Baryon Resonances studied with Photoproduction of Mesons

Crystal Ball, Crystal Barrel, TAPS collaborations

- Introduction
- Experiments
- Single Meson Production Channels
- Multiple Meson Production Channels
- Conclusions

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Structure of the Nucleon

- complex many body system
  - valence quarks
  - sea quarks
  - gluons

- models - effective dof’s:
  - 3 equivalent constituent quarks
  - quark - diquark models (fewer states)
  - quarks - flux tubes etc. (more states)
  - chiral soliton models (anti-decuplet states)
  - coupled channel dynamics (molecule-like states)

- comparison: known excited states - constituent quark model (Capstick & Roberts)

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low lying excited states

Notation:

\( L_{2I2J} : L=0(S),1(P),2(D),... \)

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Experimental Options:

- **Final states:**
  - single meson production:
    \[ \gamma p \rightarrow p\pi, \eta, \eta', \omega; \Sigma K, \Sigma K^* \ldots \]
  - multiple meson production:
    \[ \gamma p \rightarrow p\pi\pi, \pi\eta, \pi\omega \ldots \]

- **Observables:**
  - angular distributions
    \[ \frac{d\sigma}{d\Omega} \]
  - Dalitz plots
    \[ M(N, m_i), M(m_1, m_2) \]
  - polarization dof:
    - linearely pol. beams
    - circularly pol. beams
    - longitudinally pol. targets
    - transversely pol. targets
    - recoil polarization
    \[ \rightarrow \Sigma, R, T \]
    \[ \rightarrow E, G, H, F \]
    \[ \rightarrow \ldots \]

- **Isospin: Neutron targets**
  - electromagnetic excitation
  - isospin dependent

- **Quasifree photoproduction**
  - (off the deuteron)

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polarisation degrees of freedom

Longitudinally polarised proton target ✓
Transversely polarised ✓

D. Watts et al., Edinburgh

Nucleon polarisation: scattering in carbon ✓
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Electron Stretcher Accelerator (ELSA)

- Booster synchrotron: 0.5 - 1.6 GeV
- Stretcher ring: 0.5 - 3.5 GeV
- Beamlines for SR experiments
- Medium energy physics experiments
- GDH
- Crystal Barrel
- Møller Polarimeter
- Compton Polarimeter
- Compton polarimeter
- LINAC 1 (20 MeV)
- LINAC 2 (26 MeV)
- EKS
- Electron stretcher accelerator (ELSA)
- Desy cavity
- Half cell of ELSA
- PETRA cavity
- DORIS cavity
- Tune jump quadrupole
- Superconducting solenoid
- Extraction septa
- Injection septa
- Skew quadrupoles
- Detector tests
- Möllers polarimeter
- Pol. e⁻ source (50 keV)
- Beamlines for SR experiments

Instruments:
- Dipole (horizontal)
- Dipole (vertical)
- Quadrupole
- Skew Quadrupole
- Sextupole
- Combined-Function Magnet
- Solenoid
- Radio Frequency
- Electron gun
- (26 MeV)
- (20 MeV)

Experiments:
- EKS: 0 m - 5 m - 10 m - 15 m
MAMI accelerator in Mainz

Mainz Microtron (MAMI)
continuous wave electron accelerator, max. beam energy 883 MeV

0. Stage: Linac (2.5 GHz, 3.45 MeV)

1.-3. Stage: Racetrack Microtrons:
- microbunches of 0.4ns
- linear accelerator structures
- constant B field ⇒ varying radii (18, 51, 90 return cycles)
- very efficient acceleration and continuous mode
- high current (0.1mA)

4. Stage: Harmonic Double Sided Microtron
maximum energy: 1.5 GeV

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experimental setups - Ball, Barrel and TAPS and ...

- **Bonn ELSA accelerator:**
  - Crystal Barrel (CsI), TAPS (BaF$_2$) forward wall, inner detectors
  - $E_\gamma \leq 3.5$ GeV, lin. pol.: available, circ. pol.: available

- **Mainz MAMI accelerator:**
  - Crystal Ball (NaJ), TAPS (BaF$_2$) forward wall, inner detectors
  - $E_\gamma \leq 0.8$ (1.5) GeV, lin. pol.: available, circ. pol.: available

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TAPS Crystal Ball - at MAMI

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$\eta$ photoproduction from the nucleon at threshold:
- dominance of the $S_{11}(1535)$ resonance...

