td>
<td>$1/2, 3/2$</td>
<td>$(\Delta\pi)_{(\ell=0,2)}$</td>
<td>8</td>
<td>$D_{13}(1520)$, $D_{13}(1700)$</td>
</tr>
<tr>
<td>$3^-\over2$</td>
<td>$1/2, 3/2$</td>
<td>$(p\rho)_{(s=3/2;\ell=0,2)}$</td>
<td>4</td>
<td>$D_{33}(1700)$</td>
</tr>
<tr>
<td>$5^+\over2$</td>
<td>$1/2, 3/2$</td>
<td>$(\Delta\pi)_{(\ell=1)}$</td>
<td>4</td>
<td>$F_{15}(1680)$</td>
</tr>
<tr>
<td>$5^-\over2$</td>
<td>$1/2, 3/2$</td>
<td>$p\sigma$</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>$5^-\over2$</td>
<td>$1/2, 3/2$</td>
<td>$(\Delta\pi)_{(\ell=2)}$</td>
<td>4</td>
<td>$F_{15}(1675)$</td>
</tr>
<tr>
<td><strong>t-channel $\rho$</strong></td>
<td>$1/2, 3/2$</td>
<td>$\lambda_\rho = +1, -1$</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

Total # of waves: 37

Focus on $W < 1.9 \text{ GeV/c}^2$
### Waves used in the following analysis

<table>
<thead>
<tr>
<th>$J^P$</th>
<th>$M$</th>
<th>Isobars</th>
<th>Motivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1/2^+$</td>
<td>1/2</td>
<td>$\Delta\pi (={\Delta^{++}\pi^-, \Delta^0\pi^+})$</td>
<td>$P_{11}(1440), P_{11}(1710)$</td>
</tr>
<tr>
<td>$1/2^-$</td>
<td>1/2</td>
<td>$\Delta\pi, (\rho\rho)_{(s=1/2)}$</td>
<td>$S_{11}(1535), S_{11}(1650), S_{31}(1620)$</td>
</tr>
<tr>
<td>$3/2^+$</td>
<td>1/2, 3/2</td>
<td>$(\Delta\pi)<em>{(l=1)}, (\rho\rho)</em>{(s=1/2)}, (\rho\rho)_{(s=3/2;l=1,3)}$</td>
<td>$N^*(1440)\pi,$ $P_{13}(1720), P_{33}(1600)$</td>
</tr>
<tr>
<td>$3/2^-$</td>
<td>1/2, 3/2</td>
<td>$(\Delta\pi)_{(l=0,2)}$</td>
<td>$D_{13}(1520), D_{13}(1700), D_{33}(1700)$</td>
</tr>
<tr>
<td>$5/2^+$</td>
<td>1/2, 3/2</td>
<td>$(\Delta\pi)_{(l=1)}, p\sigma$</td>
<td>$F_{15}(1860)$</td>
</tr>
<tr>
<td>$5/2^-$</td>
<td>1/2, 3/2</td>
<td>$(\Delta\pi)_{(l=2)}$</td>
<td>$D_{15}(1675)$</td>
</tr>
</tbody>
</table>

- Total of 35 waves (complex amplitudes)
- Diffractive production ("t-channel") also included
Partial wave fits to $p\pi^+\pi^-$ data for $W = 1.69 - 1.71$ GeV

4 waves

37 waves
Dalitz Plot for $p\pi^+\pi^-$

Data

Monte Carlo

$1.475 < W < 1.500 \text{ GeV}/c^2$
Comparison with Isobar Model Fit

... shows good agreement between the two methods
Can we discover new baryons with this technique?

$F_{15}(1680)$

$P_{13}(1720)$?

$M \sim 1650$ MeV, $\Gamma \sim 115$ MeV

$M \sim 1770$ MeV, $\Gamma \sim 85$ MeV

Mass shifts due to interference effects?
Other searches for new baryon states.
New N* resonance in J/ψ decays?

