Excited Nucleons
Spectrum and Structure

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Excited nucleons – some markers

✓ **1952**: First glimpse of the $\Delta(1232)$ in $\pi p$ scattering

✓ **1964**: Excited baryons are essential in establishing the quark model and the color degrees of freedom. The $\Delta^{++}$ state is not allowed in a quark model without color.

✓ **1990**: A broad effort to verify the quark model predictions of the spectrum and to understand the relevant degrees of freedom (missing resonances).

✓ **2010**: Research in DSE/QCD and LF RQM show, when nucleon resonances are excited at different distance scales ($Q^2$), their transition form factors probe the dynamical quark mass function $m_q(q)$.

✓ **2015**: Baryon resonances play a critical role in the interpretation of the evolution of the universe during the first microseconds.
History of the Universe and N*’s

Dramatic events occur in the microsecond old universe during the transition from the QGP phase to hadron phase.

- Chiral symmetry is dynamically broken
- Quarks attain masses dynamically
- Color confinement occurs
- Transition driven by excited baryons

With existing accelerators we can explore these events in isolation.
From the H spectrum to the N* spectrum

- Understanding the hydrogen atom requires understanding its emission spectrum of sharp energy levels
  - From the Bohr model to QED

- Understanding the proton requires understanding its energy spectrum of broad energy levels.
  From the Quark model to strong QCD

Role of experiment:

⇒ Map the excitation spectrum more completely and accurately.
What do we learn from excited baryons?

• Only now do we have experimental, phenomenological, and theoretical tools to more fully explore baryon spectrum and structure.

• The N* spectrum reflects the underlying degrees of freedom and the effective forces between them that relate to quark confinement.

• Vigorous experimental program is underway along two avenues
  • Search for undiscovered states in photoproduction (ELSA, JLab, MAMI, .. )
  • Identify the relevant degrees of freedom of prominent states versus distance scale in electroproduction (JLab/JLab12)

• New developments in theory – LQCD, DSE, LC SR, LF RQM, ..
Search for excited baryons – some reaction channels

- data acquired - analyzed/published

|       | σ  | Σ  | T  | P  | E  | F  | G  | H  | T_x | T_z | L_x | L_z | O_x | O_z | C_x | C_z |
|-------|----|----|----|----|----|----|----|----|-----|-----|-----|-----|-----|-----|-----|
| pπ^0 | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓   | ✓   | ✓   | ✓   | ✓   | ✓   |
| nπ^+ | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓   | ✓   | ✓   | ✓   | ✓   | ✓   |
| pη  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓   | ✓   | ✓   | ✓   | ✓   | ✓   |
| pη' | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓   | ✓   | ✓   | ✓   | ✓   | ✓   |
| pω/φ | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓   | ✓   | ✓   | ✓   | ✓   | ✓   |
| K^+Λ | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓   | ✓   | ✓   | ✓   | ✓   | ✓   |
| K^+Σ^0 | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓   | ✓   | ✓   | ✓   | ✓   | ✓   |
| K^+Σ^0* | ✓ 💫 | | | | | | | | | | | | | |
| K^0Λ | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓   | ✓   | ✓   | ✓   | ✓   | ✓   |
| K^0Σ^0 | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓   | ✓   | ✓   | ✓   | ✓   | ✓   |
| K^0Σ^0* | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓  | ✓   | ✓   | ✓   | ✓   | ✓   | ✓   |

SDME

γp → X

γn → X

Tensor polarization SDME

11/21/2016 V. Burkert INT Workshop N* Spectrum and Structure
Establishing the N* and Δ* Spectrum

V.B., T.S.-H. Lee

sQCD

LQCD

N*, Δ*

DSE, RQM

Reaction Theory
Dispersion Relations

Data

Amplitude analysis

Hadronic production

Electromagnetic production

Aznauryan. V.B., PPNP 67 (2012)

Tiator, Drechsel, Kamalov, Vanderhaeghen, EPJST 198 (2011)
$K^+\Lambda$ Fit with PDG states $< 2$ GeV

Includes ***, **** PDG states

Do these discrepancies indicate resonances are missing from the fit?

PDG(2010) states insufficient to fit $K\Lambda$ data

Shows the importance of polarization data
Establishing the N* spectrum, cont’d

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

BnGa group (2012)

$\frac{d\sigma}{d\Omega}$, $\mu$b/sr

1965

2195

M. Mc Cracken et al. (CLAS), Phys. Rev. C81, 025201, 2010

A.V. Anisovich et al., EPJ A48, 15 (2012)
Establishing the N* spectrum, cont’d

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

The high precision $K^+\Lambda$ data are the basis for the discovery of several N* states.

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

A new nucleon state: N(1900)3/2+

- Bump first seen in SAPHIR cross section data but assigned to different J^P.

