Baryon Spectroscopy at ELSA

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MAMI and Beyond, 30.3-3.4, 2009, Mainz

- Motivation
- Crystal Barrel experiment
- Recent Results
- Summary and Outlook

supported by the DFG within the SFB/TR16
Introduction

Experiments at ELSA, Jlab and MAMI to determine the Nucleon properties:

electron scattering:

\[ e^- + N \rightarrow e^- + N \]

(schematic view)

Nucleon properties to be measured

- $\mu$ magnetic moment
- $\langle r^2 \rangle$ radius (elect. -, mag. -, axial) form factor
- $\alpha, \beta, \gamma_i$ polarizabilities + form factor
- $M^*$ excitation spectrum
- $\mu^*$ transition moment + form factor
- $A_{1/2}, A_{3/2}, S_{1/2}$ helicity amplitude

ELSA: focus on excitation spectrum
Introduction

- 3.2 GeV photon beam at ELSA used to study meson photoproduction

Breit Wigner Resonances

Total Photon Absorption Cross Section

Spectroscopic Notation

\[ X = S(l_{\pi} = 0); P(l_{\pi} = 1); \ldots \]
PDG 2008: Status on nucleon resonances

only 7 $N^*$ and 5 $\Delta^*$

established in the region $1400 \text{ MeV} < W < 2000 \text{ MeV}$

- Energy pattern for the dominant states
  - Constituent Quark Models
  - Dynamical Models
  - Lattice QCD

- Various nucleon models predict many more states
  - weak coupling to $\pi N$ final state
  - insufficient data base
**Experimental program for N**

Common effort at ELSA, JLab and MAMI,

- Precision data for different final states \((p\pi^0, p\pi^0\pi^0, p\eta, ....)\)
- Polarization experiments (beam, target and recoil)
  “complete experiment”

\[
\begin{align*}
\gamma + p &\rightarrow X \\
\gamma + p &\rightarrow p + \pi^- + \pi^+ \\
\gamma + p &\rightarrow p + \pi^0 + \pi^0 \\
\gamma + p &\rightarrow p + \pi^0 \\
\gamma + p &\rightarrow K^+ + \Lambda \\
\gamma + p &\rightarrow p + \eta
\end{align*}
\]
Complete Experiment

\[ \gamma + N \rightarrow N + \pi \]

8 well chosen observable have to be measured to determine the production amplitudes \( F_1, F_2, F_3 \) and \( F_4 \)

- \( \pi \)- threshold until \( \Delta^{+}(1232) \)- region

**additional constraints:**

(a) s- and p- wave approximation

(b) Fermi- Watson theorem

\[ \gamma + N \rightarrow N + \pi \quad \text{same } I, J \text{ in the final state} \]
\[ \pi + N \rightarrow N + \pi \quad \Rightarrow \text{same scattering phase } \delta_{IJ} \]

**two observable sufficient for “complete experiment”**

- differential cross section : \( d\sigma/d\Omega \)
- beam asymmetry : \( \Sigma \)  
  
  success of MAMI B

- above \( \pi\pi \)- threshold
  
  Fermi- Watson theorem not valid any more
  
  More observable needed to find unique partial wave solution
# Observables in Meson Photoproduction

<table>
<thead>
<tr>
<th>Photon polarization</th>
<th>Target polarization</th>
<th>Recoil nucleon polarization</th>
<th>Target and recoil polarizations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$X\ Y\ Z_{(\text{beam})}$</td>
<td>$X'\ Y'\ Z'$</td>
<td>$X'\ X'\ Z'\ Z'$</td>
</tr>
<tr>
<td>unpolarized</td>
<td>$\sigma$</td>
<td>$-\ P$</td>
<td>$T_x\ L_x\ T_z\ L_z$</td>
</tr>
<tr>
<td>linear</td>
<td>$\Sigma$</td>
<td>$H\ (-P)\ G$</td>
<td>$(-L_z)\ (T_z)\ (L_x)\ (-T_x)$</td>
</tr>
<tr>
<td>circular</td>
<td>$-\ F\ -\ E$</td>
<td>$O_x\ (-T)\ O_z$</td>
<td>$C_x\ -\ C_z$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$E$</td>
<td></td>
</tr>
</tbody>
</table>