New data from BEPC (e^+e^- collider in Beijing) suggest a new N* state at ~2068 MeV observed in:

\[ e^+e^- \rightarrow J/\psi \rightarrow NN\pi \]

Why is there no Δ(1232) peak?

- Isospin conservation in decay \( I_{\pi N} = \frac{1}{2} \).

![Graphs showing particle interactions](image-url)
Strangeness Photoproduction

Dominant resonances

$S_{11}(1650)$
$P_{11}(1710)$
$P_{13}(1720)$

$D_{13}(1895)$ ?
Strangeness Photoproduction

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

- Sample of data covering the full kinematic range in energy and angles for \( K^+\Lambda \) and \( K^+\Sigma \), including recoil polarization
- Data indicate significant resonance contributions, interfering with each other and with non-resonant amplitudes.
- Extraction of resonance parameters requires a large effort in partial wave analysis and reaction theory.
Strangeness in electroproduction

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

**forward hemisphere**

\[ 0. < \cos(\Theta_K) < 1., \ Q^2 = 0.7 \text{ (GeV/c)}^2 \]

**backward hemisphere**

\[ -1. < \cos(\Theta_K) < 0., \ Q^2 = 0.7 \text{ (GeV/c)}^2 \]
Resonances in $\gamma p \rightarrow p\omega$?

Model: Y. Oh

- OPE + Pomeron
- $N^*$ Capstick model
- Sum
Pentaquark baryons - are we discovering a new form of matter?
Mesons: quark-antiquark pair

Baryons: three quarks (valence)

Pentaquarks: 4 quarks + 1 antiquark

QCD requires that hadrons must be colorless
Types of Pentaquarks

• “Non-exotic” pentaquarks
  – The antiquark has the same flavor as one of the other quarks
  – Difficult to distinguish from 3-quark baryons

  Example: uuds̅̅, same quantum numbers as uud
  Strangeness = 0 + 0 + 0 - 1 + 1 = 0

• “Exotic” pentaquarks
  – The antiquark has a flavor different from the other 4 quarks
  – They have quantum numbers different from any 3-quark baryon
  – Unique identification using experimental conservation laws

  Example: uudds̅
  Strangeness = 0 + 0 + 0 + 0 + 1 = +1
Hadron Multiplets

Mesons $\bar{q}q$

Baryons $qqq$

Baryons built from $qqqqq\bar{q}$

\begin{itemize}
  \item $\kappa$
  \item $\pi$
  \item $\bar{\kappa}$
  \item $\Delta^-$
  \item $\Delta^{++}$
  \item $\Omega^-$
  \item $\Xi^+$
  \item $\Xi^-$
  \item $N$
  \item $\Xi$
  \item $\Sigma$
\end{itemize}
The Anti-decuplet in the Chiral Soliton Model


Symmetries give an equal spacing between “tiers”

$\Gamma < 15 \text{ MeV}$

Assumption in model

$S = +1$  \[ \Theta^+(1530) \]

$S = 0$  \[ N(1710) \]

$S = -1$  \[ \Sigma(1890) \]

$S = -2$  \[ \Xi(2070) \]

$180 \text{ MeV}$
The Anti-decuplet in the Chiral Soliton Model


... and in the Quark Model

\( \Theta^+(1530) \)

\( uudd\bar{s} \)

\( udd(uu + ss) \)

\( uds(uu + dd + ss) \)

\( uus(\bar{d}d + ss) \)

\( \Sigma(1890) \)

\( dss(uu + d\bar{d}) \)

\( uuss(\bar{d}d + \bar{d}\bar{d}) \)

\( \Xi(2070) \)

\( ddss\bar{u} \)

\( dss(\bar{u}u + d\bar{d}) \)

\( uuss(\bar{u}u + d\bar{d}) \)

\( uussd\bar{d} \)
Some quark descriptions of the $\Theta^+$ Pentaquark

(qq)$\bar{q}$ description (Jaffe, Wilczek)

$(ud)$

$L=0$

$L=1$

$L=1$, one unit of orbital angular momentum needed to obtain as in the $\chi_{SM}$

