Excited Baryon Program: Theoretical Developments

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Objectives:

Perform *theoretical* analyses of meson production data

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- **Extract** $N^*$ parameters:
  - Masses, Widths, Form factors

- **Interpret** $N^*$ parameters:
  - Hadron models with *effective degrees of freedom*
  - Lattice QCD

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Understand *non-perturbative* QCD:

- **Confinement** mechanism

- Chiral dynamics of *meson* cloud of baryons

- . . . .
Current focus:

- Identify baryon excited states at \( W > 1.7 \) GeV

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Establish symmetry property \((SU(6) \oplus O(3)\) or ????)

--- old --- >>>>>> --- current ---

Recent PDG assessment: 1- and 2-star states are **doubtful**
• Extract and interpret $N-N^*$ form factors

→

Reveal

– The quark sub-structure of baryon excited states

– The meson cloud effects
General Considerations

- Baryon excited states are **coupled** to meson-baryon reaction channels to form **resonances** ($N^*$)

  \[ T = t^R + t^{nr} \]

  - $t^R$: changes of internal structure ($N \rightarrow \Delta, N(1440), \cdots$)
  - $t^{nr}$: non-resonant interactions between reaction channels (Meson exchanges \cdots)

- Many reaction channels
  \[ \gamma N, \pi N, \eta N, \omega N, K\Lambda, K\Sigma, \pi\pi N(\pi\Delta, \rho N, \sigma N) \]

  \[ \rightarrow \]

A multi-channel and multi-resonance reaction problem
Example: $\gamma N \rightarrow KY$

Must include:

- **coupled-channel effects:**
  
  - $\gamma p \rightarrow \pi N \rightarrow KY$
  
  - $\gamma p \rightarrow \pi \pi N \rightarrow KY$

- at least about 10 known $N^*$ resonances
Theoretical Development

Very far from predicting meson-baryon reactions from QCD

Current effort:

- Develop reaction models to extract $N^*$ parameters
- Interpret $N^*$ parameters using available hadron structure calculations
Note:

Analysis based on dispersion relations is difficult:

- cannot handle multi-particle channels ($\pi\pi N$)
- not applicable at high $Q^2$ region

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Develop alternative reaction models

- K-matrix models (On-shell approximation, PWA)

$$S = \frac{1 + iK}{1 - iK}$$

$$K \sim V(\text{tree} - \text{diagram})$$

- GWU-VPI (SAID), Mainz (MAID), JLab-Yerevan, CMU (PWA)
- Giessen, GWU, KVI, Bonn-Gatchina, JLab-MSU (JM06), Valencia, Hiroshima-Onomichi, ⋅⋅⋅
• Dynamical Models

\[ S = 1 + 2iT \]
\[ T = V + \int VGT \]

→

Account for reaction mechanisms in the short-range (off-shell) region where we want to map out \( N^* \) structure

– Sato-Lee, Gross-Surya, Dubna-Mainz-Taipei, Fuda-Alharbi, Ohio-Utrecht, Saclay-Pitt-ANL, Pascalutsa-Vanderhaeghen, Julich, ..
Two approaches are complementary:

- K-matrix models solve algebraic equations
  → very efficient in processing multi-channel data to get first-run results of $N^*$ parameters
- Dynamical models account for short-range (off-shell) mechanisms
  → related to hadron structure calculations for interpreting $N^*$ parameters
1. $\gamma N \rightarrow \Delta(1232)$ form factors

- $Q^2$-evolution of meson cloud is discovered
• Hadron structure calculations are tested

— Quark Model ——————————LQCD ———
———( Bare ) ———————————-( Dressed ) ————

$G_M(Q^2)$

$G_E(Q^2)$

$G_C(Q^2)$

$Q^2$ (GeV$^2$)

Lattice QCD

MAMI (R. LEUKEL)
MAMI (S. STAVE)
BATES
MAMI (N. SPARVERIS)
CLAS06
CLAS02

$Q^2$ (GeV$^2$)

$Q^2$ (GeV$^2$)
2. $N-N^*(1440)$ form factors agree with Quark Model

Red curves: S. Capstick and B.D. Keister
Green curves: I. Aznauryan
3. New states at $W > 1.7$ GeV are suggested

Example: Coupled-channel fit to $\gamma p \rightarrow K^+\Lambda$ data of JLab

(B. Julia-Diaz et al. 2006)
Several new states have also been suggested in the K-matrix analyses by Giessen group, GWU group, Bonn-Gatchina group, CLAS collaboration (JM06).

Note:

- Need to be further confirmed by analyses including polarization data and more complete coupled-channel analyses.
- Need to be verified by dynamical model analyses.
Necessary next step:

Strengthen the collaborations between empirical analyses (PWA, K-matrix analyses) and theoretical efforts (dynamical models, hadron structure calculations).

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Establish Excited Baryon Analysis Center (EBAC) at the Theory Center of Jefferson Laboratory.
Excited Baryon Analysis Center (EBAC)

Theory Center, Jefferson Laboratory

- **Established**: January, 2006

- **Goal**: Reach a DOE milestone by 2009

"Complete the combined analysis of available single pion, eta and kaon photo-production data for nucleon resonances and incorporate analysis of two-pion final states into the coupled channel analysis of resonances.”
1. **On-going** theoretical projects:

- Perform Dynamical Coupled-Channel Analysis
  - $\pi N$, $\eta N$, $\pi \pi N$ production
  - $\omega N$, $KA$ production

- Develop collaborations with other theoretical efforts
  - Coupled-channel analysis by the **Julich** group
    (J. Haidenbauer, C. Hanhart, S. Krewald, Ulf-G. Meißner, A. Sibirtsev, K. Nakayama, H. Haberzettl)
  - **EBAC-Saclay** Coupled-channel analysis of $\eta$, $K$ photoproduction
First results from EBAC

- Fits of $\pi N$ amplitudes

(dashed curves: $N^*$ contributions)
• Start to analyze $\gamma p \rightarrow \pi^+ \pi^- p$ data of JLab

Plans:

• 2007 - 2008 : Analysis of $\pi, \eta, \pi\pi$ production data
• 2008 -2009 : full coupled analysis including $\omega, K$ production data
2. Provide **theoretical** input to the data analyses by **experimental** groups

- Include the coupled-channel effects in the combined analyses of $\pi, \eta, \pi\pi$ production data by CLAS collaboration
- Collaborations with other experimental groups will be developed

3. Projects being developed:

- Development of reaction models at high $Q^2$ region, accessible to JLab’s 12 GeV upgrade
- Investigation of the connections with Lattice QCD calculations
Recent LQCD Calculations
(Provided by LHPC)

Nucleon Mass Spectrum

Question:
How to compared with the extracted $N^*$ resonance energies?
Dynamical Coupled–Channel Analysis at EBAC

Theory Center, JLAB