### Data only for:
- Differential cross section: $\sigma$
- Beam asymmetry: $\Sigma$
- Double polarization: $E$

### Sensitive to: $\text{Re}(P_1 \cdot P_2)$

### Data needed for:
- Target asymmetry: $T$
- Recoil polarization: $P$
- Double polarization: $G$

### Sensitive to: $\text{Im}(P_1 \cdot P_2)$

Crystal Barrel experiment at ELSA: polarized photons, polarized targets and $4\pi$ acceptance
Crystal Ball experiment at MAMI: polarized photons, polarized targets and $4\pi$ acceptance
Electron Stretcher Accelerator (ELSA)

booster synchrotron
0.5 - 1.6 GeV

stretcher ring
0.5 - 3.5 GeV

detector tests
(under construction)
Crystal Barrel Set Up at ELSA

Diagram showing the components of the setup:
- Polarized Target
- Gas-Cherenkov
- TAPS
- Forward Detector
- Crystal Barrel + Inner detector
- Goniometer
- Tagging system
- Photon intensity monitor
- Beam Dump
Crystal Barrel Set Up at ELSA

- Crystal Barrel detector
  1230 CsI crystals

- Inner-detector
  cylinder of 513 scintillating fibers

- forward detector (FWPlug)
  90  CsI crystals with PM’s, 12°-30°

- forward detector (MiniTAPS)
  216 BaF₂, 1°-12°

Close to 4π coverage
Polarized Photons

Linearly polarized photons:
- coherent bremsstrahlung
- diamond radiator

Circularly polarized photons:
- longitudinally polarized electrons
- helicity transfer to photon

High polarization at low photon energies: \( p_{\gamma}^{\text{Lin}} = 70\% \)

High polarization at high photon energies: \( p_{\gamma}^{\text{Cir}} = 65\% \)

(H. Eberhard) (S. Kammer)
Polarized Target

„Frozen Spin Target“

horizontal cryostat with integrated solenoid to freeze up the spin

**Target:** Butanol (C$_4$H$_9$OH)

**Polarization:** DNP at high B-field (2.5 T) „freeze“ up the spin (0.4 T) relaxation time T~500h

Bonn: H. Dutz, S. Goertz
Bochum: W. Meyer, S. Reichertz
Polarized Target

Running time over 2500 hours in year 2008

High. polarization
\[ P_+ = 83.4\% \]
\[ P_- = -80.9\% \]

fast build-up
05h04min (May/June)
05h39min (August)

Pol.-time
06h10min

horizontal cryostat in experimental area

data taking
Polarization Observables

\[ \bar{\gamma} \bar{p} \rightarrow p \pi^0 \]

Linearly polarized photons: \( p_{\gamma}^{Lin} \)
Circularly polarized photons: \( p_{\gamma}^{Cir} \)
Longitudinally polarized protons: \( p_z \)

\[
\frac{d\sigma}{d\Omega}(\theta, \phi) = \frac{d\sigma}{d\Omega}(\theta) \left(1 - p_{\gamma}^{Lin} \Sigma \cdot \cos(2\phi) - p_{\gamma}^{Lin} p_z G \cdot \sin(2\phi) + p_{\gamma}^{Cir} p_z E \right)
\]

Linearly polarized photons \( \rightarrow \) beam asymmetry \( \Sigma \)
Circularly polarized photons \( \rightarrow \) double polarization asymmetry \( E \)
Longitudinally polarized protons \( \rightarrow \) double polarization asymmetry \( G \)

Crystal Barrel experiment at ELSA: New preliminary results for \( G \) and \( E \)
Meson photoproduction

\( \tilde{\gamma} + p \rightarrow p + \eta \)

Photon helicity couplings: \( A_{1/2} \) and \( A_{3/2} \)

- \( S_{11}(1535) \): \( A_{1/2} (S_{11}(1535)) \) only
- \( D_{13}(1520) \): \( A_{1/2} (D_{13}(1520)) \) and \( A_{3/2} (D_{13}(1520)) \)
- \( P_{13}(1720) \): \( A_{1/2} (P_{13}(1720)) \) and \( A_{3/2} (P_{13}(1720)) \)

Total cross section:
\[
\sigma_{\text{tot}} \sim |A_{1/2}(S_{11})|^2 + |A_{1/2}(P_{13})|^2 + |A_{3/2}(P_{13})|^2 + \ldots
\]

Crystal Barrel/TAPS Results

Beam asymmetry: \[ \Sigma \]
\[ \vec{\gamma} + p \rightarrow p + \eta \]

Higher sensitivity because of interference between different resonance contributions
\[ \Sigma \sim A_{1/2}(S_{11}) \ast A_{1/2}(P_{13}) + \ldots. \]

D. Elsner et al., EPJ A33 (2007) 147
Helicity dependent total cross section

**reaction:** \( \vec{\gamma} + \vec{p} \rightarrow X \)

circularly polarized photons
longitudinally polarized proton

### Helicity dependent total cross section

![Graph showing helicity dependent total cross section with data points for different energies and labels for unpolarized and polarized H (PDG) data.]