$J^P = \frac{1}{2}^+$

$(qq\bar{q})(qq)$ description (Karliner, Lipkin)

two color non-singlets

$(ud)$

$L=1$

$(uds)$

distance $> \text{color magnetic force}$

$LQCD$:

$J^P = \frac{1}{2}^-$

$\frac{1}{2}^+$

no signal

2 groups

1 group

1 group
Evidence for $\Theta^+$ Pentaquark

G. Rosner
$\Theta^+(1540)$ as seen with e.m. probes

*T. Nakano et al., PRL91, 012002 (2003)*

The LEPS experiment at SPring8

$\gamma^{12}C \rightarrow K^-K^+X$

- $K^+K^-$ observed at forward angles.
  Interaction on neutron ensured by veto for protons.

- After corrections for Fermi motion a peak of ~20 events is observed in $K^-$ miss. mass.

Comment: First claim of $\Theta^+$, but low statistics result.
CEBAF Large Acceptance Spectrometer

**Torus magnet**
6 superconducting coils

**Liquid $D_2 (H_2)$ target +**
$\gamma$ start counter; e minitorus

**Drift chambers**
argon/CO$_2$ gas, 35,000 cells

**Time-of-flight counters**
plastic scintillators, 684 PMTs

**Large angle calorimeters**
Lead/scintillator, 512 PMTs

**Gas Cherenkov counters**
e/$\pi$ separation, 216 PMTs

**Electromagnetic calorimeters**
Lead/scintillator, 1296 PMTs
**CLAS - Exclusive production from deuterium**

Photon beam on deuterium

\[ E_\gamma = 1 - 3 \text{ GeV} \]

\[ \gamma D \rightarrow K^- pK^+ n \]

- **K^-pK^+ event reconstruction**

Kaon time relative to proton time

\[ \Delta t_K = t - \frac{R}{\beta_c c}; \beta_c = \frac{p}{\sqrt{p^2 + m_K^2}} \]

[TOF particle id]

[Event reconstruction diagram]
Process identification and event selection

**Missing mass technique**

\[ \gamma D \rightarrow K^- p K^+ n \]

- Events vs. Neutrons mass
- 3-body Dalitz plot
- \( |\Delta t_{pK}| \leq 0.75 \) ns
- \( 0.8, 0.85, 0.9, 0.95, 1, 1.05, 1.1 \) GeV/c^2
- \( 0, 50, 100, 150, 200, 250, 300 \) Events
- \( \Lambda(1520) \)
- \( \phi(1020) \)
- Cut
**CLAS** - The Θ⁺(1540) on Deuterium.

**Removal Cuts:**
- \( M(K^+K^-) < 1.070 \text{ GeV} \) - removes \( \phi(1020) \)
- \( 1.485 < M(pK^-) < 1.551 \text{ GeV} \) - removes \( \Lambda(1520) \)
- \( p_n < 80 \text{ MeV/c} \) - removes spectator neutrons
- \( p_{K^+} > 1 \text{ GeV/c} \) - reduces background at \( M(nK^+) > 1.7 \text{ GeV} \)
Θ⁺(1540) in CLAS

Requires rescattering from proton to allow detection of proton in CLAS.

S. Stepanyan et al., PRL91, 252001 (2003)
**CLAS – Exclusive Production on Hydrogen**

$4.8 < E_\gamma < 5.4 \text{ GeV}$

$\gamma p \rightarrow K^+K^-\pi^+n$

- Further cuts are motivated by assumptions on production mechanism.
Exclusive Production on Hydrogen

Possible production mechanism

- Select t-channel process by tagging forward $\pi^+$ and reducing $K^+$ from t channel processes

\[ \cos\theta_{\pi^+}^* > 0.8 \]
\[ \cos\theta_{K^+}^* < 0.6 \]

(in c.m. frame)
CLAS - $\Theta^+(1540)$ on protons

$E_\gamma = 3 - 5.4 \text{ GeV}$

$\gamma p \rightarrow \pi^+ K^+ K^- n$

$M(nK^+)$

Significance = 7.8 $\sigma$

$M= 1555 (7)(10)$

$\Theta^+$ production through $N^*$ resonance decays?