- State fully established in BnGa multi-channel analysis making use of very precise KΛ cross section and polarization data, and is now **in RPP.**

- State confirmed in an effective Langrangian resonance model analysis of γp → K^+Λ.
  
  \[ O. V. Maxwell, PRC85, 034611 \]

- State confirmed in a covariant isobar model single channel analysis of γp → K^+Λ.
  
  \[ T. Mart, M. J. Kholili, PRC86, 022201 \]

- First baryon resonance observed and multiply confirmed in electromagnetic meson production.

  \[ \Rightarrow \text{Candidate for **** state.} \]

*** “Existence is very likely but further confirmation of decay modes is required”.
## Evidence for new Baryons and Decays

<table>
<thead>
<tr>
<th>State N((mass)J^p)</th>
<th>PDG pre 2010</th>
<th>PDG 2016</th>
<th>KΛ/Σ</th>
<th>πN</th>
<th>Nγ</th>
</tr>
</thead>
<tbody>
<tr>
<td>N(1710)1/2^+</td>
<td>***</td>
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<tr>
<td>N(1880)1/2^+</td>
<td>**</td>
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<tr>
<td>N(1895)1/2^-</td>
<td>**</td>
<td>**</td>
<td>*</td>
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<tr>
<td>N(1900)3/2^+</td>
<td>**</td>
<td>***</td>
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<tr>
<td>N(1875)3/2^-</td>
<td>***</td>
<td>***</td>
<td>*</td>
<td>***</td>
<td></td>
</tr>
<tr>
<td>N(2120)3/2^-</td>
<td>**</td>
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</tr>
<tr>
<td>N(2000)5/2^+</td>
<td>*</td>
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<tr>
<td>N(2060)5/2^-</td>
<td>**</td>
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</tbody>
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Lower mass N*/$\Delta^*$ states in 2016

Mass degenerate spin multiplets or parity \textbf{duplicates} from restoration of chiral symmetry? Do new states fit into the $\textbf{SU(6)}$ spin-flavor symmetry of the CQM?
Status of light quark states in CQM

SU(6) × O(3)

2010

“missing” states

D. Menze 1980’s
Do new states fit into CQM?

SU(6)×O(3)

2016

Just the first results of this effort. The campaign goes on ...

Do new states fit into \((qq)q\) model?

Naïve version of quark-diquark model ruled out (point-like diquarks).
Do new states fit with LQCD projections?

Known states:
- N(1675) 5/2-
- N(1700) 3/2-
- N(1520) 3/2-
- N(1650) 1/2-
- N(1875) 3/2-
- N(1895) 1/2-
- N(2060) 5/2-
- N(2120) 3/2-


Ignoring the mass scale, new states fit with the $J^P$ values predicted from LQCD.

Lowest $J^+$ states 500 - 700 MeV high
Lowest $J^-$ states 200 - 300 MeV high
Polarized $K^{+}\Lambda$ production

C.A. Paterson et al., PRC93 (2016) 065201

ANL-Osaka  BnGa 2014  BnGa 2014 refit
At high mass polarization is essential $\rho(\gamma,\pi N)$

- Need polarization data at high masses.


**Beam-target polarization asymmetry**
Beam asymmetry off neutron $\Sigma_n$ \[ \tilde{\gamma}n \rightarrow p\pi^- \]

Data need to be included in multi channel partial wave analysis
Precision data to establish the N* spectrum

Reaction is isospin filter => only sensitive to I=1/2 states

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

Cross section of $\gamma p \rightarrow p\phi \rightarrow p\bar{K}K$

Channel sensitive to high mass N*\(s\) with large s-bar content.

$\phi \rightarrow K^+K^{-}$, $\phi \rightarrow K^0_s K^0_{l}$

B. Dey et al. (CLAS), PR C89 (2014) 5, 055208
K.P. Adhikari et al. (CLAS), PR C89 (2014) 5, 055206
Pseudo pentaquark in $\gamma p \rightarrow p\phi \rightarrow pKK$?

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

Possible diquark-anti-triquark pair formation similar to what is proposed for the $P_{c}^{+}(4450)$ resonance seen in $pJ/\psi$.

$\cos \theta_{c.m.}^{\phi} = 0.925$

B. Dey et al. (CLAS), PR C89 (2014) 5, 055208

K.P. Adhikari et al. (CLAS), PR C89 (2014) 5, 055206

Need to be included in multi channel pw analysis.

