Measurement of the double polarization observables $G$ in pion photoproduction off the proton

Karsten Spieker

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September 21th, 2015
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Motivation

Excitation spectrum of the nucleons

What is matter made of?

molecules atom nucleus nucleon quark

Motivation: Analogy to atomic spectroscopy

Neon emission spectrum

→ Direct information on the dynamics of the atom, i.e. fine structure!
Motivation

Excitation spectrum of the nucleons

What is matter made of?

molecules  atom  nucleus  nucleon  quark

Nucleon spectroscopy (open questions)

- Excitation spectrum of the nucleon provides information about interaction/dynamics of constituents

- How many degrees of freedom:

  e.g.:  or  ?
Motivation

Excitation spectrum of the nucleons

What is matter made of?

→ Due to short life time, broad and overlapping resonances!
→ **NO direct information on the dynamics of the constituents!**
Motivation

Excitation spectrum of the nucleons

How to analyze the excitation spectrum?

- Study $\gamma N \rightarrow N^* / \Delta^* \rightarrow N \pi^0, N \eta, N \eta', N \pi^0 \pi^0, N \pi^+ \pi^- \cdots$
- Experiments, e.g., **Crystal Ball**@MAMI, Crystal Barrel@ELSA, CLAS@Jefferson Lab
- Theory vs Experiment: most resonances found via $\pi N \rightarrow N^* / \Delta^* \rightarrow X$

![Graph showing excitation spectrum and resonance peaks](image)

$\gamma + p \rightarrow X$

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

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

$\gamma + p \rightarrow p + \eta$

$\gamma + p \rightarrow p + \eta'$

Motivation

Polarization observables

- Scattering amplitude can be described by 4 complex amplitudes (CGLN-amplitudes)
- These CGLN-amplitudes can be described by **multipoles**
- These multipoles are directly related to **polarization observables**

Overview of the polarization observables in the 2-body kinematic system for the photoproduction of a pseudoscalar meson

<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>σ, Σ</td>
<td>X Y Z(beam)</td>
<td>X' Y' Z'</td>
<td>X' X' Z' Z'</td>
</tr>
<tr>
<td>linear</td>
<td>T</td>
<td>P</td>
<td></td>
</tr>
<tr>
<td>circular</td>
<td>(-P) (-G)</td>
<td>O_x' (-T) O_z'</td>
<td></td>
</tr>
<tr>
<td>Target polarization</td>
<td>H</td>
<td></td>
<td>X Z X Z</td>
</tr>
<tr>
<td>unpolarized</td>
<td>F</td>
<td>C_x' C_z'</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

- Note: σ, Σ, T, P + 4 double polarization observables are needed for model independent solution

Motivation

Multipole expression of $G$ for $l \leq 1$ in single pion photoproduction off the proton

$$\frac{d\sigma}{d\Omega} \cdot G(\cos \theta) = \text{Im}\{M_{1-}^* (E_{1+} - M_{1+}) - 2E_{1+}^* M_{1+}\} \cdot 3 \sin^2 \theta$$

$$\approx \text{Im}M_{1-} \Re M_{1+} \cdot 3 \sin^2 \theta$$

→ sensitive to the $M_{1-}$ partial wave
→ **sensitive to Roper Resonance $P_{11}(1440)$!**

solid line: real part, dotted lines: imaginary part
Motivation

Comparison of dominant multipole contributions from the different PWA

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Motivation

Sensitivity studies of the BnGa PWA for the $2\pi^0$ channel off the proton

\[ \cos \theta_{2\pi} \]

\[ G \]

\[ E_\gamma = (430-490) \text{ MeV} \]
\[ E_\gamma = (490-550) \text{ MeV} \]
\[ E_\gamma = (550-610) \text{ MeV} \]
\[ E_\gamma = (610-670) \text{ MeV} \]
\[ E_\gamma = (670-730) \text{ MeV} \]
\[ E_\gamma = (730-790) \text{ MeV} \]

\[ \text{S/D-wave ratio decay of } D_{13}(1520) \rightarrow \Delta \pi \]
BG2014-01: S/D=3
BG2014-02: S/D=1.5