- **unpolarisierter \(^1\)H (PDG):**
  - GDH-MAMI: 0.8 GeV
  - GDH-ELSA: 1.0 GeV
  - GDH-ELSA: 1.4 GeV
  - GDH-ELSA: 1.9 GeV
  - GDH-ELSA: 2.4 GeV
  - GDH-ELSA: 2.9 GeV

reaction: $\vec{\gamma} + \vec{p} \rightarrow p + \pi^0$

circularly polarized photons
longitudinally polarized proton

count rate difference
preliminary acceptance correction

Preliminary results (M. Gottschall)

$N_{1/2} - N_{3/2}$

$P_{33}(1232)$
$S_{11}(1535)$
$F_{15}(1680)$
+$\ldots$

$|\sigma_{1/2} - \sigma_{3/2}|$
Helicity dependent cross section

reaction: $\gamma + \bar{p} \rightarrow p + \pi^0$

Angular distributions sensitive to interference between resonances

Preliminary results (M. Gottschall)
Helicity dependent cross section

reaction: \( \vec{\gamma} + \vec{p} \rightarrow p + \eta \)

circularly polarized photons
longitudinally polarized proton

Preliminary results (M. Gottschall)

\( N_{1/2} - N_{3/2} \)
Helicity dependent cross section

reaction: \( \vec{\gamma} + \vec{p} \rightarrow p + \eta \)

Preliminary results (M. Gottschall)

\[ N_{1/2} - N_{3/2} \]

count rate difference
Helicity dependent cross section

reaction: $\gamma^- + p \rightarrow p + \pi^0 + \pi^0$

circularly polarized photons
longitudinally polarized proton

Preliminary results (D. Piontek)
Polarization Observables

\[ \gamma \, \vec{p} \rightarrow p \, \pi^0 \]

- Linearly polarized photons: \( p_{\gamma}^{\text{Lin}} \)
- Circularly polarized photons: \( p_{\gamma}^{\text{Cir}} \)
- Longitudionally polarized protons: \( p_z \)

\[
\frac{d\sigma}{d\Omega}(\theta,\phi) = \frac{d\sigma}{d\Omega}(\theta) \left( 1 - p_{\gamma}^{\text{Lin}} \Sigma \cdot \cos(2\phi) - p_{\gamma}^{\text{Lin}} p_z G \cdot \sin(2\phi) + p_{\gamma}^{\text{Cir}} p_z E \right)
\]

G-measurement: linearly pol. photons and long. pol. Target

1.) Coherent peak at 600 MeV, \( \gamma \, \vec{p} \rightarrow p \, \pi^0 \)
   interference between P33(1232) and P11(1440)

2.) Coherent peak at 1100 MeV, \( \gamma \, \vec{p} \rightarrow p \, \pi^0 \) and \( \gamma \, \vec{p} \rightarrow p \, \eta \)
   interference between P13(1720), P11(1710) and D13(1520)

3.) Coherent peak at 1700 MeV, \( \gamma \, \vec{p} \rightarrow p \, \pi^0 \) and \( \gamma \, \vec{p} \rightarrow p \, \eta \)
   interference between P13(1720), P11(1710) and D15(2070)
Double Polarization Experiment for $G$

reaction: $\vec{\gamma} + \vec{p} \rightarrow p + \pi^0$

\[
\frac{d\sigma}{d\Omega}(\theta, \phi) = \frac{d\sigma}{d\Omega}(\theta) \left( 1 - p_{\gamma}^{\text{Lin}} \Sigma \cdot \cos(2\phi) - p_{\gamma}^{\text{Lin}} p_z G \cdot \sin(2\phi) \right)
\]

first online spectra with

- linearly polarized photons
- longitudinally polarized proton
Double Polarization Experiment for $G$

\[
\frac{d\sigma}{d\Omega}(\theta, \phi) = \frac{d\sigma}{d\Omega}(\theta) \left( 1 - p_{\gamma}^{Lin} \Sigma \cdot \cos(2\phi) - p_{\gamma}^{Lin} p_{z} G \cdot \sin(2\phi) \right)
\]

reaction: $\vec{\gamma} + \vec{p} \rightarrow p + \pi^{0}$

linearly polarized photons
longitudinally polarized proton

Clear effect from $G$ observed
G-Asymmetry for pπ₀

reaction: \( \vec{\gamma} + \vec{p} \rightarrow p + \pi^0 \)

missing mass cut
fit to the \( \phi \)-distribution

\[
\frac{d\sigma}{d\Omega}(\theta, \phi) = \frac{d\sigma}{d\Omega}(\theta) \left( 1 - p_{\gamma}^{Lin} \Sigma \cdot \cos(2\phi) - p_{\gamma}^{Lin} p_z G \cdot \sin(2\phi) \right)
\]

