Baryon Spectroscopy: an overview

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substituting

Volker Burkert
Hall-B leader at JLab
Baryon Spectroscopy reveals the workings of QCD.

\[
\mathcal{L}_{\text{QCD}} = \sum_{q=u,d,s,c,b} \bar{q} \left( i \gamma_\mu D^\mu - m_q \right) q - \frac{1}{4} \mathcal{F}^{\mu \nu} \mathcal{F}_{\mu \nu}
\]
color wave-functions

\[ p^+ = \frac{1}{\sqrt{N_c}} \left[ u\bar{d} + u\bar{d} + u\bar{d} + u\bar{d} + \ldots \right] \]

\[ p = \frac{1}{\sqrt{6}} \left[ uud + uuuds + uuuds \right. \]
\[ \left. - uud - uuuds - uuuds \right] \]
Motivation

• Understanding the working of QCD: non-perturbative low energy scale ($\approx$ GeV)
Motivation

- Understanding the working of QCD: non-perturbative low energy scale ($\approx \text{GeV}$)

Baryons

Mesons
Motivation

- Understanding the working of QCD: non-perturbative low energy scale ($\approx$ GeV)
Motivation

- Understanding the working of QCD: non-perturbative low energy scale ($\approx$ GeV)

hadronic degrees of freedom
Why do we study N*’s?

“Nucleons are the stuff of which our world is made. As such they must be at the center of any discussion of why the world we actually experience has the character it does. I am convinced that completing this chapter in the history of science is one of the most interesting and fruitful areas of physics for at least the next 30 years. “ Nathan Isgur, NStar2000, Newport News, Virginia.

- Only now do we have experimental, phenomenological, and theoretical tools to fully explore baryon spectrum and structure.
- The N* spectrum reflects the underlying degrees of freedom and the effective forces between them.

- Vigorous experimental program needed along two avenues
  - Search for undiscovered states in photoproduction (ELSA, GRAAL, JLab, MAMI)
  - Identify the relevant degrees of freedom for prominent states versus distance scale in meson electroproduction (JLab/JLab12)
- New developments in theory connect to QCD – LQCD, DSE/QCD, AdS/QCD

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Motivation

- Understanding the working of QCD: hadronic degrees of freedom.
- Connection between constituent and current quarks.

Current-quarks of perturbative QCD evolve into constituent quarks at low momentum.

Numerical simulations of unquenched lattice QCD (Bowman et al.)

Dyson-Swinger equation (Bhagwat et al.)
QCD-inspired Constituent Quark Models

States classified by isospin, parity and spin within each oscillator band.

Infant Quark Model

QCD-inspired Constituent Quark Models

Findings:

• Linear Regge trajectories

• Only lowest few in each band seen with 4★ or 3★ status

• $g(\pi N)$ couplings predicted to decrease rapidly with mass in each oscillator band

• Higher levels predicted to have larger couplings to $K\Lambda$, $K\Sigma$, $\pi\pi N$, …
2 quarks in nucleon assumed to be quasi-bound in a color isotriplet; diquark-quark is a net color isosinglet.

all possible internal di-quark excitations ⇔ full spectrum of CQM

internal di-quark excitations are frozen out (spin 0; isospin 0) ⇔ large reduction in the number of degrees of freedom ⇔ predicts less N* states than seen in \( \Xi N \)

the challenge: ⇔ unravel the N* spectrum
Excited Baryons from L QCD

- Exhibits the SU(6) x O(3)-symmetry features
- Counting of levels consistent with non-rel. quark model
- Striking similarity with quark model
- No parity doubling


Problems are not solved!
search all channels: not just $pN$

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pN → pN scattering

\[ \frac{d\sigma}{dW} \]

\begin{align*}
1234 \text{ MeV} & \quad 1449 \text{ MeV} & \quad 1678 \text{ MeV} & \quad 1900 \text{ MeV}
\end{align*}

\begin{align*}
p^+p & \rightarrow p^+p & p^-p & \rightarrow p^-p & p^-p & \rightarrow p^0n
\end{align*}

\begin{align*}
q & \quad q & \quad q
\end{align*}
pN → pN scattering

1234 MeV

1449 MeV

1678 MeV

1900 MeV
pN amplitudes

Isospin 1/2
Imaginary T

Julia-Diaz, Lee, Matsuyama, Sato
Photonuclear cross sections
Search for new $N^*$ and $\Delta^*$ states

- Precision measurements of photo-induced processes in wide kinematics, e.g. $\gamma p \rightarrow \pi N, \eta p, K\gamma, .., \gamma n \rightarrow \pi N, K^0\gamma^0, ..$

- Polarization observables are essential

- More complex reactions, e.g. $\gamma p \rightarrow \omega p, \rho\phi, \pi\pi p, \eta\pi N, K^*\gamma, ..$ may be sensitive to high mass states through direct transition to ground state or through cascade decays

Engagement of groups to extract physics in theoretically sound analyses is essential.

