RESULTS FROM POLARIZED EXPERIMENTS
FROM LEGS AND GRAAL

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Outline

• Introduction: missing resonances and hadronic degrees of freedom

• The Legs and Graal Experimental set-ups.

• Results for $\Sigma$ beam polarization asymmetries at Graal:

  \[ \gamma + n \rightarrow \pi^0 + n \]

  \[ \gamma + n \rightarrow \pi^- + p \]

  \[ \gamma + N \rightarrow \omega + N \]

• Results for $O_x$ and $O_y$ double polarization asymmetries for $k^+ \Lambda$ photoproduction on the proton at Graal.

• Results on $E$ and $G$ double polarization asymmetries at Legs:

  \[ \gamma + H\Delta \rightarrow \pi^0 p \]

  \[ \gamma + H\Delta \rightarrow \pi^+ n \]

• Conclusions
• Chiral symmetry breaking of the QCD Lagrangian generates Constituent Q 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.
• Chiral symmetry breaking of the QCD Lagrangian generates Constituent $Q$ 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.

• 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 $K\Lambda$, $K\Sigma$, $\pi\pi N$, ...
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

\[
\begin{array}{|c|c|c|c|c|c|c|}
\hline
N^* & Status & S \ U(6) \otimes U(3) & Parity & \Delta^* & Status & S \ U(6) \otimes U(3) & Parity \\
\hline
P_{13}(938) & **** & (56, 0^+) & + & P_{31}(1232) & **** & (56, 0^+) & + \\
S_{13}(1535) & **** & (70, 0^+) & - & S_{31}(1620) & **** & (70, 0^+) & - \\
S_{33}(1650) & **** & (70, 0^+) & - & D_{33}(1700) & *** & (70, 1^+) & - \\
D_{13}(1520) & **** & (70, 0^+) & - & D_{33}(1700) & *** & (70, 1^+) & - \\
D_{33}(1675) & **** & (70, 0^+) & - & & & & \\
\hline
P_{11}(1520) & **** & (56, 0^+) & + & P_{31}(1875) & **** & (56, 2^+) & + \\
P_{11}(1710) & *** & (70, 0^+) & + & P_{31}(1835) & **** & (70, 0^+) & + \\
P_{11}(1880) & *** & (70, 2^+) & + & P_{31}(1835) & **** & (70, 0^+) & + \\
P_{11}(1975) & *** & (20, 1^+) & + & P_{31}(1835) & **** & (70, 0^+) & + \\
\hline
P_{13}(1720) & **** & (56, 2^+) & + & P_{33}(1600) & *** & (56, 0^+) & + \\
P_{13}(1870) & **** & (70, 0^+) & + & P_{33}(1920) & *** & (56, 0^+) & + \\
P_{13}(1910) & **** & (70, 2^+) & + & P_{33}(1985) & *** & (70, 2^+) & + \\
P_{13}(1950) & **** & (70, 2^+) & + & P_{33}(1985) & *** & (70, 2^+) & + \\
P_{13}(2030) & **** & (20, 1^+) & + & P_{33}(1985) & *** & (70, 2^+) & + \\
\hline
F_{13}(1680) & *** & (56, 2^+) & + & F_{33}(1905) & *** & (56, 2^+) & + \\
F_{13}(2000) & ** & (70, 2^+) & + & F_{33}(2000) & ** & (70, 2^+) & + \\
F_{13}(1995) & ** & (70, 2^+) & + & F_{33}(2000) & ** & (70, 2^+) & + \\
F_{13}(1990) & ** & (70, 2^+) & + & F_{33}(2000) & ** & (70, 2^+) & + \\
\hline
\end{array}
\]

the challenge: ⇔ unravel the N* spectrum
Experimental Requirements

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

Both Legs and Graal experiment were constructed to meet all above requirements in the energy ranges:

\[ E_\gamma = (180 - 450) \text{MeV} \quad \text{and} \quad E_\gamma = (500 - 1500) \text{MeV} \]
Polarized photon beams: Compton backscattering

