Nucleon Resonance Physics

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- Introduction
- Establishing the N* spectrum
- Identifying the effective DoF’s
- Conclusions & outlook
From the hydrogen spectrum to the $N^*$

- Understanding the hydrogen atom’s ground state requires understanding its excitation spectrum. => From the Bohr model of the atom to $QED$.

- Understanding the proton’s ground state requires understanding its excitation spectrum. => From the constituent quark model to $QCD$.
Some historical markers

1952: First glimpse of the $\Delta(1232)$ in $\pi p$ scattering shows internal structure of the proton

1964: Baryon resonances essential in establishing the quark model and the color degrees of freedom.

1989: Broad effort to address the “missing baryons” puzzle

2010: First successful attempt to predict the nucleon spectrum in LQCD

2015: Understanding of the baryon spectrum needed to quantify the transition from the QGP to the confinement phase of nucleons in the early universe.
Excited baryons are at the transition of the QGP to the confinement of quarks and gluons in hadrons.

Can we understand this transition from the known excited baryons states?
Many projected $q^3$ states are still missing or are uncertain.
What do we want to learn?

- Understand the effective degrees-of-freedom underlying the N* spectrum and the forces between them.

A vigorous experimental program is underway worldwide with the aim
- search for undiscovered states in meson photoproduction at CLAS, CBELSA, GRAAL, MAMI, and LEPS
- confirm or dismiss weaker candidates (*, **, ***)
- characterize the systematic of the spectrum

Measure the strength of resonance excitations versus distance scale in meson electroproduction at JLab to identify effective degrees of freedom (JLab).
Establishing the N* and Δ* Spectrum

- Multi-GeV polarized cw beam, large acceptance detectors, polarized proton/neutron targets.
- Very precise data for 2-body processes, e.g. γp→Nπ, Nη, Kγ, in wide kinematics (angle, energy)
- More complex reactions needed to access high mass states, Nππ, Nπη, Nω/ϕ, ...

Extract s-channel resonances

V.B., T.S.H. Lee, 2004
Establishing the N* spectrum, cont’d

Essential new data on hyperon production

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

M. Mc Cracken et al. (CLAS), Phys.RevC81,025201,2010

Establishing the N* spectrum, cont’d

Strangeness production $\gamma p \rightarrow K^+\Lambda \rightarrow K^+ p \pi^-$

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


The high precision K\Lambda data are the basis for discovery/evidence of/for several states.
Establishing the N* spectrum - N(1900)3/2⁺

- Bump first seen in SAPHIR K⁺Λ data but due to systematics in the data misinterpreted as J^P=3/2⁻.

✓ State was solidly established in BnGa multi-channel analysis making use of very precise CLAS KΛ crs and polarization data, let to the *** in PDG2012.

✓ State confirmed in an effective Langrangian resonance model analysis of γp → K⁺Λ.
  
  O. V. Maxwell, PRC85, 034611, 2012

✓ State confirmed in a covariant isobar model single channel analysis of γp → K⁺Λ.
  
  T. Mart, M. J. Kholili, PRC86, 022201, 2012

✓ First baryon resonance observed and multiply confirmed in electromagnetic meson production.
  
  => Candidate for **** state.
Lower mass $N^*/\Delta^*$ spectrum in 2015

Are we seeing mass degenerate spin multiplets? Do these states fit into the SU(6) spin-flavor symmetry?
Constituent Quark Model & SU(6)xO(3)

SU(6)xO(3)
Do new states fit into $Q^3$ QM?

Quark Orbital Angular Momentum

Excitation Energy

- $0h\omega$
- $1h\omega$
- $2h\omega$
- $3h\omega$

2015

16
5
12

(56,0+)
(70,0+)

(56,1-)
(70,1-)

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

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

(56,3-)
(70,3-)
(20,3-)
Do new states fit into Q-Q\(^2\) model?

Quark Orbital Angular Momentum

Excitation Energy

Naïve quark-diquark model
Do new states fit into LQCD projections?

Lowest $J^+$ states 500 -700 MeV high

Lowest $J^-$ states 200-300 MeV too high

Ignoring the mass scale, new candidate states fit with the $J^p$ values predicted from LQCD. The field would really benefit from more realistic Lattice masses for $N^*$ states.
The number of known excited strange baryon states (PDG) is insufficient to account for the QCD phase cross over from the QGP phase to the baryon phase.

- Evidence for missing strange baryons
- Evidence observed also for missing charm and light quark baryons
- Motivates an excited baryon program of all quark flavors.

The RHIC operation plan for 2016 includes an energy scan to map out this behavior.