By Volker Burkert

(Over)complete experiments

- Process described by 4 complex, parity conserving amplitudes
- 8 well-chosen measurements are needed to determine amplitude.
- Up to 16 observables measured directly
- 3 inferred from double polarization observables
- 13 inferred from triple polarization observables

The holy grail of baryon resonance analysis

Experimental Requirements

- Tagged and polarized photon beam
- Large acceptance detector
- H and D polarized targets

Modern experiments are constructed to meet all above requirements:

- GRAAL
  \[ E_X = (500 - 1500) \text{ MeV} \]

- CLAS in Hall-B
  \[ E_X = (500 - 6000) \text{ MeV} \]

- BGO-OD&Crystal Barrel@BONN
  \[ E_X = (500 - 3000) \text{ MeV} \]

- Crystal Ball@MAINZ
  \[ E_X = (100 - 1500) \text{ MeV} \]
Polarized photon beams: Compton Backscattering

- **Hi**s below threshold
- **Legs** **W**33(1232) resonance region
- **Graal** **E**g = 0.6-1.5 GeV / **W**=1.4-1.9 GeV
  Region of the second and third baryon resonances **η**, **K**, **ω**, thresholds
- **Leps** **E**g = 1.5-2.5 GeV
  **η’** thresholds
Polarized photon beams: Compton Backscattering

GRAAL/ESRF

LEGS/BNL

LEPS/SPRING8

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The Graal detector:
Large Acceptance Graal Apparatus for Nuclear Experiments

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CEBAF

Continuous Electron Beam Accelerator Facility

- E: 0.75 – 6 GeV
- \( I_{\text{max}} \): 200 mA
- Duty Cycle: 100%
- \( (E)/E \): 2.5\times10^{-5}
- Polarization: ≥85%
- Simultaneous distribution to 3 experimental Halls

Injector

Experimental Halls

A

B

C
CEBAF Large Acceptance Spectrometer

- Torus magnet
  6 superconducting coils

- Electromagnetic calorimeters
  Lead/scintillator, 1296 photomultipliers

- Target + Start counter

- Drift chambers
  35,000 cells

- Time-of-flight counters
  Plastic scintillators, 684 photomultipliers

- Gas Cherenkov counters
  e/ separation, 256 PMTs
Circularly polarized photons

- Circularly polarized beam produced by longitudinally polarized electrons
- CEBAF electron beam polarization >85%
- tagged flux ~ 50 - 100MHz for k > 0.5 E₀

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

Linearly polarized photons: coherent bremsstrahlung on oriented diamond crystal

Data for PERP 1.3 GeV
Calculation

Polarization corresponding to calc
(Peaking at > 90%)
Longitudinal Polarization: above 80%
Relaxation time: > 2000 hours
Polarization procedure< 6 hours
Data taking: 5-6 days

Very reliable.
HDIce polarized target

**HDIce Solid Deuterium-Hydride (HD) – a new class of polarized target**

- Spin can be moved between H and D with RF transitions
- All material can be polarized with almost no background

- Designed for both $\gamma$ (w Start Counter) and $e^-$ (w mini-Torus) running
- 13 mW cooling at 0.3 K

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**Graphs:**

1. $\gamma + \hat{H}D \rightarrow \pi^0(p)$
   - $Z^2 = 1$
   - $A = 1-2$
   - Missing Energy (MeV)

2. $\gamma + C\hat{H}OH \rightarrow p(\pi^0)$
   - $Z^2 \sim 50$
   - $A = 12-16$
   - Missing Energy (MeV)
Longitudinal and Transverse Polarizations: \(> 60\%\)
Relaxation time: \(> 1\) year
Polarization procedure \(\geq 3\) months
Data taking: \(\geq \) months
Very complicated target transfer technology.
HD-Ice

H D polarization during g14

tgt 21a

tgt 19b

tgt 22b

\[ P(H) \text{ (\%)} \]

-20

0

20

40

0

10

rf spin flip

rf spin flip

rf H => D spin transfer

rf H => D spin transfer

Down Sweep (%)