Experimental setup

A2@MAMI

long. polarized electrons incident on diamond crystal in combination with long. polarized butanol target

→ Measurement of G & E at the same time!
→ Perfectly suited to identify charged and neutral final states!
Experimental setup

long. polarized electrons incident on diamond crystal in combination with long. polarized butanol target

linearity polarized photons

for different coherent edges

→ Measurement of G & E at the same time!
→ Perfectly suited to identify charged and neutral final states!
Experimental setup

A2@MAMI

long. polarized electrons incident on diamond crystal in combination with long. polarized butanol target

circularly polarized photons

\[ p_\gamma = \frac{4E_\gamma E_0 - E_\gamma^2}{4E_0^2 - 4E_\gamma E_0 + 3E_\gamma^2} \] with \( p_\gamma \approx 77\% \) (Mott-polarimeter)

→ Measurement of G & E at the same time!
→ Perfectly suited to identify charged and neutral final states!
Experimental setup

A2@MAMI

long. polarized electrons incident on diamond crystal in combination with long. polarized butanol target

→ Measurement of G & E at the same time!
→ Perfectly suited to identify charged and neutral final states!
Experimental setup

long. polarized electrons incident on diamond crystal in combination with long. polarized butanol target

carbon target for background studies

→ Measurement of G & E at the same time!
→ Perfectly suited to identify charged and neutral final states!

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Selection of Events

Kinematic Cuts

\[ \gamma p \rightarrow p \pi^0 \rightarrow p 2\gamma \]

→ 2 neutral particles + 1 charged particle in the final state!

Mass Cuts

- Cut on the proton mass: \( m_{mm} = (938 \pm 3\sigma(E_\gamma)) \) MeV
- Cut on the meson mass: \( m_{\gamma\gamma} = (135 \pm 3\sigma(E_\gamma)) \) MeV

\[ E_\gamma = 464 - 497 \text{ MeV} \]

\[ -0.22 < \cos \theta < -0.11 \]


Selection of Events

Kinematic Cuts

Angular Cuts

- Reaction products decay in one plane:
  \[ \phi_{\text{diff}} = |\phi_\pi - \phi_p| = (180 \pm 3\sigma) ^\circ \]

- Comparison of the calculated & reconstructed proton polar angle:
  \[ \theta_{\text{diff}} = |\theta_{\text{cal}} - \theta_{\text{rec}}| = (0 \pm 3\sigma) ^\circ \]

---

Sun Sep 20 10:48:32 2015

\[ \text{deg}p,\text{rec} \theta - \text{p,calc} \theta \]

\[ E_\gamma = 464 - 497 \text{ MeV} \]

\[ -0.22 < \cos \theta < -0.11 \]

---

Sun Sep 20 10:54:12 2015

\[ \text{deg}p,\text{rec} \theta - \text{p,calc} \theta \]

\[ E_\gamma = 464 - 497 \text{ MeV} \]

\[ -0.22 < \cos \theta < -0.11 \]
Extraction of the polarization observables

Angular distribution $N_B(\theta, \phi)$

- Butanol ($C_4H_9OH$) has unpolarized protons in carbon and oxygen

\[
N_B(\theta, \phi) = (N_H + N_C)(\theta) \cdot \left(1 - \left(\frac{N_H \Sigma_H + N_C \Sigma_C}{N_H + N_C}\right)\right) \delta_l \cos 2(\phi - \alpha) + \left(\frac{N_H}{N_H + N_C}\right) \delta_l \Lambda_z G_H \sin 2(\phi - \alpha)
\]

→ $\Sigma_B$ contains distribution from bound protons

→ Double polarization observable $G$ requires longitudinally polarized target → Find the fraction of reaction on polarized protons → Dilution factor
Extraction of the polarization observables

