Measurement of the double polarization observables E and G at the Crystal Ball experiment at MAMI

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for the A2 collaboration

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Outline

1 Motivation

2 The Crystal Ball experimental setup

3 Event selection

4 Determination of E and G

5 Preliminary results
**Why baryon spectroscopy?**

**Goal:** Understanding nucleon excitation spectra  
↔ Understanding dynamics of the constituents inside the nucleon

- many more resonances expected in quark models or lattice QCD than experimentally observed
- What are the relevant degrees of freedom?
- most resonances observed in $\pi N \rightarrow$ some resonances might not couple to $\pi N$

→ Talk by Jan Hartmann, Monday 11:30  
→ Talk by Prof. Leinweber, Tuesday 10:00

Photoproduction reactions are excellent tool to probe excitation spectra!
Photoproduction reactions

Study of different reaction channels gives access to different resonant structures
⇒ Worldwide effort to get high precision data (ELSA, JLab, MAMI, ...)

\[ \gamma + p \rightarrow X \]
\[ \gamma + p \rightarrow p + \pi^- + \pi^+ \]
\[ \gamma + p \rightarrow p + \pi^0 + \pi^0 \]
\[ \gamma + p \rightarrow p + \eta \]
\[ \gamma + p \rightarrow p + \eta' \]
Importance of polarization observables

- Scattering amplitude $f \leftrightarrow 4$ complex amplitudes (CGLN amplitudes)
  $$f(F_1(W, \cos \theta_{cm}), F_2(W, \cos \theta_{cm}), F_3(W, \cos \theta_{cm}), F_4(W, \cos \theta_{cm}))$$

- PWA: $F_1 = \sum_{l=0}^{\infty} (lM_{l+} + E_{l+}) P'_{l+1} + [(l+1)M_{l-} + E_{l-}] P'_{l-1}$
  - $E_{l\pm}(W), M_{l\pm}(W)$: Multipoles
  - $P'_{l\pm 1}(\cos \theta_{cm})$: Legendre polynomials

- Measurable observables $\leftrightarrow$ Multipoles $\leftrightarrow$ Resonance parameters

F.N. Afzal Measurement of the double polarization observables $E$ and $G$ at the Crystal Ball experiment at MAMI

\[ \gamma p \rightarrow p\eta \]

\[ \sigma \sim |E_{0+}|^2 + |E_{1+}|^2 + |M_{1+}|^2 + |M_{1-}|^2 + \ldots \]
\[ \Sigma \sim -2E_{1+}^*M_{1+} + 2M_{1-}^*E_{1+} - 2M_{1-}^*M_{1+} + \ldots \]

$\Rightarrow$ Polarization observables are sensitive to interference terms!
• Located at Inst. of Nuclear Physics, Mainz, Germany
• Unpolarized or longitudinally polarized electrons
• Acceleration in 3 race track microtrons (RTM1-3) to 855 MeV (MAMI-B)
• Acceleration in harmonic double-sided microtron (HDSM) to 1600 MeV (MAMI-C)

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The Crystal Ball experiment at MAMI in Mainz

More talks from A2:
- Prof. Bernd Krusche, Monday 14:55
- Dr. Sergey Prakhov, Tuesday 15:00
- Dr. Vahe Sokhoyan, Thursday 11:00
- Dr. Dominik Werthmueller, Thursday 12:00
Polarized $e^-$ beam on diamond radiator

First experimental attempt to measure $E$ and $G$ with longitudinally polarized electron beam in combination with a diamond crystal using linearly and circularly polarized photons within same beam time!