Up Sweep (%)
quench

field rotation

\[ g14 \text{ days} \]
<table>
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<th>Reaction Channels</th>
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<td>$\gamma p \rightarrow \pi^0 p, \pi^+ n$</td>
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<td>$\gamma n \rightarrow \omega n$</td>
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$g \rho \rightarrow p^+ n$ Photon asymmetry $S$
g_{\mu} p^+ n \text{ Helicity asymmetry } E

circularly polarized beam – longitudinally polarized target (g9a-FROST)
g9a data compared to current PWA analyses in the energy range 730 – 2300 MeV for fixed angular bins

J. McAndrew, Edinburgh
Strangeness production $\gamma p \rightarrow K^+\Lambda \rightarrow K^+p\pi^-$

$M.$ Mc Cracken et al. (CLAS), Phys. Rev. C 81, 025201, 2010  
Strangeness production \( \gamma p \rightarrow K^+ \Lambda \rightarrow K^+ p \pi^- \)

M. Mc Cracken et al. (CLAS), Phys. Rev. C 81, 025201, 2010


A.V. Anisovich et al., EPJ A48, 15 (2012)
$\gamma p \rightarrow K^+\Lambda$ Photon Asymmetry $S$
$K^+\Lambda$ Helicity Asymmetry E

Helicity asymmetry $E$ for $E_t = 1.5$ GeV

Helicity asymmetry $E$ for $E_t = 1.6$ GeV

Helicity asymmetry $E$ for $E_t = 1.725$ GeV

Helicity asymmetry $E$ for $E_t = 1.9$ GeV

R. A. Schumacher, Carnegie Mellon University, ECT*, 9-26-2011

L. Casey, Catholic U.
Double Polarization Observables in K+ Photoproduction

\[
\frac{2N^x_+}{N^x_+ + N^x_-} = 1 + \alpha \frac{2P_\gamma O_x}{\pi} \cos \theta_p^x
\]

\[
\frac{2N^z_+}{N^z_+ + N^z_-} = 1 + \alpha \frac{2P_\gamma O_z}{\pi} \cos \theta_p^z
\]

\[207x557\]

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T in K⁺ Photoproduction

From Oₓ, Oₓ and T results:

- Ghent Isobar RPR Model:
  \[ S_{11}(1650) \quad P_{11}(1710) \quad P_{13}(1720) \]
  \[ P_{13}(1900) \quad D_{13}(1900) \]

- Bonn Gatchina Model:
  \[ S_{11}(1535) \quad S_{11}(1650) \quad P_{13}(1720) \quad P_{11}(1840) \]
  \[ P_{13}(1900) \]
The \( \Xi \) appears 100% polarized when created with a fully polarized beam.
The N(1900)3/2⁺ State

- State solidly established in coupled-channel analysis making use of very precise KΛ data, resulting in *** assignment in PDG2012.

- State was confirmed in covariant isobar model analysis (T. Mart & M. J. Kholili arXiv:1208.2780) of single channel analysis γp → K⁺Λ.

- Confirmed in an effective Langrangian resonance model analysis (O. V. Maxwell, PRC85,034611, 2012) of photo- and electroproduction of single channel K⁺Λ data.

- State may be ready for promotion to **** assignment and to become the first baryon resonance observed and confirmed in electromagnetic meson production.
$N^*, D^*$ spectrum from EBAC

Kamano, Nakamura, Lee, Sato 2012
N*, D* spectrum from EBAC & Bonn-Ga

Pole Mass (GeV)

Kamano, Nakamura, Lee, Sato 2012

EBAC
PDG 4*
PDG 3*

PDG
EBAC
BoGa

N*: 3*, 4*
18
16
24

N*: 1*, 2*
5

L2I2J

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N/\Delta spectrum in RPP 2012

Photoproduction data from JLAB, ELSA, GRAAL, LEPS

From Bonn-Gatchina coupled-channel analysis with precision photo-production of K \Lambda, K \Sigma and polarization observables.