- Preliminary results CB (A. Thiel)
- GRAAL data
Asymmetries for $p\pi^0$

reaction: $\vec{\gamma} + \vec{p} \rightarrow p + \pi^0$

linearly polarized photons
longitudinally polarized proton

Preliminary results
(A. Thiel)

GRAAL data

prediction
partial wave analysis

- BoGa
- SAID
- MAID
Asymmetries for $p\pi^0$

reaction: $\bar{\gamma} + \bar{p} \rightarrow p + \pi^0$

- Preliminary results (A. Thiel)
- GRAAL data

BoGa
SAID
MAID

prediction
partial wave analysis
Asymmetries for $p\pi^0$

reaction: $\bar{\gamma} + \bar{p} \rightarrow p + \pi^0$

Preliminary results
(A. Thiel)

GRAAL data

prediction
partial wave analysis

- BoGa
- SAID
- MAID
Energy dependence

Beam-Asymmetry $\Sigma$ at $\theta = 90$

- Red line: without $P_{11}$ (1440)
- Blue line: without $D_{13}$ (1520)
- Green line: without $F_{15}$ (1680)

Double-Polarization-Asymmetry $G$ at $\theta = 90$

Preliminary results
(A. Thiel)
Asymmetries for $p\eta$

reaction: $\gamma^- + \vec{p} \rightarrow p + \eta$

missing mass cut
fit to the $\phi$-distribution

$$\frac{d\sigma}{d\Omega}(\theta, \phi) = \frac{d\sigma}{d\Omega}(\theta) \left( 1 - p_{\gamma}^{Lin} \Sigma \cdot \cos(2\phi) - p_{\gamma}^{Lin} p_z G \cdot \sin(2\phi) \right)$$
Asymmetries for $p\eta$

reaction: $\vec{\gamma} + \vec{p} \rightarrow p + \eta$

linearly polarized photons
longitudinally polarized proton

- Preliminary results (A. Thiel HK69.6)
- CB (D. Elsner)

- Partial wave analysis
- prediction

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- BoGa
- SAID
- MAID
reaction: \( \gamma + \vec{p} \rightarrow p + \pi^0 \)

First round of double polarization experiments with CB at ELSA:
- Energy range for G: 600-1300 MeV
- Energy range for E: 500-2100 MeV

Future plans for CB at ELSA:
- Extend energy range to 3 GeV
- Transversally polarized target in preparation

Future plans for Crystal Ball at MAMI C:
- G: 150-800 MeV
- E: 150-1500 MeV
Summary

- First round of double polarization experiments with Crystal Barrel at ELSA
- Preliminary results for the double polarization observable G and E
- Aim: reach “complete” experiment
- Model independent partial wave analysis
- Will shed new light on the nucleon excitation spectrum
Nucleon Resonances

Pion-Production

\[ \gamma + N \rightarrow N^* \rightarrow N + \pi \]

Eta-Production

\[ \gamma + N \rightarrow N^* \rightarrow N + \eta \]

Kaon-Production

\[ \gamma + N \rightarrow N^* \rightarrow K^+ + \Lambda \]

Problem: overlapping resonances
Polarization observable

ELSA and MAMI: polarized photons and polarized targets
\[
\gamma + p \rightarrow p + \eta
\]

**Meson photoproduction**

- \(\pi, \eta, \rho, \omega, K, \ldots\)
- \(N^*, N, N^*, \Delta, \Lambda, \Sigma\)

**Photon helicity couplings:**

- \(S_{11}(1535): A_{1/2}(S_{11}(1535))\) only
- \(D_{13}(1520): A_{1/2}(D_{13}(1520))\) and \(A_{3/2}(D_{13}(1520))\)

**Total cross section:**

\[\sigma_{\text{tot}} \sim |A_{1/2}(S_{11})|^2 + |A_{1/2}(D_{13})|^2 + |A_{3/2}(D_{13})|^2 + \ldots\]

V. Crede, O. Bartolomy et al.,
PRL 94 (2005) 012004,
EPJ A33 (2007) 133