Angular distribution $N_B(\theta, \phi)$

$$N_B \mid_{\pm \Lambda_z} (\theta, \phi) = (N_H + N_C)(\theta) \cdot \left( 1 - \left( \frac{N_H \Sigma_H + N_C \Sigma_C}{N_H + N_C} \right) \delta_I \cos 2(\phi - \alpha) + \left( \frac{N_H}{N_H + N_C} \right) \delta_I \Lambda_z G_H \sin 2(\phi - \alpha) \right)$$

Dilution Factor

$E_\gamma = (464-497)$ MeV

$$D = \frac{N_H}{N_H + N_C} = \frac{N_H}{N_B} = \frac{N_B - s(E_\gamma)N_C}{N_B} = 1 - s(E_\gamma) \frac{N_C}{N_B} \text{ with } N_B \approx N_H + N_C$$
Extraction of the polarization observables

Angular distribution $N_B(\theta, \phi)$

$$N_B\mid_{\pm \Lambda_z} (\theta, \phi) = \left(\frac{N_H\Sigma_H + N_C\Sigma_C}{N_H + N_C}\right) \cdot \left(1 - \frac{N_H\Sigma_H + N_C\Sigma_C}{N_H + N_C}\right) \cdot \delta l \cos(\phi - \alpha) + \left(\frac{N_H}{N_H + N_C}\right) \cdot \delta l \Lambda_z G_H \sin(\phi - \alpha)$$

$\phi$-asymmetries for different settings

$E_\gamma = (464-497)$ MeV and $-0.22 < \cos \theta_\pi \leq -0.11$

---

**CMS**

$\alpha = -45^\circ$ and $\Lambda_z \uparrow$

$\alpha = +45^\circ$ and $\Lambda_z \uparrow$

$\alpha = -45^\circ$ and $\Lambda_z \downarrow$

$\alpha = +45^\circ$ and $\Lambda_z \downarrow$

---

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Extraction of the polarization observables

Absolute normalized determination

- Sum of different $\phi$-asymmetries results in unpolarized cross section
  $\rightarrow$ Normalize the different settings before they are shifted!

$$N_B(\theta, \phi)' = 1 - \Sigma B \delta_l \cos 2\phi + D \delta_l \Lambda_z G_H \sin 2\phi$$

$$f(\theta, \phi) = 1 + B \cos 2\phi + C \sin 2\phi$$

Shifted and normalized $\phi$-asymmetries and their sum

$E_\gamma = (464-497) \text{ MeV}$ and $-0.22 < \cos \theta_\pi < -0.11$
Results of the polarization observables

Beam asymmetry $\Sigma_B$ - Comparison with recent results

\[ \cos^{-1}(\theta) \]

$E_\gamma = (266-299) \text{ MeV}$
$E_\gamma = (365-398) \text{ MeV}$
$E_\gamma = (464-497) \text{ MeV}$
$E_\gamma = (563-596) \text{ MeV}$
$E_\gamma = (662-695) \text{ MeV}$
$E_\gamma = (761-794) \text{ MeV}$
$E_\gamma = (299-332) \text{ MeV}$
$E_\gamma = (398-431) \text{ MeV}$
$E_\gamma = (497-530) \text{ MeV}$
$E_\gamma = (596-629) \text{ MeV}$
$E_\gamma = (695-728) \text{ MeV}$
$E_\gamma = (794-827) \text{ MeV}$


