The Baryon Spectroscopy Experimental Program
Annalisa D’ANGELO
University of Rome “Tor Vergata” and INFN Rome Tor Vergata
Motivation

Baryons

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Motivation

- Understanding the working of QCD:

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

• Motivation: understanding the working of QCD

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

• Hadronic degrees of freedom.
• The experimental tools: beam, target, detector.
• Selected experimental results.
• Outlook and conclusions.
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
the constituent quark mass arises from low momentum gluons attaching them selves to current quarks.

Field excitation generates mass from nothing: mass is field energy.

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QCD-inspired Constituent Quark Models

- Chiral symmetry breaking of the QCD Lagrangian generates Constituent Quarks with effective masses - confirmed by LQCD and DSE calculations.

- Asymmetry of the baryon wave function is guaranteed by color, but color degrees of freedom are integrated out and play no dynamical role.

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

\[ \begin{array}{c|c|c|c|c|c|c|c|c|c|c|c|c} \hline \text{Mass (MeV)} & 3000 & 2500 & 2000 & 1500 & 1000 & \text{States} & 9/2_+ & 7/2_+ & 5/2_+ & 3/2_+ & 1/2_+ & \text{J} \pi \\hline \text{L}_{\pi} & P_{13} & P_{11} & F_{13} & F_{17} & H_{19} & S_{11} & D_{13} & G_{17} & G_{19} & I_{11} & I_{13} \\hline \end{array} \]

QCD-inspired Constituent Quark Models

Findings:

• Linear Regge trajectories

• only lowest few in each band seen (in $\pi N$) 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 $K\Lambda$, $K\Sigma$, $\pi\pi N$, ...

Shaded boxes: experimental results
Thick segments: theoretical predictions

QCD-inspired di-Quark Models

- 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 πN

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

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


Problems are not solved!
Photonuclear cross sections
From the Experiment to Theory

Experiment
- cross section,
- spin observables

Amplitude analysis
- → multipole amplitudes
- → phase shifts

Reaction Theory
- dynamical frameworks

Theory
- LQCD,
- quark models,
- QCD sum rules,
- ...

Coupled channels:
- resonance parameter
- Extraction
- EBAC, Bonn-Ga, Julich

σ, dσ/dΩ, Σ, P, T
(beam-target) E, F, G, H,
(beam-recoil) C_x, C_z, O_x, O_z,
(target-recoil) L_x, L_z, T_x, T_z,
Idealized path to search for N*, Δ* states via meson photo-production:

(1) determine the production amplitude from experiment
search for resonant structure: Argand circles, phase motion speed plots, etc.

(2) separate resonance and background components
determine resonant γN* and decay couplings; contact with LQCD, DSE, Hadron models

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(A. Sandorfi et al.)
Idealized path to search for $N^*$, $\Delta^*$ states via meson photo-production:

(1) determine the production amplitude amplitude from experiment
search for resonant structure: Argand circles, phase motion speed plots, etc.

(2) separate resonance and background components
determine resonant $\gamma N^*$ and decay couplings; contact with LQCD, DSE, Hadron models

Never been done after 50 years of experiments

Without exp Amplitudes models have conjectured resonances and adjusted couplings to compare with limited data
Complete experiments in pseudoscalar meson photoproduction

\[ \gamma + N \rightarrow m + N \]

Spin states

\[
\begin{array}{cccc}
\pm 1 & \pm \frac{1}{2} & 0 & \pm \frac{1}{2} \\
2 & x & 2 & x & 2
\end{array}
\]

8 possible spin states \( \rightarrow \) 4 independent complex amplitudes describe the transition matrix

\[ F_\lambda = \vec{J} \cdot \vec{\epsilon}_\lambda = iF_1 \vec{\sigma} \cdot \vec{\epsilon}_\lambda + F_2 (\vec{\sigma} \cdot \hat{k})(\vec{\epsilon} \cdot \vec{\epsilon}_\lambda) + iF_3 (\vec{\sigma} \cdot \hat{k})(\hat{q} \cdot \vec{\epsilon}_\lambda) + iF_4 (\vec{\sigma} \cdot \hat{q})(\hat{q} \cdot \vec{\epsilon}_\lambda) \]

CGLN amplitudes in terms of Pauli matrixes:

are conveniently expanded into multipoles
Polarization observables in $J^P = 0^-$ meson photo-production:

\[ \text{SHKL, J Phys G38 (11) 053001} \]