- total cross section

- expected energy dependence for resonances:
  $S_{11}(L_{NN\eta} = 0): \sigma \propto (E_\gamma - E_{thres})^{1/2}$
  $P_{11}(L_{NN\eta} = 1): \sigma \propto (E_\gamma - E_{thres})^{3/2}$
  $D_{13}(L_{NN\eta} = 2): \sigma \propto (E_\gamma - E_{thres})^{5/2}$

- strong dominance of $S_{11}(1535)$, background small
  (vector mesons, Born terms), some interference with $S_{11}(1650)$

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\( \eta \) photoproduction from the nucleon at threshold:
...and a tiny little bit of \( D_{13}(1520) \)

- angular distributions

\[
\frac{d\sigma}{d\Omega} = \frac{q_\eta}{k_\gamma} \left[ A + B \cos(\Theta^*) + C \cos^2(\Theta^*) \right]
\]

\( \Rightarrow b_\eta(D_{13}) = 0.23 \pm 0.04 \% \)

(Tiator et al., Chiang et al.)

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target asymmetry at threshold

- measured target asymmetries

A. Bock et al. PRL 81 (1998) 534

![Graphs showing target asymmetries at different energies](image1)

- target asymmetry enforces 'unnatural' phase between multipoles related to $D_{13}(1520)$ and $S_{11}(1535)$

(L. Tiator et al., PRC60 (1999) 035210)

- Same problem in polarization observables from electroproduction

(H. Merkel et al. PRL 99 (2007) 132301)

- isobar models etc. cannot reproduce the observed 'node'

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polarization observables in $\eta$ photoproduction

with phase rotation

on a quasi-free proton

on a quasi-free neutron

only $\pm 10\%$

up to $30\%$

L. Tiator, priv. com.
resonances coupling to $\eta$ photoproduction

branching ratios and elm. couplings (PDG):

<table>
<thead>
<tr>
<th>state</th>
<th>$b_\eta$ [%]</th>
<th>$A^p_{1/2}$</th>
<th>$A^p_{3/2}$</th>
<th>$A^n_{1/2}$</th>
<th>$A^n_{3/2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_{13}(1520)$</td>
<td>0.23±0.04</td>
<td>-24</td>
<td>166</td>
<td>59</td>
<td>139</td>
</tr>
<tr>
<td>$S_{11}(1535)$</td>
<td>30 - 55</td>
<td>90</td>
<td></td>
<td>-46</td>
<td></td>
</tr>
<tr>
<td>$S_{11}(1650)$</td>
<td>3 - 10</td>
<td>53</td>
<td></td>
<td>-15</td>
<td></td>
</tr>
<tr>
<td>$D_{15}(1675)$</td>
<td>0 ± 1</td>
<td>19</td>
<td>15</td>
<td>-43</td>
<td>-58</td>
</tr>
<tr>
<td>$F_{15}(1680)$</td>
<td>0 ± 1</td>
<td>-15</td>
<td>133</td>
<td>29</td>
<td>-33</td>
</tr>
<tr>
<td>$D_{13}(1700)$</td>
<td>0 ± 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_{11}(1710)$</td>
<td>6.2±1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_{13}(1720)$</td>
<td>4±1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- $D_{15}(1675)$ has stronger electromagnetic coupling to the neutron than to the proton but parameters quite uncertain:
  $A^p_{1/2}=6 - 34, A^p_{3/2}=3-30, A^n_{1/2}=-(21-57), A^n_{3/2}=-(30-77)$
  $b_\eta=0 - 1\%$ (PDG), $b_\eta=17\%$ (ETA-MAID, Chiang et al.)
- interference structure in $S_{11}$-sector?

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Data:
- TAPS: B. Krusche et al., PRL74 (195) 3736
- GRAAL: F. Renard et al., PLB528 (2002) 215
- CLAS: M. Dugger et al., PRL89 (2002) 222002
- Crystal Barrel: V. Crede et al., PRL94 (2005) 012004

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what is expected for $n(\gamma, \eta)n$ - why is it interesting?