Structure of excited baryons

- effective degrees of freedom
- transition charge densities
- running quark mass

\[ \Rightarrow \text{nature of states} \]

\[ N(1675)\frac{5}{2}^- \]
\[ N(1520)\frac{3}{2}^- \]
\[ N(1535)\frac{1}{2}^- \]
\[ N(1440)\frac{1}{2}^+ \]
\[ N(1710)\frac{1}{2}^+ \]
\[ \Delta(1232)\frac{3}{2}^+ \]
\[ N(940)\frac{1}{2}^+ \]

I.G. Aznauryan et al., Analysis of \( p(e,e'N\pi) \); V.I. Mokeev et al., Analysis of \( p(e,e'p\pi^+\pi^-) \)
Total cross section at $W < 2.1$ GeV

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

$Q^2 = 1.7$ GeV$^2$

$Q^2 = 3.15$ GeV$^2$

K. Park et al., PR C77 (2008) 015208; PR C91 (2015) 045203
How do light quarks acquire mass?

As the Universe cools down, the quarks acquire mass and form resonances before stable nucleons are formed.

=> Measure N* observables that are sensitive to the quark mass.
Quarks get stripped off their dressing

Electron beams allow changing the momentum transfer to a specific N*, which allows probing the running quark mass.
For $G_M$ the MB contributions are significant at $Q^2 \leq 3$-4 GeV$^2$

No clear trend towards asymptotic behavior $R_{EM} \rightarrow +100\%$
The 1\textsuperscript{st} radial excitation of the 3-quark core emerges as the probe penetrates the MB cloud. Non-quark contributions are significant at $Q^2 < 2.0$-2.5 GeV$^2$.
**N(1535)1/2⁻ helicity amplitudes**


**Inferred MB contributions significant at $Q^2 < 1.5 \text{ GeV}^2$.**
N(1520)3/2⁻ helicity amplitudes

Inferred MB contributions significant at $Q^2 < 1.5-2.5 \text{ GeV}^2$. 
On proton target the transverse amplitudes are predicted to be suppressed by 1966 Moorhouse selection rule. => Expect MB contributions to lead at all $Q^2$.

- $A_{1/2}$ drops much faster with $Q^2$.
- CQM predicts much larger amplitudes on neutrons.

$\Rightarrow$ Meson-baryon contributions large for $A_{1/2}$ at $Q^2 \leq 3\text{GeV}^2$,

$\Rightarrow A_{3/2}$ drops much faster with $Q^2$. 

- CQM predicts much larger amplitudes on neutrons.
Fourier transform in $Q^2$ of transition form factors result in the IMF in transition charge densities from the proton to the two states.

The $N(1440)$ exhibits a softer core and wider clouds than $N(1535)$.

FT involves integral in $Q^2 \to \infty$ => need data at higher $Q^2$.
N* physics with CLAS12 at JLab12

- E12-09-003 - Electroexcitation of Nucleon Resonances at high Q^2
  R. Gothe et al.

- E12-06-108A – Exclusive N*->KY studies with CLAS12, D. Carman et al.

- E12-11-005A – Photoproduction of the very strangest baryons
  L. Guo et al.

- E12-16-10: Search for Hybrid Baryons with CLAS12 – A. D’Angelo et al.

- E12-16-010A – Exclusive N*->KY studies with CLAS12, D. Carman et al.
Hybrid Baryons $q^3 G$


Cover very low $Q^2$ range with very high statistics using the Forward Tagger Facility in CLAS12
Probing the running quark mass at JLab12

**Roper resonance**

![Graph showing Roper resonance](image)

**Running quark mass**

![Graph showing running quark mass](image)

- Accessible at 6 GeV
- Accessible at 12 GeV

Probe the transition of dressed quarks to elementary quarks.
Summary/Outlook

• Excited baryons played a critical role in the evolution of the universe from the QGP phase to the hadron freeze out phase.

• High precision photoproduction data are the basis for the discovery of baryons and to improve evidence for poorly known states. Polarization observables are essential at high masses.

• Multi-channel partial wave analysis frameworks have been key in further establishing the nucleon excitation spectrum.

• Vector meson cross section and polarization data have great potential but have not been (fully) included in coupled channel frameworks.

• Electroexcitation of prominent states supported by advances in theory (DSE, FF RQM) reveals the N* quark core at $Q^2 > 3$ GeV$^2$ and allows quantifying the meson-baryon contributions.
Outlook

• Charge transition density of the Roper N(1440) appears to have a softer central quark core and a wider "cloud" than the N(1535) transitions. Need to go to higher Q^2 to probe the quark core more accurately.

• The N* program at higher energies will probe the running quark mass function at high Q^2, search for gluonic excitations at low Q^2, and search for doubly strange (Ξ*) and triply strange (Ω^-*) states.

• For the search of new states in meson electroproduction we need to expand the multi-channel partial wave analysis to include virtual photons.

• Strangeness channels and multi-meson channels may be key in searching for high mass states.