- **Hiγs →** below π threshold
- **Legs → Δ33(1232) resonance region**
- **Graal →** $E_γ = 0.6\text{–}1.5$ GeV / $W=1.4\text{–}1.9$ GeV Region of the second and third baryon resonances η, K, ω, thresholds
- **Leps →** $E_γ = 1.5\text{–}2.5$ GeV
  η′, φ thresholds
Polarized photon beams: Compton backscattering and Bremsstrahlung

LEGS beam polarization

GRAAL beam polarization
\[ \Sigma \] measurements at Graal on proton and deuteron targets

\[ \circ \quad \gamma + p \rightarrow \pi^0 + p \quad \bullet \quad \gamma + p(+n) \rightarrow \pi^0 + p(+n) \]

Very nice agreement between free and quasi-free results on the proton.
We may assume that results from quasi-free neutrons may represent the free neutron response (→ final state interactions and re-scattering are negligible)
$\Sigma$ for $\pi^0$ photoproduction on qfn

Multipole extraction in MAID2007

Second $P_{11}(1700)$ resonance

\[ P_{11}(1700) \]

$\Gamma_{\text{tot}} = 70\,\text{MeV}$

$\beta_\pi = 0.1$

Modified photo-couplings

--- MAID2007 qfn

--- mod MAID2007 qfn

EPJ A 42,151 (2009)
$\Sigma$ results on $\bar{\gamma} + n (+p) \rightarrow \pi^- + p (+p)$ at GRAAL

$P_{R} = 82,045209 (2010)$
Multipole modifications due to $\Sigma$ results on $\vec{\gamma} + n (+p) \rightarrow \pi^- + p (+p)$ at GRAAL
\( \vec{\gamma} + p \rightarrow \omega + p \) : Differential Cross-Section

Low \( t \) diffractive behavior:
Vector Dominance Model (1960), J.J. Sakurai
\[ \rightarrow \text{Pomeron exchange} \]
\[ \rightarrow \pi^0/\eta \text{ exchange} \]
\[ \{ \text{\( t \)-channel} \]

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

Large \( t \) behavior: \( s\)- and \( u\)-channel contributions
\[ \rightarrow \text{intermediate resonant states (N*).} \]

- - - - - - - pseudo-scalar meson exchange
- - - - - - - Pomeron exchange
- - - - - - - direct and crossed nucleon terms
- - - - - - - N* excitation

Oh,Titov, Lee
PRC63 (2001) 025201
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

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

$\omega \rightarrow \pi^+ \pi^- \pi^0$
**Σ results on** $\gamma + p \rightarrow \omega + p$ **at GRAAL**: $\omega \rightarrow \pi^0\gamma$ and $\omega \rightarrow \pi^+\pi^-\pi^0$

- **Graal** $\omega \rightarrow \pi^0\gamma$
- **Graal** $\omega \rightarrow \pi^+\pi^-\pi^0$
- **Bonn** $\omega \rightarrow \pi^0\gamma$
- **PRL96(06)** $\omega \rightarrow \pi^+\pi^-\pi^0$

---

**Zhao model**

- **s and u-channel including $P_{13}(1720)$**
- **s and u-channel no $P_{13}(1720)$**
$\Sigma$ results on $\bar{\gamma} + p \rightarrow \omega + p$ and $\bar{\gamma} + p (+n) \rightarrow \omega + p (+n)$ 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
\[ \Sigma \text{ results on } \vec{\gamma} + n (+p) \rightarrow \omega + n (+p) \text{ at GRAAL} \]
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.

Isobar model requires the inclusion of a “missing” $D_{13}(1895)$ resonance to reproduce the cross section data.