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<th>Photon beam</th>
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<th>Recoil</th>
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<td>$H$</td>
<td>$G$</td>
<td>$O_{x'}$</td>
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<td>$-\Sigma$</td>
<td>$-P$</td>
<td>$-T$</td>
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<tr>
<td>circular $P_c^\gamma$</td>
<td>$F$</td>
<td>$-E$</td>
<td>$C_{x'}$</td>
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</tbody>
</table>

16 different observables, each appearing twice:

- single-pol observables can be measured from double-pol asymmetry
- double-pol observables can be measured from triple-pol asymmetry
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**

\[ E_\gamma = (500 - 1500) \text{MeV} \quad \text{and} \quad E_\gamma = (500 - 6000) \text{MeV} \]

**CLAS in Hall-B**

**Crystal Barrel@BONN**

\[ E_\gamma = (500 - 3000) \text{MeV} \quad \text{and} \quad E_\gamma = (100 - 1500) \text{MeV} \]

**Crystal Ball@MAINZ**
Polarized photon beams: Compton Backscattering

- $\gamma \gamma \rightarrow \text{below } \pi \text{ threshold}$
- $\text{Legs } \rightarrow \Delta_{33}(1232) \text{ resonance region}$
- $\text{Graal } \rightarrow E_\gamma = 0.6-1.5 \text{ GeV } / W=1.4-1.9 \text{ GeV}$
  Region of the second and third baryon resonances $\eta$, $K$, $\omega$, thresholds
- $\text{Leps } \rightarrow E_\gamma = 1.5-2.5 \text{ GeV}$
  $\eta'$, $\phi$ thresholds

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Polarized photon beams: Compton Backscattering

GRAAL/ESRF
LEGS/BNL
LEPS/SPRING8

σ (μb)

E_γ (GeV)

η threshold → η’ threshold → ω threshold → KΛ threshold

λ = 351 nm 1.5 GeV
λ = 515 nm 1.1 GeV

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The Graal detector: Lagranγe

Large Acceptance Graal Apparatus for Nuclear γ Experiments

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CEBAF

Continuous Electron Beam Accelerator Facility

- E: 0.75 – 6 GeV
- \( I_{\text{max}} \): 200 mA
- Duty Cycle: \( \sim \) 100%
- \( \sigma(E)/E \): 2.5 \times 10^{-5}
- Polarization: \( \geq 85\% \)
- Simultaneous distribution to 3 experimental Halls
CEBAF Large Acceptance Spectrometer

- Torus magnet
  - 6 superconducting coils

- Gas Cherenkov counters
  - e/π separation, 256 PMTs

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

- Drift chambers
  - 35,000 cells

- Target + start counter

- Electromagnetic calorimeters
  - Lead/scintillator, 1296 photomultipliers
Hall B Photon Tagger

- $E_\gamma = 20$-95% of $E_0$
- $E_\gamma$ up to $\sim 5.8$ GeV
- $dE/E \sim 10^{-3}$ of $E_0$
Circularly polarized photons

- Circularly polarized beam produced by longitudinally polarized electrons
- CEBAF electron beam polarization >85%
- tagged flux ~ 50 - 100MHz for \(k > 0.5 \, E_0\)

\[
P_{\gamma} = P_e \cdot \frac{4k - k^2}{4 - 4k + 3k^2}
\]
Linearly polarized photons: coherent bremsstrahlung on oriented diamond crystal

Data for PERP 1.3GeV
Calculation

Polarization corresponding to calc
(Peaking at > 90%)

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**Polarized targets: frozen spin butanol FROST at CLAS**

**Polarizing Mode**

- Microwaves ON
- Polarizing magnet ON
- Holding magnet OFF
- Temperature ~1/2 K
- Photon beam OFF

**Longitudinal Polarization:** above 80%

**Relaxation time:** > 2000 hours

**Polarization procedure:** < 6 hours

**Data taking:** 5-6 days

**Very reliable.**
Polarized targets: frozen spin butanol FROST at CLAS

Longitudinal Polarization: above 80%
Relaxation time: > 2000 hours
Polarization procedure < 6 hours
Data taking: 5-6 days

Very reliable.