- total cross sections for proton and neutron from MAID model with and without $D_{15}(1675)$ (Eta-MAID, W.T. Chiang et al., NPA 700 (2002) 429)
- previous data from MAMI only at lower incident photon energies

predictions from chiral soliton models: $P_{11}$-like state of the anti-decuplet has strong photon-coupling to the neutron and large $\eta N$ decay branching ratio
quasifree $\eta$-photoproduction off the deuteron (PhD thesis I.Jaegle)

- cross section for $\gamma n \rightarrow \eta n$ from two analyses with very different systematics:
  1. $\eta$ in coincidence with recoil neutrons
  2. Difference of inclusive cross section and $\eta$ in coincidence with recoil protons

![Graph showing $\eta$-photoproduction cross sections vs. $E_\gamma$](image)

$\sigma[\mu b]$ vs. $E_\gamma[\text{MeV}]$ for different channels and models:
- $\sigma(\text{NN$\eta$X})$
- $\sigma(\text{n$p$}$eta$)$
- $\sigma(\text{n$p$}$eta$)$ (Weiss et al.)
- $\sigma(\eta\pi)$
- $\sigma(p$eta$)$
- $\sigma(n$eta$)$
- $\sigma(n$p$ eta$)$-$\sigma(p$eta$)$
- $\sigma(\eta\pi)$

$\sigma_{n/\sigma_p}$ for different analyses:
- Weiss et al.
- MAID
- Shklyar et al.

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comparison of free and quasi-free cross sections

- quasi-free total cross sections corrected for Fermi smearing with correction factors calculated by folding known free proton cross section, respectively ETA-MAID prediction with momentum distribution of bound nucleons.

result:
- in $S_{11}(1535)$ peak below 0.9 GeV perfect agreement between free and quasi-free proton data and quasi-free neutron data scaled by 2/3.

Fit parameters for $S_{11}$ Breit-Wigner:
- proton:
  $W=1538$ MeV, $\Gamma=157$ MeV, $A_{1/2}^p=103$
- neutron:
  $W=1538$ MeV, $\Gamma=148$ MeV, $A_{1/2}^n=85$

- narrow structure around 1 GeV in neutron/proton ratio, width is only upper bound

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angular distributions

$\cos(\Theta_\eta) \cos(\Theta_{\eta^*})$

- $\eta p, qf$
- $\eta n, qf$
- $\eta p, \text{free folded}$

Comparison with models

$E_\gamma = 800 \text{ MeV}, W = 1542 \text{ MeV}$

$E_\gamma = 1000 \text{ MeV}, W = 1660 \text{ MeV}$

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de-folding of Fermi smearing

- for events with neutron in TAPS $(\cos(\Theta^*_n) < -0.1)$
  neutron energy from time-of-flight
- comparsion: $W$ from photon energy (Fermi smeared) -
  $W$ from nucleon - meson
  4-vectors (resolution smeared)
- de-folded proton cross section similar to free proton,
  de-folded neutron cross section shows structure around 1.7 GeV:
  position: $W = 1683$ MeV
  width: $\Gamma = 60 \pm 20$ MeV
  (resolution dominated)
Double Polarisation Experiments at ELSA (U. Thoma, priv. com.)

Online spectra: circularly polarised beam, longitudinally polarised target

\( \gamma p \rightarrow p \eta \):

\( \eta \rightarrow \gamma \gamma \)

⇒ First asymmetries observed
resonances in photoproduction of $\eta'$-mesons

- experiments: ‘resonance’ like structure around 1.8 GeV
- known resonances ($\sqrt{s} \approx 2$ GeV):
  $P_{13}(1900)$ (*), $F_{17}(1990)$ (**),
  $F_{15}(2000)$ (**), $D_{13}(2080)$ (**),
  $S_{11}(2090)$ (*), $P_{11}(2100)$ (*);
  no branching ratios known
- quark model predictions:
  many states, strongest coupling of $\eta'$ to: $S_{11}(2090)$, $D_{13}(2080)$

analyses of previous photoproduction data:
- Mukhopadhyay et al. (1995):
  effective Lagrangian approach fitted to old data:
  dominance of $D_{13}(2080)$ resonance
- Plötzke et al. (1998):
  BW resonances, SAPHIR 5-track events:
  dominance of $S_{11}$ and $P_{11}$ resonances
  with poles close to 2 GeV
- Link (2000):
  Regge parameterization, SAPHIR 3-track events:
  dominance of Regge exchange, possibly $S_{11}$ state at threshold
- Sibirtsev et al. (2003):
  SAPHIR data (3-track events renormalized)
  dominance of $\rho$, $\omega$ poles in $t$-channel,
  small contribution from $S_{11}(1535)$ resonance
- Chiang et al. (2003):
  reggeized model, SAPHIR 5-track events:
  strong contribution from Regge exchange,
  $S_{11}$ with pole around 1950 MeV,
  possibly $P_{11}$ and/or $P_{13}$ (poles close to 1950 MeV)