**Linearly polarized photons**
- diamond radiator needed
- coherent bremsstrahlung
- coherent edges at:
  350 MeV, 450 MeV, 550 MeV, 650 MeV, 750 MeV and 850 MeV

**Circularly polarized photons**
- longitudinally polarized electrons needed
- helicity transfer to photons
- Mott/Møller measurement:
  $p_e \approx 75\% - 78\%$

\[
p_{\gamma} = \frac{4E_{\gamma}E_0 - E_{\gamma}^2}{4E_0^2 - 4E_{\gamma}E_0 + 3E_{\gamma}^2} \cdot p_e
\]
Dubna-Mainz frozen spin polarized target

- polarization via Dynamic Nuclear Polarization DNP
- 70 GHz microwave irradiation at 2.5 T is used to transfer the electrons polarization to protons
- $^3\text{He}/^4\text{He}$ dilution cryostat with 25 mK holding coil and 0.63 T
- relaxation time $\tau \approx 2000$ h
- $9 \cdot 10^{22}$ pol. protons per cm$^2$ in the target cell
- $p_T$ up to 90%
- carbon target needed for background studies
Selection process of $\gamma p \rightarrow \gamma \gamma p$

Selected events had to fulfill kinematic constraints:

- 3 hits in calorimeters ($p + 2\gamma$)
- Time coincidence of beam photons and final state meson
- Energy dependent $3\sigma$-cuts:
  - Proton: Calculated as missing particle of $\gamma p \rightarrow \gamma \gamma X$
  - Invariant mass of $\gamma \gamma$
  - Agreement of missing mass and measured charged particle in $\theta$
  - Coplanarity-cut: $\Delta \Phi = |\Phi_{\gamma \gamma} - \Phi_p| = 180^\circ$
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\[ E = 840 \text{ MeV} \]
Determination of E and G

Differential cross section for pseudo-scalar meson photoproduction using elliptically polarized photons in combination with a longitudinally polarized target:

\[
\frac{d\sigma}{d\Omega}(\theta, \phi) = \frac{d\sigma}{d\Omega_0}(\theta)[1 - P_{\text{lin}} \Sigma \cos(2(\alpha - \phi)) - P_z (-P_{\text{lin}} G \sin(2(\alpha - \phi)) + P_{\text{circ}} E)]
\]

Integrating over all possible helicity states:

\[
N_B \mid_{\pm P_z} (\theta, \phi) = N_B(\theta) \cdot [1 - P_{\text{lin}} \Sigma_B \cos(2(\alpha - \phi)) + dP_{\text{lin}} P_z G \sin(2(\alpha - \phi))]
\]

All 4 settings are normalized, shifted to 0° and added up

E_\gamma = 464 \text{ MeV, } \cos \theta = -0.15
Determination of E and G

Differential cross section for pseudo-scalar meson photoproduction using elliptically polarized photons and longitudinally polarized target:

\[
\frac{d\sigma}{d\Omega}(\theta, \phi) = \frac{d\sigma}{d\Omega_0}(\theta) \left[ 1 - P_{\text{lin}} \Sigma \cos(2(\alpha - \phi)) - P_z \left( - P_{\text{lin}} G \sin(2(\alpha - \phi)) + P_{\text{circ}} E \right) \right]
\]

Integrating over \(\phi\):

\[
N_B \left|_{\pm P_z} \right. (\theta) = N_B(\theta) \cdot \left[ 1 - dP_{\text{circ}} P_z E \right]
\]

\[
E = \frac{\sigma^{1/2} - \sigma^{3/2}}{\sigma^{1/2} + \sigma^{3/2}} = \frac{N_B^{1/2} - N_B^{3/2}}{N_B^{1/2} + N_B^{3/2}} \cdot \frac{1}{d} \cdot \frac{1}{P_{\text{circ}} P_z}
\]
Determination of the dilution factor

- Dilution factor: amount of polarizable protons in the selected data

\[ d = 1 - s_c \cdot \frac{N_C}{N_B} \]

- Scaling factor \( s_c \) takes acceptance and flux differences of butanol and carbon beam times into account

![Graph showing \( \Delta \Phi \) and \( \cos \theta \) distributions for different energy levels with data points for butanol and carbon, and their differences.