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Polarized targets: frozen spin butanol FROST at CLAS

Frozen Spin Mode
- Microwaves OFF
- Polarizing magnet OFF
- Holding magnet ON
- Temperature ≤0.05 K
- Photon beam ON

Polarize (+)
Polarize (-)
Polarize (+)
Polarize (-)

Take data
Take data
Take data

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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
Longitudinal and Transverse Polarizations: > 60%
Relaxation time: > 1 year
Polarization procedure ≈ 3 months
Data taking: ≈ months
Very complicated target transfer technology.
HD-Ice

$H \rightarrow D$ polarization during g14

tgt 21a

tgt 19b

tgt 22b

rf H flip

P(D) (%)

field rotation

pseudo quench

beam steering

field rotation

up sweep

Down Sweep

days since 12/1/11

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Measured Reaction Channels

- $\gamma p \rightarrow \pi^0 p, \pi^+ n$
- $\gamma p \rightarrow \eta p$
- $\gamma p \rightarrow \eta' p$
- $\gamma p \rightarrow KY (K^+ \Lambda, K^+ \Sigma^0, K^0 \Sigma^+)$
- $\gamma p \rightarrow \pi^+ \pi p \: \omega p, \rho p, \phi p$

- $\gamma n \rightarrow \pi^+ \pi n$
- $\gamma n \rightarrow \eta n$
- $\gamma n \rightarrow \pi p$
- $\gamma n \rightarrow \pi^+ \pi n$
- $\gamma n \rightarrow \Sigma^- K^+, \Lambda K^0$
- $\gamma n \rightarrow \omega n$

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γp→π^+n Photon asymmetry Σ

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$\gamma p \rightarrow \pi^+ n$ Helicity asymmetry E

circularly polarized beam – longitudinally polarized target (g9a-FROST)

S. Strauch
\( \gamma p \rightarrow \pi^+ n \) Helicity asymmetry \( G \)

\[
\frac{d\sigma}{d\Omega}(\theta, \phi) = \frac{d\sigma}{d\Omega}(\theta)[1 - p_T \Sigma \cos(2\phi) + p_T^2 G \sin(2\phi)]
\]

- g9a data compared to current PWA analyses in the energy range 730 – 2300 MeV for fixed angular bins

J. McAndrew, Edinburgh

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$\gamma p \rightarrow p\pi^0$ Photon asymmetry $\Sigma$

M. Dugger

MAID 2007

SAID 2009

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Very nice agreement between free and quasi-free results on the proton

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We may assume that results from quasi-free neutrons may represent the free neutron response $\rightarrow$ final state interactions and re-scattering are negligible.
\[ \Sigma \] for $\pi^0$ photoproduction on qfn

Multipole extraction in MAID2007

Second $P_{11}(1700)$ resonance

$P_{11}(1700)$

\[ \Gamma_{tot} = 70\text{MeV} \]

\[ \beta_\pi = 0.1 \]

$P_{13}(1720)$

modified photo-couplings

--- MAID2007 qfn

--- mod MAID2007 qfn
\Sigma results on $\gamma + n \to \pi + p$ at GRAAL

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Multipole modifications due to $\Sigma$ results on $\gamma + n (+p) \rightarrow \pi^- + p (+p)$ at GRAAL

by I. Strakowsky

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Multipole modifications due to $\Sigma$ results on $\gamma + n (+p) \rightarrow \pi^- + p (+p)$ at GRAAL

The $\eta$ cusp is visible
CLAS G10: $\gamma n \rightarrow \pi^- p$
CLAS Photon asymmetry $\Sigma \gamma n \rightarrow \pi^- p$

- Previous data (Alspector, PRL 28, 1403 ('72), Abrahamian, SJNP 32, 69 ('80), Adamyan, JPG 15, 1797 ('89)).
CLAS Photon asymmetry $\gamma n \rightarrow \pi^- p$

- Previous data (Alspector, PRL 28, 1403 ('72), Abrahamian, SJNP 32, 69 ('80), Adamyan, JPG 15, 1797 ('89)).
\[ \gamma n \rightarrow \pi^- p \text{ from CLAS} \]

**Systematics:**

- **Exp:** 6-9%
- **FSI:** 2-3%

\[ \chi^2/\Delta p = \frac{45636}{626} = 72.9 \quad [\text{SN11 - no fit}] \]

\[ \chi^2/\Delta p = \frac{1580}{626} = 2.5 \quad [\text{GB12 - fit}] \]

New SAID fit

- CLAS data appear to have fewer angular structures than the earlier fits.