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N* spectrum in LQCD

Projected new states constrained largely from meson photoproduction

\[ m_\pi = 396 \text{MeV} \]

New candidate states may be accommodated in LQCD projections
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| **Neutron target** |         |         |     |     |     |     |     |     |       |       |       |       |       |       |       |       |
| $p\pi^-$ | ✓       | ✓       | ✓   | ✓   | ✓   | ✓   | ✓   | ✓   |       |       |       |       |       |       |       |       |
| $p\rho^-$ | ✓       | ✓       | ✓   | ✓   | ✓   | ✓   | ✓   | ✓   |       |       |       |       |       |       |       |       |
| $K^-\Sigma^+$ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| $K^0\Lambda$ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| $K^0\Sigma$ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| $K^0\Sigma^0$ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| $K^0\Sigma^0$ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

- - published, ✓ - acquired, ✓ - planned
$N^*$ states in $\gamma p \rightarrow p \omega \rightarrow p\pi^+\pi^-(\pi^0)$


• Spin density matrix elements $\rho_{00}^0, \rho_{1-1}^0, \rho_{10}^0$ in blue - blue shades. Previous world data in red.

SDMEs with linearly and circularly polarized beams are being finalized. Together with $\rho_{00}^0, \rho_{1-1}^0, \rho_{10}^0$ they represent precise data sets for coupled-channel analyses.
The data are used as input to a single channel event-based, energy independent partial wave analysis (the first ever for baryons).

\( \omega \) photoproduction is dominated by the well-known \( F_{15}(1680) \) and \( G_{17}(2190) \), and the “missing” \( F_{15}(2000) \).

results on $\bar{\gamma} + p \rightarrow \omega + p$ at GRAAL:

$\omega \rightarrow \pi^0 \gamma$ and $\omega \rightarrow \pi^+ \pi^- \pi^0$

- Q. Zhao
  - s and u-channel including $P_{13}(1720)$
  - PRC63(2001)025203

- Bonn-Gatchina dominant $P_{13}(1720)$

- Giessen model
  - PRC71(2005)055206

- Oh,Titov and Lee
  - PRC66 (2002)015204

- M. Paris
  - PRC79 (2009) 025208

$\omega \rightarrow \pi^0 \gamma$
$\omega \rightarrow \pi^+ \pi^- \pi^0$
Electroexcitation of $N/\Delta$ resonances

- Probe resonance strength vs photon virtuality $Q$
- How do effective dof change with distance scale?
- Nature of excited states: QQQ, QQQG, MB

SU(6)$\times$O(3)

\[ \begin{array}{c}
\text{N}(1520)^{3/2}\
\text{N}(1535)^{1/2}\
\text{\Delta}(1700)^{3/2}\
\text{N}(1680)^{5/2}\
\text{N}(1720)^{3/2}
\end{array} \]

\[ \begin{array}{c}
\text{N}(940)
\end{array} \]

$\pi, \eta, \pi\pi$

$\Lambda_{1/2}, \Lambda_{3/2}, S_{1/2}$

$E, M, S$ multipoles

NStar2013 Peniscola, Spain
Electrocouplings of ‘Roper’ N(1440)1/2+

I. Aznauryan et al. (CLAS), PRC80, 055203 (2009), V. Mokeev et al. (CLAS), PRC86, 035203 (2012)

- $A_{1/2}$ dominant amplitude at high $Q^2$ indicates radial QQQ excitation
- Significant meson-baryon coupling at small $Q^2$
Hybrid states have same $J^P$ values as $Q^3$ baryons. How to identify them?
- Overpopulation of $N1/2^+$ and $N3/2^+$ states compared to QM projections?
- Transition form factors in electroproduction have different $Q^2$ dependence.
Separating $Q^3 G$ from $Q^3$ states?


Lowest mass $QQQG$ state $N1/2^+$

- $A_{1/2}(Q^2)$ dominant amplitude at high $Q^2$ indicates radial $QQQ$ excitation
- Significant meson-baryon coupling at small $Q^2$

For hybrid “Roper”, transverse amplitude $A_{1/2}(Q^2)$ drops off faster with $Q^2$, and $S_{1/2}(Q^2) \sim 0$. 
Conclusions

• Precise new data including double polarization data available or soon to be available, some data sets are “complete”.

• EBAC and Bo-Ga have produced their own baryon spectrum.

• For the first time the role of photoreaction data as been recognized by the PDG to impact the existing evidence of Nstar resonances, which seem to rule out di-quark models.

• Community achieved important milestone in the search for new baryon states from photoproduction – 6 new candidates, 2 almost certain in RPP 2012. Two further confirmations for N(1900)3/2⁺.

• Precise ω (and φ) photoproduction data available, can constrain the PWA in the search for high mass states. Should be included in coupled-channel PWA.

• The Q² dependence of resonance transition form factors may be employed to separate hybrid baryons from ordinary baryons.

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