- Dugger et al. (CLAS-data, 2006):
  $S_{11}(1535)$ and $P_{11}(1710)$ resonances and $t$-channel
- Nakayama and Haberzettl (2006):
  $S_{11}$, $P_{11}$, $P_{13}$, $D_{13}$ resonances and $t$-channel

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quasifree $\eta'$-photoproduction off the deuteron (PhD thesis I. Jaegle)

- same game as before...preliminary results

- at high incident photon energies $t$-channel dominated, at low energies resonance contributions?

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double pion photoproduction: the different charge channels

- $\gamma p \rightarrow p\pi^+\pi^-$
- $\gamma p \rightarrow n\pi^0\pi^+$
- $\gamma p \rightarrow p\pi^0\pi^0$

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double $\pi^0$ photoproduction

interpretation by Laget model:

BoGa analysis of most recent Mainz and Bonn data:

P$_{11}$ small, D$_{13}$ strong, D$_{33}$ strong, double-bump structure from interference between D$_{11}(1520)$ and D$_{33}(1700)$
identification of double $\pi^0$-channel

- invariant mass spectrum
- missing mass spectra

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total cross sections: $\gamma p \rightarrow n\pi^0\pi^+$, $\gamma p \rightarrow p\pi^0\pi^0$  

- $\gamma p \rightarrow n\pi^0\pi^+$ cross section
- $\gamma p \rightarrow p\pi^0\pi^0$ cross section

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invariant mass distributions: $\pi^0\pi^+ - n$

- $\pi^0 - n$ invariant mass
- $\pi^+ - n$ invariant mass
invariant mass distributions: $\pi^0\pi^0 - p$

- $\pi^0 - n$ invariant mass
- threshold region

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invariant mass distributions: \( \pi^0\pi^0, \pi^0\pi^+ \)

- \( \pi^0 - \pi^+ \) invariant mass
- \( \pi^0 - \pi^0 \) invariant mass

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similar results for $\gamma p \rightarrow \pi^0 \eta p$

- **Identification**
- **Invariant mass distributions**
- **Total cross section**

**Identification**

- Dominant final states:
  - $\Delta(1232)\eta$
  - $N(1535)\pi$
  - $p\Delta(980)$

**Invariant mass distributions**

**Total cross section**

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beam-helicity asymmetry (circularly pol. beam)
final results: $\gamma p \rightarrow n\pi^0\pi^+$, $\gamma p \rightarrow p\pi^0\pi^0$ (PhD thesis F.Zehr)

$\gamma p \rightarrow n\pi^0\pi^+$

$\gamma p \rightarrow p\pi^0\pi^0$

---: Fix et al.
- - -: Roca et al., full model
.....: Roca et al., w/o. $D_{13} \rightarrow N\rho$

---: Fix et al.
- - -: Bonn/Gatchina PWA

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π⁰π⁰ photoproduction off the deuteron

**Preliminary**

γn→π⁰π⁰n measured in 2 different ways:

- π⁰π⁰ in coincidence with the recoil neutron
- difference of inclusive cross section and in coincidence with the recoil proton

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Conclusions

Very active experimental program for investigation of Baryon Resonances at ELSA and MAMI exploring:

- High quality tagged photon beams
- (Almost) $4\pi$ detectors for photons, charged, and neutral particles
- Linearly and circularly polarized photon beams
- Longitudinally and transversely polarized targets
- Polarization of recoil protons
- Many different single and multiple meson production reactions
- Deuterium targets as quasi-free neutron targets

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Summary

exclusive, quasifree $\eta$-photoproduction off deuteron:
- large difference for resonance contributions to $p(\gamma, \eta)p$ and $n(\gamma, \eta)n$
- narrow structure in excitation function off neutron
- next steps: (double) polarization observables, better neutron ToF resolution

$\eta'$-photoproduction off the deuteron:
- large difference in total cross section and shape of angular distributions around cross section maximum for free proton

double pion photoproduction
- precise invariant mass distributions for $\pi^0\pi^0$ and $\pi^0\pi^+$
- precise beam-helicity asymmetries for $\pi^0\pi^0$ and $\pi^0\pi^+$
- first results for $n(\gamma, \pi^0\pi^0)n$: peak in cross section ratio around 900 MeV

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