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by I. Strakowsky
**Neutron Multipoles from GB12**


- **Overall:** the difference between **MAID07** and **SAID-GB12** is rather small but... Resonances may be essentially different

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- Significant changes have occurred at high energies
- Comparisons to earlier **SAID** fits and fit from the **Mainz** group show that the new **GB12** solution is much more satisfactory at higher energies

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**MAID07:**

- **S11**
  - $A_{1/2} = -58 \pm 6$ [-51]
  - $A_{3/2} = -40 \pm 10$ [9]

- **D13**
  - $A_{1/2} = -46 \pm 6$ [-77]
  - $A_{3/2} = -115 \pm 5$ [-154]

**GB12**

- **P11**
  - $A_{1/2} = 48 \pm 4$ [54]

**SN11**

- **BW for πN SP06**

**GZ12**

- **F15**
  - $A_{1/2} = 26 \pm 4$ [-28]
  - $A_{3/2} = -29 \pm 4$ [-38]

---

Cross section data show a structure at \(W=1900\) MeV.

Coupled-channel analysis finds that \(S_{11}(1650), P_{11}(1710)\) and \(P_{13}(1720)\) have the most significant decay widths in the \(K^+\Lambda\) channel. \(S_{11}(1800)\) and \(P_{13}(1900)\) also seem to play a role:

- “missing” \(D_{13}(1895)\) (Mart&Bennhold)
- \(P_{13}(1900)\) (Nikonov et al.)
- \(P_{11}(1900)\) (Ghent model)
- KKN bound state

Martinez Torres et al.  
arXiv:09023633[nucl-th]
$P_\Lambda$ in: $\gamma+p \rightarrow K^+ + \Lambda$ at Graal

From $\Sigma$ and $P$ measurements:

- Saclay Model:
  $S_{11}(1700)\, P_{13}(1800)\, D_{13}(1850)$

- Ghent Isobar Model:
  $D_{13}(1900)$

- Reggeized Model:
  $P_{13}(1900)\, D_{13}(1900)$

- Bonn Coupled Channel Model:
  $D_{13}(1875)$

$$W(\cos \theta_p) = \frac{1}{2} \left( 1 + \alpha \left| \bar{P}_\Lambda \right| \cos \theta_p \right)$$

$$P_\Lambda = \frac{2}{\alpha} \left( \frac{N(\cos \theta_p > 0) - N(\cos \theta_p < 0)}{N(\cos \theta_p > 0) + N(\cos \theta_p < 0)} \right)$$

$$\alpha = 0.642 \pm 0.013$$
Double Polarization Observables in $K^+\Lambda$ Photoproduction

\[ \frac{2N^x_+}{N^x_+ + N^{-x}_+} = \left(1 + \alpha \frac{2P\gamma O_x}{\pi} \cos \theta^x_\rho \right) \]

\[ \frac{2N^z_+}{N^z_+ + N^{-z}_+} = \left(1 + \alpha \frac{2P\gamma O_z}{\pi} \cos \theta^z_\rho \right) \]

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T in K⁺Λ Photoproduction

From Oₓ, Oᵧ 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:
  \[ S_{11}(1535) \quad S_{11}(1650) \quad P_{13}(1720) \quad P_{11}(1840) \]
  \[ P_{13}(1900) \]
\( \gamma p \rightarrow K^+ \Lambda: C\chi/Cz \)

- Nikonov et al.’s refit of Bonn-Gachina multi-coupled-channel isobar model
- mix includes: S11 wave, P13(1720), P13(1900), P11(1840)
- \( K^+ \Sigma^0 \) cross sections also better described with P13(1900)
- Promote this “missing” resonance from ** to **** status.
- P13(1900) is found in qqq quark models, but not in quark-diquark models

\[ C\chi Cz \text{ without } N^*(1900)P_{13} \quad C\chi Cz \text{ with } N^*(1900)P_{13} \]

Bradford et al.

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The $\Lambda$ appears 100% polarized when created with a fully polarized beam.
$\gamma p \rightarrow K^+ \Lambda$ Photon Asymmetry $\Sigma$
K⁺Λ Helicity Asymmetry E

Helicity asymmetry E for $E_K = 1.5$ GeV

Helicity asymmetry E for $E_K = 1.6$ GeV

Helicity asymmetry E for $E_K = 1.725$ GeV

Helicity asymmetry E for $E_K = 1.9$ GeV

preliminary
• Energy and angle averages are consistent with unity.