V. Kubarovsky et al., PRL 92, 032001 (2004)
CLAS - $\Theta^+$ production mechanism?

$E_\gamma = 3 - 5.4$ GeV

$\gamma p \rightarrow \pi^+ K^+ K^- n$

7.8σ significance
$M = 1555 (7)(10)$
$\Gamma \sim 35$ MeV

- $\Theta^+$ production through $N^*$ resonance decays?
- Cut on $\Theta^+$ mass, and plot $M(nK^+K^-)$
What do π⁻p scattering data say?

π⁻p cross section data in PDG have a gap in the mass range 2.3–2.43 GeV.
Evidence for $\Theta^+$ Pentaquark

This is a lot of evidence! So, what is the problem?

$JP = \frac{1}{2}^-$

$pp \rightarrow \Sigma^+\Theta^+$.
So, what is the problem?

- If Pentaquark baryons exist it is the most important finding in hadronic physics since the J/Ψ discovery. It is absolutely necessary to obtain fully convincing experimental data.

- Many experiments see positive Θ⁺ signal with specific kinematical cuts, taken together they represent an impressive significance. However, few experiment have fully convincing results:
  - significance is often optimistically estimated ~4–6σ
  - background estimates are not always justified
  - masses are not fully consistent (1525–1555) MeV
  - are kinematical reflections excluded?

- Many high energy experiments present null results. This adds a level of uncertainty until we understand the sensitivities in various experiments.

- The very narrow width of ~1 MeV is not understood, although models have been developed that allow Θ⁺ widths of < 1 MeV.
A narrow resonance in \( m_{12} \) near kinematical limit may appear like a broad enhancement in \( m_{23} \) (kinematical reflection).
The $\Theta^+(1540)$ as a kinematical reflection?

Is this a more realistic background?

If kinematical reflections from $M \rightarrow K^+K^-$ can generate the $\Theta^+$ peak, they should show up in $nK^-$ as well, assume isospin symmetry.

Kinematic reflections do not seem to generate narrow $nK^-$ peak.
Nobody can *seriously* suggest that this is a kinematical reflection!

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

- 7.8\(\sigma\) significance
- \(M = 1555 (7)(10)\) MeV
- \(\Gamma \sim 35\) MeV
Is there a problem with the mass?

Mass shift could be due to different background shapes, final state interactions, and different interference effects in the two channels.
Are the null experiments sensitive to $\Theta^+(1540)$?

Several high energy experiments have analyzed their data in the search for the $\Theta^+$. In the following, I examine two of them, **BaBar** and **Belle**, both detectors to study $e^+e^-$ interactions at high energy to study B mesons. They use very different techniques, and neither has seen a signal.

**=> BaBar** studies particles produced in $e^+e^-$ annihilations and subsequent quark fragmentation processes.

**=> Belle** uses $K^+$ and $K^-$ produced in the fragmentation. They study $K^+$-nucleus scattering in their silicon (?) tracking Detectors. This is similar to the DIANA experiment that measured $K^+Xe$ in a bubble chamber where they saw a $\Theta^+$ signal.

Do these results contradict experiments that have seen a signal?
No signal observed in any $p^*$ region ($SFL > 0.0$ cm)

$0.0 < p^* < 0.5$ GeV/c

$3.5 < p^* < 4.0$ GeV/c
Hadron production in $e^+e^-$

Pentaquark production in direct $e^+e^-$ collisions likely requires orders of magnitudes higher rates than available.

Slope:
- Pseudoscalar mesons: $\sim 10^{-2} / \text{GeV}/c^2$ (need to generate one $qq$ pair)
- Baryons: $\sim 10^{-4} / \text{GeV}/c^2$ (need to generate two pairs)
- Pentaquarks: $\sim 10^{-8} / \text{GeV}/c^2$ (?) (need to generate 4 pairs)

Pentaquark production in direct $e^+e^-$ collisions likely requires orders of magnitudes higher rates than available.
Pentaquarks in Quark Fragmentation?