Results of the polarization observables

Beam asymmetry $\Sigma_B$ - Comparison with PWA solutions

$E_{\gamma} = (266-299)$ MeV

$E_{\gamma} = (299-332)$ MeV

$E_{\gamma} = (332-365)$ MeV

$E_{\gamma} = (365-398)$ MeV

$E_{\gamma} = (398-431)$ MeV

$E_{\gamma} = (431-464)$ MeV

$E_{\gamma} = (464-497)$ MeV

$E_{\gamma} = (497-530)$ MeV

$E_{\gamma} = (530-563)$ MeV

$E_{\gamma} = (563-596)$ MeV

$E_{\gamma} = (596-629)$ MeV

$E_{\gamma} = (629-662)$ MeV

$E_{\gamma} = (662-695)$ MeV

$E_{\gamma} = (695-728)$ MeV

$E_{\gamma} = (728-761)$ MeV

$E_{\gamma} = (761-794)$ MeV

$E_{\gamma} = (794-827)$ MeV

$E_{\gamma} = (827-860)$ MeV

Results of the polarization observables

Double polarization observable G - Comparison with recent results

\[ E_\gamma = (266-299) \text{ MeV} \]
\[ E_\gamma = (299-332) \text{ MeV} \]
\[ E_\gamma = (332-365) \text{ MeV} \]
\[ E_\gamma = (431-464) \text{ MeV} \]
\[ E_\gamma = (464-497) \text{ MeV} \]
\[ E_\gamma = (497-530) \text{ MeV} \]
\[ E_\gamma = (530-563) \text{ MeV} \]
\[ E_\gamma = (596-629) \text{ MeV} \]
\[ E_\gamma = (629-662) \text{ MeV} \]
\[ E_\gamma = (662-695) \text{ MeV} \]
\[ E_\gamma = (695-728) \text{ MeV} \]
\[ E_\gamma = (728-761) \text{ MeV} \]
\[ E_\gamma = (761-794) \text{ MeV} \]

\[ \cos \theta_\pi \]

▲ CBELSA/TAPS [1]  ● this work

Results of the polarization observables

Double polarization observable G - Comparison with PWA solutions

\[
\begin{align*}
\pi & \theta \cos^{-1} (-0.5 \ 0 \ 0.5 \ 1) \\
E & \gamma (266-299) \text{ MeV} \\
E & \gamma (365-398) \text{ MeV} \\
E & \gamma (464-497) \text{ MeV} \\
E & \gamma (563-596) \text{ MeV} \\
E & \gamma (662-695) \text{ MeV} \\
E & \gamma (761-794) \text{ MeV} \\
E & \gamma (398-431) \text{ MeV} \\
E & \gamma (497-530) \text{ MeV} \\
E & \gamma (596-629) \text{ MeV} \\
E & \gamma (695-728) \text{ MeV} \\
E & \gamma (794-827) \text{ MeV} \\
E & \gamma (530-563) \text{ MeV} \\
E & \gamma (629-662) \text{ MeV} \\
E & \gamma (728-761) \text{ MeV} \\
E & \gamma (827-860) \text{ MeV} \\
\end{align*}
\]

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Summary and outlook

Summary:

- Selection of the reaction $\gamma p \rightarrow p \pi^0$
- Measurement of the beam asymmetry $\Sigma_B$ and double polarization observable $G$ in the single $\pi^0$ channel
- Good agreement with recent results for the beam asymmetry $\Sigma_B$ and double polarization observable $G$

Outlook:

- Extracted the polarization observable $E$
- Analysis of $n\pi^+$ channel (Isospin separation of $M_{1-}$ partial wave)
- Analysis of $2\pi^0$ channel ($G$ & $E$ is very sensitive on $D_{13}(1520)$ resonance)
Outlook

$2\pi^0$ selection - Some first results

2-dimensional invariant mass distribution of the photon pairs

without any cuts (#events ≈ 750.000)

with all introduced cuts (#events ≈ 116.000)

However: Still huge combinatorial background.

→ Use APLCON\textsuperscript{[1]} fitter for solving this problem.

\textsuperscript{[1]} http://www.desy.de/blobel/wwwcondl.html
Outlook

2\(\pi^0\) selection - CL and result

Convidence Level (CL) and 2-dimensional invariant mass distribution of the photon pairs

\[
\begin{array}{c|c}
\text{p0} & 597.4 \pm 7.5 \\
\text{p1} & 0.5802 \pm 11.8652 \\
\end{array}
\]

with all cuts + CL>0.01 (#events \(\approx 67.000\))

"The important thing is not to stop questioning. Curiosity has its own reason for existing."