$S_{11}(1800)$ and $P_{13}(1900)$ also seem to play a role.
Polarization observables in $\vec{\gamma} + p \rightarrow k^+ + \bar{\Lambda}$

Weak $\Lambda$ decay is self-analyzing

<table>
<thead>
<tr>
<th>Photon beam</th>
<th>Target</th>
<th>Recoil</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x'$</td>
<td>$y'$</td>
<td>$z'$</td>
</tr>
<tr>
<td>$x$</td>
<td>$y$</td>
<td>$z$</td>
</tr>
</tbody>
</table>

- Unpolarized: $\sigma_0$
  - Target: $T$
  - Recoil: $P$
- Linearly $P_\gamma$: $\Sigma$
  - Target: $H$, $-P$, $-G$
  - Recoil: $O_{x'}$, $-T$, $O_{z'}$
- Circular $P_\gamma$: $F$
  - Target: $-E$, $-C_{x'}$
  - Recoil: $C_{z'}$
$\Lambda$ in: $\vec{\gamma} + p \rightarrow k^+ + \Lambda$

at Graal

$A.\text{Lleres et al., EPJ A 31, 79-93 (2007)}$

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

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

$\alpha = 0.642 \pm 0.013$

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:
  $D_{13}(1875)$

Results from polarized experiments at LEGS and GRAAL
Double Polarization Observables in K+Λ Photoproduction

A. Lleres et al., EPJ A 39, 149-161 (2009)

\[
\frac{2N_{+}^{x'}}{N_{+}^{x'} + N_{-}^{x'}} = \left(1 + \alpha \frac{2P_{\gamma}O_{x}}{\pi} \cos \theta_{p}^{x'} \right)
\]

\[
\frac{2N_{+}^{z'}}{N_{+}^{z'} + N_{-}^{z'}} = \left(1 + \alpha \frac{2P_{\gamma}O_{z}}{\pi} \cos \theta_{p}^{z'} \right)
\]
T in K+Λ Photoproduction

\[
\frac{2N_+^{\gamma'}}{N_+^{\gamma'} + N_-^{\gamma'}} = \left(1 + \frac{2P_\gamma \Sigma}{\pi} \right) \left(1 + \alpha \frac{P_\pi + 2P_\gamma T}{\pi + 2P_\gamma \Sigma} \cos \theta^{\gamma'}_p \right)
\]

From O_x, O_z 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:
  \[S_{11}(1535) \quad S_{11}(1650) \quad P_{13}(1720) \quad P_{11}(1840)\]
  \[P_{13}(1900)\]
LEGS Spin ASYmmetry Array (SASY)

\[ \Sigma \]

\[ \theta_{\text{CM}} \text{(deg)} \]

\[ \gamma + \text{HD} \rightarrow \pi^0 \]

\[ \approx 4\pi \text{ acceptance for } \pi^0 \]
Polarized targets: frozen spin HD target at LEGS

Longitudinal and Transverse Polarizations: > 60%
Relaxation time: > 1 year
Polarization procedure ≈ 3 months
Data taking: ≈ months
Very complicated target transfer technology.
Polarized targets: frozen spin HD target at LEGS

Very clean signal/background separation

<table>
<thead>
<tr>
<th>PHOTON BEAM</th>
<th>TARGET</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>γ</td>
</tr>
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</table>

- unpolarized: $\sigma_0$  
- linearly $P_\gamma$: $\Sigma$  
- circular $P_\gamma$: $F$