Pentaquarks in $e^+e^-$ (BaBaR)?:
- Current fragmentation
- Pentaquark production suppressed

Pentaquarks in $ep$? (ZEUS, H1, HERMES):
- Target fragmentation
- Pentaquarks not suppressed
What do we know about the width of $\Theta^+$?

$K^+d \rightarrow X$

\[ \Gamma_\Theta = 0.9 \pm 0.3 \text{ MeV} \] (K$^+$d $\rightarrow X)

Same width is obtained from analysis of DIANA results on K$^+$Xe scattering. (R. Cahn and G. Trilling, PRD69, 11401(2004))
Belle: The basic idea

- Small fraction of kaons interacts in the detector material. Select secondary pK pairs to search for the pentaquarks.
- Momentum spectrum of the projectile is soft. \( \Rightarrow \) low energy regime.

![Graph showing momentum spectra of \( K^+ \) and \( K^- \)]
Belle: Distribution of Secondary pK\textsuperscript{-} Vertices in Data

"Strange particle tomography" of the detector.
Belle: Mass Spectra of Secondary pK

What should we have expected here?
\[ \sigma_{\text{tot}}: K^+d \]

\[
\begin{align*}
\Theta^+ & \quad \text{width: } 0.9+/-0.3 \text{ MeV} \\
\end{align*}
\]

Only narrow momentum bin can contribute to \( \Theta^+ \) production if only 1 MeV wide and smeared by Fermi motion.

Momentum range possibly contributing to \( \Theta^+ \) production.
Belle: Mass Spectra of Secondary pK

For I=0:
\(nK^+: pK^0_s; pK^0_L\)
\[2 : 1 : 1\]

This is approx. what we should have expected here!
Assume that background events have same isospin structure as \(\Theta^+\) events.
- The $K^+$ beam gets slowed down in the Xe bubble chamber and comes to a stop if no interaction occurs.
- Every $K^+$ has the chance to generate a $\Theta^+$ within a few MeV energy bin, unless it interacts before it is sufficiently slowed down.
- This is a much more efficient way of using $K^+$ compared to using a broad band beam on a thin target.
Belle: Compare with DIANA

Kaon momentum range that may contribute to $\Theta^+$ excitation in nuclei $\sim 50$MeV/c.

Note that this restriction is absent in the DIANA experiment where the K+ looses momentum continuously throughout the interaction region, i.e. every K+ has the chance to contribute to the $\Theta^+$ signal.

$K^+\text{Si/C (thin)}$ versus $K^+\text{Xe(thick)}$

Belle versus DIANA
Mom. spectrum 850MeV/c
Summary of Θ⁺

- Existing “Null” Experiments need to prove their sensitivity to the Θ⁺ before they can claim anything. Proving a negative is, of course, difficult. The best is to reproduce the experiments that have seen the signal and repeat them with higher statistics, better systematics, etc.. This is what is happening at JLab.

- High energy experiments studying current fragmentation processes may not have sensitivity to see any signal.

- Sensitivity should be much higher in target fragmentation region (HERMES, ZEUS, H1).

- Experiments using broad band momentum spectrum in secondary interaction (K+-nucleus) must compare with DIANA and K⁺D scattering results and prove sensitivity
What’s next with CLAS?

- CLAS at JLab finished data taking with two runs
  - Statistics > 10 times with deuterium target
  - high statistics run on hydrogen target
  - Other high statistics runs at higher energy are in preparation
**CLAS - G11 “online” plots**

\[ \gamma p \rightarrow K_s K^+(n); K_s K_p; K^+ K_p; K^+ K^- \pi^+(n) \]

\[ \gamma p \rightarrow \pi^+ \pi^-(p) \]

(calibration reaction)

\[ \gamma p \rightarrow \pi^+ \pi^- K^+(n) \]
The End of my Lectures