• No model predicted this CLAS result.
New results from PDG


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<th>Resonance</th>
<th>Rating</th>
<th>(N_{pp})</th>
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Spectrum of N* resonances

EBAC

Real parts of N* pole values

Re(M pole) (GeV)

L_{2l2j}

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<thead>
<tr>
<th></th>
<th>PDG</th>
<th>Ours</th>
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<td>N* with 3*, 4*</td>
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<td>Neutron target</td>
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<tr>
<td>$\rho\pi^0$</td>
<td>$\rho\pi^-$</td>
<td></td>
</tr>
<tr>
<td>$\eta\eta'$</td>
<td>$\rho\rho^-$</td>
<td></td>
</tr>
<tr>
<td>$\rho\omega$</td>
<td>$K^\pm\Sigma^+$</td>
<td></td>
</tr>
<tr>
<td>$K^+\Lambda$</td>
<td>$K^0\Lambda$</td>
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<tr>
<td>$K^+\Sigma^0$</td>
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<tr>
<td>$K^0\Sigma^0$</td>
<td>$K^0\Sigma^0$</td>
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- **Published**: ✔
- **Acquired**: ✓
- **Planned**: ✓

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Conclusions

• For the first time a “complete experiment” has been performed for pseudoscalar meson photoproduction both on the proton and the neutron.

• 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.

• For the first time EBAC had produced its own baryon spectrum.

I would like to thank the CLAS collaboration for letting me present preliminary data and Eugene Pasyuk for providing and letting me use his slides.
Backup slides
η’ photoproduction at CLAS

1968: 11 events from the ABBHHM bubble chamber experiment
1976: 7 events from the AHHM streamer chamber experiment
1998: 250 events from the SAPHIR collaboration (first differential cross sections)
2006: over $2 \times 10^5$ events from the CLAS collaboration
2009: another few orders of magnitude from CLAS g11 data set
\[ \gamma p \rightarrow \eta' p \]

\[ \frac{d\sigma}{d\Omega} \text{ for } \gamma p \rightarrow \eta' p \]

- First CLAS data

- **SAID**
- **MAID**
- **NH** (K. Nakayama and H. Haberzettl)

M. Dagger et al. PRL 96, 062001 (2006)
## Variants of NH model

<table>
<thead>
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<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
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<td>$S_{11}(2090)$</td>
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<td>$S_{11}(1535)$</td>
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<td>$P_{11}(2100)$</td>
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<td>$P_{11}(1710)$</td>
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</table>

$g_{\eta'NN} = 0.43$  $g_{\eta'NN} = 0.25$  $g_{\eta'NN} = 1.33$  $g_{\eta'NN} = 0.002$  $g_{\eta'NN} = 1.91$
$\gamma p \rightarrow \eta' p$ 

Different versions of the model yield similar results for cross section, but quite different predictions for beam asymmetry.
\[ \gamma p \rightarrow \eta' p \]

M. Williams et al. PRC 80, 045213 (2009)

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Differential Cross-Section

Low $t$ diffractive behavior:
Vector Dominance Model (1960), J.J. Sakurai
→ Pomeron exchange
→ $\pi^0/\eta$ exchange

$t$-channel

$E_{\gamma} =$
(a) 1.23 GeV
(b) 1.45 GeV
(c) 1.68 GeV
(d) 1.92 GeV
(e) 2.80 GeV
(f) 4.70 GeV

Large $t$ behavior: $s$- and $u$-channel contributions
→ intermediate resonant states ($N^*$).

Oh, Titov, Lee
PRC63 (2001) 025201
Σ results on $\vec{\gamma} + p \rightarrow \omega + p$ 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

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

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

Graal

$\omega \rightarrow \pi^0\gamma$

Bonn

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

Zhao model

Preliminary

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Preliminary results on $\gamma + p \rightarrow \omega + p$ and $\gamma + p (\pi) \rightarrow \omega + p (\pi)$ at GRAAL

Zhao model
- $s$ and $u$-channel including $P_{13}(1720)$

- $\omega \rightarrow \pi^0 \gamma$
  - free-proton
- $\omega \rightarrow \pi^0 \gamma$
  - Quasi-free-proton
Preliminary results on \( \gamma + n (+p) \rightarrow \omega + n (+p) \) at GRAAL

\[
\begin{align*}
E_\gamma & = 1.18 \text{ GeV} \\
E_\gamma & = 1.29 \text{ GeV} \\
E_\gamma & = 1.39 \text{ GeV} \\
E_\gamma & = 1.48 \text{ GeV}
\end{align*}
\]

Zhao model

\( \omega \rightarrow \pi^0 \gamma \)

\( \omega \rightarrow \pi^0 \gamma \)

quasi-free-neutron

quasi-free-proton