Longitudinal and Transverse Polarizations: $> 60\%$  
Relaxation time: $> 1$ year  
Polarization procedure $\approx 3$ months  
Data taking: $\approx$ months  
Very complicated target transfer technology.
π⁰ photoproduction at LEGS: longitudinally polarized photons on longitudinally polarized target:

\[ \hat{E} = E \times \frac{d\sigma}{d\Omega_0} \]
π⁰ photoproduction at LEGS: longitudinally polarized photons on longitudinally polarized target:

\[ \hat{E} = E \times \frac{d\sigma}{d\Omega_0} \]
Extraction of observable $G$
linearly polarized photons on longitudinally polarized targets

\[ d\sigma = d\sigma_0(HD) + P_L^\gamma \cdot \left[ \hat{\Sigma}(HD) + \frac{1}{\sqrt{2}} P_D^T \cdot T_{20}^L(D) \right] \cdot \cos 2\phi \]

\[ + P_L^\gamma \cdot \left[ P_H \cdot \hat{G}(H) + P_D^V \cdot \hat{G}(D) \right] \cdot \sin 2\phi \]

\[ - P_C^\gamma \cdot \left[ P_H \cdot \hat{E}(H) + P_D^V \cdot \hat{E}(D) \right] + \frac{1}{\sqrt{2}} P_D^T \cdot T_{20}^0(D) \]

\[ \phi \text{-fits} \]

from $\int d\phi \text{ fits}$
G asymmetry from $\pi^+$ and $\pi^0$ photoproduction on the proton at LEGS

\[ \hat{G} = G \times \frac{d\sigma}{d\Omega_0} \]

**Surprise:** opposite sign and one order of magnitude larger than expected.

Under investigation.

D-wave component under $P_{33}(1232)$ larger than expected.
Conclusions

• $\Sigma$ asymmetry for $\pi^0$ and $\pi$ production on quasi-free neutrons provided new challenging constraints on $P_{11}(1700)$ and $P_{13}(1720)$ properties.

• $\Sigma$ asymmetry for $\omega$ photoproduction on the nucleon is a benchmark prediction for most existing models - sensitive to $P_{13}(1720)$ resonance.

• Double polarization observables in $k^+\Lambda$ photoproduction are mostly consistent with Bonn-Gatchina CC-PWA predictions - the role of the “missing” $D_{13}(1900)$ is still uncertain.

• First results on $G$ double polarization observable at LEGS suggest a strong D-wave component in the $\Delta$ resonance.

• The next step is performing complete experiments.
Backup slides
Hadron Models: 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.

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

Dyson-Swinger equation
(Bhagwat et al.)

(Craig Roberts)
Hadron Models: connection between constituent and current quarks

This effect is a dynamical chiral symmetry breaking (DCSB): a non-perturbative QCD effect that occurs also at the chiral limit

generates mass from nothing
Hadron Models: connection between constituent and current quarks

The interaction that describes color-singlet mesons also generates axial-vector isotriplet quark-quark correlations with significant attraction:

\[ m_{ud}^0 = 0.74 - 0.82 \text{ GeV} \]
\[ m_{ud}^1 = m_{uu}^1 = m_{dd}^1 = 0.95 - 1.02 \text{ GeV} \]

\( \text{di-Quarks} \)
Photonuclear cross sections

Sum: $\gamma + p$ total

- $\pi^+$
- $\pi^0$
- $\pi^+ \pi^-$
- $\pi^+ \pi^0$
- $\eta$
- $\omega$
- $K^+ \Lambda$
- $K^+ \Sigma^0$
- $K^0 \Sigma$
- $\phi$

$E_\gamma (\text{GeV})$

$\sigma (\text{mb})$

$\sigma (\text{ab})$

E$_\gamma$ (MeV)

$P_{\pi}(1250)$

$P_{\pi}(1440)$

$P_{\eta}(1450)$

$P_{\pi}(1520)$

$P_{\phi}(1680)$

$P_{\eta}(1535)$

$P_{\eta}(1600)$

$E_n$ (MeV)

$\sigma (\text{ab})$
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

σ, dσ/dΩ, Σ, P, T
(by Eugene Pasyuk)

(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

(A. Sandorfi et al.)

Coupled channels:
resonance parameter extraction

(by Eugene Pasyuk)
Idealized path to search for $N^*$, $\Delta^*$ states via meson photo-production:

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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

(A. Sandorfi et al.)