Nucleon Resonances

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Introduction
Missing resonances
N→Δ transition
Summary
Physics Goals

• Understand QCD in the strong coupling regime
  – example: bound qqq systems
  – mass spectrum, quantum numbers of nucleon excited states
  – what are the relevant degrees-of-freedom
  – wave function and interaction of the constituents

• Source of information
  – dominated by pion-induced reactions (mostly $\pi N \rightarrow \pi N$)
  – advantage:
    • strong coupling $\rightarrow$ large cross sections
    • simple spin structure
    • good quality beams
  – disadvantage: no structure information
    insensitive to states with weak $\pi N$ coupling
Theoretical Models

• Constituent quark model
  – 3 constituent quarks
  – all 3 contribute to number of states
  – non-relativistic treatment (typically)

• Refinements of the constituent quark model
  – restore relativity
  – hadronic form factors
  – coupling between decay channels

• Lattice gauge calculations
Program Requirements

Experiment

large high-quality data set for N* excitation covering
- a broad kinematical range in Q², W, decay angles
- multiple decay modes (π, ππ, η, ρ, ω, K)
- polarization information (sensitive to interference terms)

Analysis

Δ(1232): full Partial Wave Analysis possible
(isolated resonance, Watson theorem)

higher resonances
- need to incorporate Born terms, unitarity, channel coupling
- full PWA presently not possible due to lack of data (polarization)
  (substitute by assuming energy dependence of resonance)
- skills required at the boundary between experiment and theory
Quark Model Classification of N^*

“missing” P_{13}(1850) Capstick& Roberts
"Missing" Resonances?

Problem: symmetric CQM predicts many more states than have been observed (in $\pi N$ scattering)

Two possible solutions:

1. di-quark model
   fewer degrees-of-freedom
   open question: mechanism for $q^2$ formation?

2. not all states have been found
   possible reason: decouple from $\pi N$-channel
   model calculations: missing states couple to
   $N\pi\pi$ ($\Delta\pi$, $N\rho$), $N\omega$, KY

$\gamma$ coupling not suppressed $\rightarrow$ electromagnetic excitation is ideal
Electromagnetic Probe

- Helicity amplitudes very sensitive to the difference in wave functions of $N$ and $N^*$

- Can separate electric and magnetic parts of the transition amplitude

- Varying $Q^2$ allows to change the spatial resolution and enhances different multipoles

- Sensitive to missing resonance states
Standard Analysis Approach

known resonance parameters
(mass, width, quantum numbers, hadronic couplings)

Analysis

photo- and electro-production data base
(mostly differential cross sections)

electromagnetic transition form factors
e p → e X at 4 GeV

Elastic

Deep Inelastic

Δ(1232) N(1520) N(1680)

CLAS
CLAS Coverage for $e p \rightarrow e' X$

$p(e,e')X$
$E=4\text{GeV}$

$Q^2(\text{GeV}^2)$

$W(\text{GeV})$

N(1520)
N(1680)
N(940)
\Delta(1232)
missing states
deep inelastic

CLAS
CLAS Coverage for $e^+ p \rightarrow e' p X, \ E=4$ GeV

CLAS Coverage for $e^+ p \rightarrow e' p X, \ E=4$ GeV

**Diagram Description:**
- The diagram illustrates the CLAS coverage for the reaction $e^+ p \rightarrow e' p X$ at $E=4$ GeV.
- The graph shows the missing mass ($W$) versus the mass of the final state ($M_X$) in units of GeV.
- Key resonances labeled are N(1680), N(1520), Δ(1232), $\pi^0$, $\eta$, and $\omega$.
- The diagram highlights the missing states and the regions of interest for this reaction.

**Legend:**
- The CLAS logo is visible in the bottom right corner.
- The diagram is published by JLab S&T Review, July 15, 2002.
Resonance Contributions to $\gamma^* p \rightarrow p \omega$?

CLAS above resonance region

in resonance region

\begin{align*}
\sigma &\rightarrow \gamma p \\
N^* &\rightarrow p p
\end{align*}
Resonances in Hyperon Production?

$$\gamma^* p \rightarrow K^+ Y$$

**CLAS**

forward hemisphere

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

backward hemisphere

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

preliminary
Analysis performed by Genova-Moscow collaboration

step #1:
use the best information presently available

\( \Gamma_{N\pi\pi} \) from PDG
\( \Gamma_{N\gamma} \) AO/SQTM

extra strength
Attempts to fit observed extra strength

Analysis step #2:

- vary parameters of known $D_{13}$
  or
- introduce new $P_{13}$

\[
\sigma (\mu b) \\
W(\text{GeV})
\]

- $Q^2 = 0.65 \text{ GeV}^2$
- $Q^2 = 0.95 \text{ GeV}^2$
- $Q^2 = 1.30 \text{ GeV}^2$
Summary of $\gamma^* p \rightarrow p \pi^+ \pi^-$ Analysis