\( E_\gamma = 840 \text{ MeV} \)
Beam asymmetry $\Sigma_B$ (266 MeV - 563 MeV)

- this work (butanol data, K. Spieker)
- BnGa_2014_02 (PWA fit)
- BnGa_2014_01 (PWA fit)
- MAID2007 (PWA fit)
- SAID-CM12 (PWA fit)
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- SAID-CM12 (PWA fit)
Double polarization observable $G$ (266 MeV - 563 MeV)

- this work (longitudinally polarized electrons + diamond radiator K. Spieker)
  - BnGa_2014.02 (PWA fit) — BnGa_2014.01 (PWA fit) — MAID2007 (PWA pred.) — SAID-CM12 (PWA pred.)
Double polarization observable $G$ (563 MeV - 860 MeV)

- this work (longitudinally polarized electrons + diamond radiator, K. Spieker)
  - BnGa_2014_02 (PWA fit) — BnGa_2014_01 (PWA fit) — MAID2007 (PWA pred.) — SAID-CM12 (PWA pred.)
Results for E in $\pi^0$-photoproduction (240 MeV - 800 MeV)

- this work (longitudinally polarized electrons + diamond radiator → elliptically polarized photons)
- this work (longitudinally polarized electrons + amorphous radiator → only circularly polarized photons)

Very good agreement between data obtained with a diamond and an amorphous radiator!
Results for $E$ in $\pi^0$-photoproduction ($840$ MeV - $1400$ MeV)

- this work (longitudinally polarized electrons + diamond radiator $\rightarrow$ elliptically polarized photons)
- this work (longitudinally polarized electrons + amorphous radiator $\rightarrow$ only circularly polarized photons)

Very good agreement between data obtained with a diamond and an amorphous radiator!
Results for E in $\pi^0$-photoproduction (240 MeV - 800 MeV)

- this work (longitudinally polarized electrons + diamond radiator $\rightarrow$ elliptically polarized photons)
  - BnGa.2014.02 (PWA fit)
  - BnGa.2014.01 (PWA fit)
  - MAID2007 (PWA pred.)
  - SAID-CM12 (PWA pred.)

Very good agreement to existing data!
Results for $E$ in $\pi^0$-photoproduction (840 MeV - 1400 MeV)

- this work (longitudinally polarized electrons + diamond radiator $\rightarrow$ elliptically polarized photons)
  - BnGa_2014_02 (PWA fit)
  - BnGa_2014_01 (PWA fit)
  - MAID2007 (PWA pred.)
  - SAID-CM12 (PWA pred.)

$E$ vs $\cos \theta_{\text{CMS}}$

Very good agreement to existing data!
Results for $E$ in $\eta$-photoproduction

- this work (longitudinally polarized electrons + diamond radiator $\rightarrow$ elliptically polarized photons)
- CBELSA/TAPS data (taken with amorphous data, J. Müller et al., to be published soon)
  - BnGa_2014_02 (PWA pred.)
  - BnGa_2014_01 (PWA pred.)
  - $\eta$-MAID (PWA pred.)
  - SAID-GE09 (PWA pred.)

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure.png}
\caption{Measurement of the double polarization observables $E$ and $G$ at the Crystal Ball experiment at MAMI.}
\end{figure}
The double polarization observables E and G were measured at the Crystal Ball experiment at MAMI within the same beam time using longitudinally polarized electrons on a diamond radiator → linearly and circularly polarized photons

The preliminary results in $\gamma p \rightarrow p\pi^0$ are looking promising:

- Our data cover energy range down to $\Delta(1232)$ resonance region → complementary to CBELSA/TAPS and CLAS data
- Good agreement between our results for E ($E_\gamma = (220 - 1420)$ MeV), $\Sigma_B$ and G ($E_\gamma = (266 - 860)$ MeV) and existing data
- Good agreement between data obtained with a Moeller and a diamond radiator

Outlook

- Analysis of $\gamma p \rightarrow p\eta$, $\gamma p \rightarrow n\pi^+$ ...

Thank you!
Mott measurement

- Mott-scattering: electrons in gold (Z=79) interact via spin-orbit coupling with the longitudinally polarized electrons from MAMI → asymmetry in backscattering! → polarization degree of electrons

- helicity transfer from electrons to photons → circularly polarized photons

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- coherent bremsstrahlung produced on diamond crystal
- Bragg: if $\vec{q} = n \cdot \vec{g} \rightarrow$ constructive interference