Transition shifted by about 8 MeV to lower temperature (later times) due to missing excited strange baryons.

from Hot QCD
High precision data to establish the N* spectrum

SDME from $\gamma p \rightarrow p\omega \rightarrow p\pi^+\pi^-\pi^0$


- To fully exploit N* sensitivities of $p\omega$ channel, data should be included in multi-channel analysis
$\gamma p \rightarrow p\omega \rightarrow p\pi^+\pi^-\pi^0$

**N* states in $\gamma p \rightarrow p\omega \rightarrow p\pi^+\pi^-\pi^0$**

Process acts as isospin filter and is sensitive only to N* states

- Data used as input to a single channel event-based, energy-independent PWA (the first ever for baryons).
- $\omega$ photoproduction is dominated $F_{15}(1680)$, $G_{17}(2190)$, and "missing" $F_{15}(2000)$


Data with polarized beam and polarized target underway.

First observation of $G_{17}(2190) \rightarrow N\omega$, PDG2014
Channel could be be sensitive to N*’s with large s-sbar content and MB molecules or pseudo-pentaquarks?
Pseudo pentaquark in $\gamma p \rightarrow p\phi \rightarrow pKK$?

$\phi \rightarrow K^+K^-, \phi \rightarrow K^0_sK^0_l$

Structure may not be an s-channel resonance. Could it be diquark-anti-triquark pair similar to what is proposed for the $P_{c}^+$ resonances.

R. Lebed, arXiv:1510.01412

Maintain approximate collinearity
Electroexcitation of $N/\Delta$ resonances

Central question in hadron physics
What are the effective degrees of freedom at varying distance scale?

$N(1675)\frac{5}{2}^- - N(1520)\frac{3}{2}^- - N(1535)\frac{1}{2}^- - N(1440)\frac{1}{2}^+ + N(1710)\frac{1}{2}^+$

$\Delta(1232)\frac{3}{2}^+ - N(940)\frac{1}{2}^+$

$N(1680)\frac{5}{2}^+ [56,2^+]_2$

$\Delta(1232)\frac{3}{2}^+ N(1520)\frac{3}{2}^- N(1535)\frac{1}{2}^- N(1440)\frac{1}{2}^+ N(1710)\frac{1}{2}^+$

$L_{3q}$

$[70,1^{-}]_1$

$[56,0^+]_0$

$[70,0^+]_0$

$[56,2^+]_2$

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

$A_{1/2}, A_{3/2}, S_{1/2} E_{1+}, M_{1+}, S_{1+}$

$N, Y$

$N^*, \Delta^*$

$N(1675)\frac{5}{2}^- N(1520)\frac{3}{2}^- N(1535)\frac{1}{2}^- N(1440)\frac{1}{2}^+ N(1710)\frac{1}{2}^+$

$\hbar\omega$
Total cross section at $W < 2.1$ GeV

$$\gamma^* p \rightarrow \pi^+ n$$


Analysis with UIM & fixed-t DR; Recent review: I. Aznauryan, V. Burkert, Prog.Part.Nucl.Phys. 67 (2012) 1-54
Electrocouplings of ‘Roper’ in 2012

I. Aznauryan et al. (CLAS), PRC80, 055203 (2009)
V. Mokeev et al. (CLAS), PRC86, 035203 (2012)
L. Tiator et al., Chin.Phys. C33 (2009) 1069 (MAID fit)

I. Aznauryan, PR C76 (2007) 025212
Z.P. Li, V. Burkert, Zh. Li, PR D46 (1992) 70

I.T. Obukhovsky, et al., PR D84, 014004 (2011)
The “Roper” resonance in 2015

- Quark core contributions from DSE/QCD J. Segovia et al., arXiv:1504.04386
- MB cloud inferred from the CLAS data as the difference between the data and quark core evaluated in DSE/QCD, V. Mokeev et al., arXiv:1509.05460
- EFT employing π, ρ, N, N’. T. Bauer, S. Scherer, L. Tiator, PR C90 (2014) 1, 015201

The structure of the Roper is driven by the interplay of the core of three dressed quarks in the 1st radial excitation and the external meson-baryon cloud.
MB contribution to $\gamma_p N(1675)_{5/2}^-$

Quark components to the helicity amplitudes of the $N(1675)_{5/2}^-$ are strongly suppressed for proton target.

Single Quark Transition: $A_{1/2}^p = A_{3/2}^p = 0$

I.G. Aznauryan, V.D. Burkert, PR C92 (2015) 1, 015203; K. Park et al. (CLAS), PR C91 (2015) 045203

- Measures the meson-baryon contribution to $\gamma^* p N(1675)_{5/2}^-$ directly
- Can be verified on $\gamma^* n N(1675)_{5/2}^-$ which is not suppressed