CLAS data at variance with N* information in PDG

Describing data requires

• major modifications of the parameters of known resonances, or

• introduction of new $P_{13}$ resonance with

  (consistent with “missing” $P_{13}$ state, but mass lower than predicted)

Next steps:

• more experimental data already in hand

• combined analysis with other decay channels: $\pi N$, $\eta N$, $K\Lambda$

M = 1.72 +/- 0.02 GeV
$\Gamma_T = 88 +/- 17$ MeV
$\Delta \pi : 0.41 +/- 0.13$
$N\rho : 0.17 +/- 0.10$
Electromagnetic Probe

- Helicity amplitudes very sensitive to the difference in wave functions of $N$ and $N^*$
- Can separate electric and magnetic parts of the transition amplitude
- Varying $Q^2$ allows to change the spatial resolution and enhances different multipoles
- Sensitive to missing resonance states
N $\rightarrow \Delta(1232)$ Transition Form Factors

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

(E/M) $\quad$ (S/M) $\quad$ (A. Buchmann, E. Henley, 2000)

- E/M: ~0.03 $\sim$ 0.1
- S/M: ~0.01

pion cloud
one-gluon exch.
pQCD

+1 const.
Multipoles $E_{1+}/M_{1+}$, $S_{1+}/M_{1+}$ (before 2001)
Kinematics and Cross Sections

example:
\[ e + p \rightarrow e' + p + \pi^0 \]

\[
\frac{d\sigma}{d\Omega_e dE' e d\Omega_\pi} = \Gamma_t \left( \sigma_t + \varepsilon \sigma_l + \varepsilon \sigma_{tt} \cos 2\phi_\pi + \sqrt{2\varepsilon (\varepsilon + 1)} \cdot \sigma_{tl} \cos \phi_\pi \right)
\]
$Q^2 = 0.40 \text{(GeV/c)}^2$, $\Delta Q^2 = 0.100 \text{(GeV/c)}^2$
Multipole Analysis for $\gamma^* p \rightarrow p \pi^0$

CLAS

$Q^2 = 0.9 \text{ GeV}^2$

\[ |M_{1+}|^2 \]

\[ \text{Re}(E_{1+}M_{1+}^*) \]

\[ |M_{1+}|^2 \]

\[ \text{Re}(S_{1+}M_{1+}^*) \]
Multipoles $E_{1+}/M_{1+}$, $S_{1+}/M_{1+}$ (2002)
Theoretical Interpretation of $E_{1^+}/M_{1^+}$, $S_{1^+}/M_{1^+}$
N→∆ Transition, what’s next?

- systematic uncertainties in extraction of $E_{1+}/M_{1+}$ from $ep\rightarrow e'p\pi^0$ around 0.5%
  - differences in treatment of background terms (models not constrained)
  - will become more severe for higher $Q^2$ ($\Delta$ dropping faster)

- more experimental information in hand (analysis in progress)
  - cross sections $ep\rightarrow e'p(\pi^0)$ $Q^2 = (1.5 - 5.5)$ GeV$^2$
  - single-spin asymmetry $\sigma_{TL}$ for $e^-p\rightarrow e'p(\pi^0)$ and $e^-p\rightarrow e^+\pi^+(n)$
  - polarization transfer in $e^-p\rightarrow e'^-p(\pi^0)$
  - differential cross sections for $e^-p\rightarrow e'^+\pi^-n$ ($\Delta$ less important)

- experiments in the near future
  - extend $Q^2$ range to 0.05 GeV$^2$ (end of 2002)
  - extend $Q^2$ range to ~7 GeV$^2$ (1st half of 2003)
Polarized Beam Observables

CLAS

$\sigma_{LT'}$ response function for

$\vec{e} \ p \rightarrow \vec{e} \ p \ \pi^0$

$\sigma_{LT'} = 0$ if only a single diagram contributes (sensitive to the interference between $\Delta$ and background)
Polarization Measurement in $\vec{e} \ p \rightarrow e' \ \vec{p} \ (\pi^0)$

Hall A

$Q^2 = 1 \text{ GeV}^2$

$W = 1.232 \text{ GeV}$

Results sensitive to non-resonant contributions

Parametrisations of available data

--- SAID

---- MAID
$\pi^+$ Electroproduction

CLAS

$W$, GeV/c$^2$

$\mu_b$/sr

$\theta^*$, deg
Summary

• Understanding the structure of bound qqq systems is a central problem for the study of QCD in the strong coupling regime

• Specific issue #1: identify relevant degrees-of-freedom
  – finally getting electromagnetic data of sufficient quality to study missing resonance problem
  – initial data strongly suggest resonance contributions that cannot be explained by known baryon states

• Specific issue #2: probing details of quark wave functions
  – consistent data set for $N \rightarrow \Delta$ transition up to $Q^2 = 4 \text{ GeV}^2$
  – $E_{1+}/M_{1+}$ small and negative
  – data emphasize the importance of pion degrees-of-freedom and relativity