(Albert Einstein, 1879-1955)
Double polarization observable $E$
Appendix

Double polarization observable E - Comparison with PWA solutions

![Graph showing comparison between experimental data and various PWA solutions](image)

- BG2014-01 [1]
- BG2014-02 [1]
- MAID-07 [2]
- SAID-CM12 [3]
- this work
- CBELSA/TAPS [4]


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Double polarization observable $E$ - Comparison with PWA solutions

\[ E = (820-860) \text{ MeV} \]
\[ E = (860-900) \text{ MeV} \]
\[ E = (900-940) \text{ MeV} \]
\[ E = (940-980) \text{ MeV} \]
\[ E = (1060-1100) \text{ MeV} \]
\[ E = (1100-1140) \text{ MeV} \]
\[ E = (1140-1180) \text{ MeV} \]
\[ E = (1180-1220) \text{ MeV} \]
\[ E = (1220-1260) \text{ MeV} \]
\[ E = (1260-1300) \text{ MeV} \]
\[ E = (1300-1340) \text{ MeV} \]
\[ E = (1340-1380) \text{ MeV} \]
\[ E = (1380-1420) \text{ MeV} \]
Double polarization observable $E$ in $\eta$-photoproduction

[Diagram showing the variation of $E$ with $\cos \theta_{CMS}$ for different $E_\gamma$ values (750 MeV to 1350 MeV).]

[Legend for the graph: BG2014-01 [1], BG2014-02 [1], $\eta$ MAID, SAID-GE09, A2 [2], CBELSA/TAPS [3].]

Appendix

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Sensitivity studies - BnGa

\[
\pi^+ p \rightarrow \Delta^+ \pi^- 
\]

\[
\frac{S}{D} \text{-wave ratio decay of } D_{13}(1520) \rightarrow \Delta \pi 
\]

BG2014-01: S/D=3
BG2014-02: S/D=1.5

\[
\frac{S}{D} \text{-wave ratio decay of } D_{33}(1940) \rightarrow \Delta \pi 
\]

BG2014-01: S/D=1/5
BG2014-02: S mostly

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Pull-distributions

<table>
<thead>
<tr>
<th>Distribution</th>
<th>Constant</th>
<th>Mean</th>
<th>Sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>pullbeam_E</td>
<td>2297 ± 12.3</td>
<td>0.194 ± 0.005</td>
<td>1.117 ± 0.005</td>
</tr>
<tr>
<td>pullgamma_Ecb</td>
<td>9225 ± 25.4</td>
<td>-0.03041 ± 0.00255</td>
<td>1.031 ± 0.01</td>
</tr>
<tr>
<td>pullgamma_Etaps</td>
<td>651.8 ± 6.6</td>
<td>-0.07162 ± 0.00972</td>
<td>1.07 ± 0.01</td>
</tr>
<tr>
<td>pullproton_thetacb</td>
<td>2010 ± 11.6</td>
<td>-0.09238 ± 0.00494</td>
<td>1.011 ± 0.004</td>
</tr>
<tr>
<td>pullproton_thetataps</td>
<td>548.2 ± 6.2</td>
<td>-0.2653 ± 0.00944</td>
<td>1.041 ± 0.008</td>
</tr>
<tr>
<td>pullproton_phicb</td>
<td>1878 ± 10.6</td>
<td>-0.08059 ± 0.00519</td>
<td>1.095 ± 0.004</td>
</tr>
</tbody>
</table>

Not fitted:

- pullgamma_thetacb
- pullgamma_phicb
- pullproton_thetacb
- pullproton_phicb

Mean, Sigma, and pull values are given as ± values.
Energy dependent selection - Theta