E. Santopinto and M. M. Giannini, PRC 86, 065202 (2012)
Light-cone N* transition charge densities

\[ A_{1/2} = e^{\frac{Q_-}{K (4M N M)^{1/2}}} \left\{ F_{1}^{NN} + F_{2}^{NN} \right\} , \]

\[ S_{1/2} = e^{\frac{Q_-}{2K (4M N M)^{1/2}}} \left( \frac{Q_-}{2M} \right) \left( \frac{M + M_N}{Q^2} \right) \left\{ F_{1}^{NN} - \frac{Q^2}{(M + M_N)^2} F_{2}^{NN} \right\} \]

\[ \rho_0^{NN^*}(b) = \int_0^\infty \frac{dQ}{2\pi} Q J_0(b Q) F_1^{NN^*}(Q^2) \]

\[ \rho_T^{NN^*}(b) = \rho_0^{NN^*}(b) + \sin(\phi_b - \phi_S) \int_0^\infty \frac{dQ}{2\pi} \frac{Q^2}{(M^* + M_N)} J_1(b Q) F_2^{NN^*}(Q^2) \]

Exp: \( 0 < Q^2 < 4.5-7 \text{ GeV}^2 \)

\[ J_m = +\frac{1}{2} \rightarrow -\frac{1}{2} \]
What have we have learned from N* studies?

• Major progress made during past ~5 years in the search for new N* and Δ* states. All new states can be accommodated in CQM and LQCD. Naïve (non-dynamical) quark-diquark model is ruled out.

• Knowledge of $Q^2$ - dependence is absolutely necessary to understand the nature (internal structure) of excited states. The Roper IS the 1st radial excitation of the $q^3$ core, obscured at large distances by meson cloud effects.

• Leading amplitude of prominent low mass states, e.g N(1440)$1/2^+$ and N(1535)$1/2^-$ well described at $Q^2 > 2-3$GeV by QCD modeling in DSE/QCD, LC SR and LF RQM.

• Light-front transition charge densities for the Roper and N(1535) show significant differences in transverse spatial distributions.
Where are we going?

- Baryon resonances of all flavors were driving the evolution of the universe at the transition from the QGP to confined quarks in nucleons. A quantitative understanding of this transition requires the search for the missing excited states of all flavors.

- Much of the published data with potential of accessing new states have not been implemented in multi channel analyses (e.g. $p\omega$, $p\phi$, $K^*\Lambda$) but they are important in the search for higher mass states. Precise polarization data critical and are in production.

- Need to measure electro-excitation of states at higher $W$ and in large $Q^2$ range. Need to include Include $N\pi$, $N\pi\pi$, $K\Lambda/K\Sigma$ final states.

- Electro-excitation of prominent states up to highest $Q^2$ to probe the transition from the dressed to the bare quark core with CLAS12.

- Search for hybrid baryons ($q^3G$). Electro-excitation needed to distinguish hybrid baryons from $q^3$ states with CLAS12.
Questions for Discussion

• Implementation of momentum-dependent quark mass into model calculations.
• Using Breit-Wigner masses versus poles positions in analysis of electroproduction data.
• Long-wavelength limit (Siegert’s theorem)
  – Is it unique limit for each resonance or does mixing play a role? How to treat states that mix, e.g. N(1535)1/2− and N(1650)1/2−
• Extension of pwa in meson photo- to electroproduction
Electrocouplings of $\gamma_\nu p N(1535) 1/2^-$

Is it a 3-quark state or a hadronic molecule?

- MB contributions may account for discrepancies at low $Q^2$.
- MB contributions from chiral unitary model analyses due to $K\Lambda$ and $p\phi$ components.

I.V. Anikin, V.M. Braun, N. Offen, PR D92 (2015) 1, 014018
Electrocouplings of $\gamma_NpN(1535)_{1/2}^-$

- Chiral unitary model analyses: state may have a significant coupling to $K\Lambda$ and $p\phi$
- Sizeable $qqqss\bar{s}$ admixture in the wave function?
- Large $ss\bar{s}$ could explain sign of $S_{1/2}$ at $Q^2 < 2$ GeV$^2$ contrasting LFQM predictions.
Missing baryon resonances and HIC

The number of observed excited baryon states (PDG) is insufficient to account for the cross over from non-interacting quarks (QGP) to the baryon phase.

- Evidence for missing strange and charmed baryons
- Discrepancy observed also for light quark baryons
- Motivates an excited baryon program of all quark flavors.

Roper $M_{1-}$ Multipole amplitude for $\gamma^* p \rightarrow \pi^+ n$

At $Q^2 = 1.7 - 4.2$, resonance behavior is seen in these amplitudes more clearly than at $Q^2 = 0$

DR and UIM give close results for real parts of multipole amplitudes

$Q^2 = 0$

$Q^2 = 2.05 \text{ GeV}^2$
Probing the running quark mass at JLab12

Nucleon resonance transitions amplitudes probe the quark mass function from constituent quarks to dressed quarks and elementary quarks.

R. Gothe et al. E12-09-003
Electrocouplings in RPP 2015

\(\Delta(1232)\)

\(N(1675)\)

\(N(1680)\)

\(N(1440)\)

\(N(1520)\)

\(N(1535)\)

**N AND \(\Delta\) RESONANCES**

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