- E, 233-266 MeV: μ = -1.62, σ = 1.69
- E, 266-299 MeV: μ = -1.82, σ = 1.60
- E, 299-332 MeV: μ = -1.66, σ = 1.69
- E, 332-365 MeV: μ = -0.78, σ = 1.60
- E, 365-398 MeV: μ = -0.09, σ = 3.98
- E, 398-431 MeV: μ = 0.15, σ = 3.53
- E, 431-464 MeV: μ = 0.32, σ = 3.69
- E, 464-497 MeV: μ = 0.66, σ = 3.69
- E, 497-530 MeV: μ = 0.73, σ = 3.64
- E, 530-563 MeV: μ = 0.85, σ = 3.53
- E, 563-596 MeV: μ = 0.82, σ = 3.48
- E, 596-629 MeV: μ = 0.99, σ = 3.75
- E, 629-662 MeV: μ = 0.96, σ = 3.88
- E, 662-695 MeV: μ = 0.80, σ = 3.70
- E, 695-728 MeV: μ = 0.90, σ = 3.96

energy dependent cut ranges

Δθ [deg]

Eγ [MeV]

- butanol
- scaled carbon
- reconstructed hydrogen
- fit function
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Appendix

$\cos \theta_\pi$ dependent selection - Theta for $E_\gamma = (464 - 497) \text{ MeV}$
Appendix

$\cos \theta_{\pi}$ dependent selection - Theta for $E_{\gamma} = (464 - 497)$ MeV

$\mu$: -2.77, $\sigma$: 1.28
$-0.89 < \cos \theta < -0.76$
$\mu$: -3.00, $\sigma$: 1.47
$-0.78 < \cos \theta < -0.67$

$\mu$: -3.00, $\sigma$: 1.99
$-0.67 < \cos \theta < -0.56$
$-0.33 < \cos \theta < -0.22$
$0.00 < \cos \theta < 0.11$
$0.33 < \cos \theta < 0.44$
$0.67 < \cos \theta < 0.78$

$\Delta \theta_{p}[\text{deg}]$

$\Delta \theta [\text{deg}]$

$\cos \theta_{\pi}$

- butanol
- scaled carbon
- reconstructed hydrogen
- fit function
### Selected events

<table>
<thead>
<tr>
<th>edge [MeV]</th>
<th>event class 1 ([ \times 10^6 ])</th>
<th>event class 2 ([ \times 10^4 ])</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>2.5</td>
<td>9.66</td>
</tr>
<tr>
<td>450</td>
<td>1.7</td>
<td>56.43</td>
</tr>
<tr>
<td>550</td>
<td>0.54</td>
<td>36.67</td>
</tr>
<tr>
<td>660</td>
<td>0.13</td>
<td>15.14</td>
</tr>
<tr>
<td>750</td>
<td>0.05</td>
<td>7.96</td>
</tr>
</tbody>
</table>

For eventclass 1 roughly \(4.92 \times 10^6\) and for event class 2 roughly \(1.26 \times 10^6\) reconstructed hydrogen events!

**For the amount of background in event class 1**

![Graph showing overall background percentage](image)

**Overall background**

- **Overall background**: 0%
- **Overall background**: 10%
- **Overall background**: 20%
- **Overall background**: 30%

**Variables**:
- \(E_\gamma\) [MeV]: Photon energy
- \(\cos \theta_\pi\): Pion cosine

**Measurement**: Measurement of the double polarization observables \(G\) in pion photoproduction off the proton - September 21th, 2015

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Selected events

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For event class 1 roughly $4.92 \times 10^6$ and for event class 2 roughly $1.26 \times 10^6$ reconstructed hydrogen events!

amount of background in event class 2

For event class 1 roughly $4.92 \times 10^6$ and for event class 2 roughly $1.26 \times 10^6$ reconstructed hydrogen events!
dE over E cuts (CB and PID) - Additional cuts
Appendix

dE over E cuts (TAPS and VETOs) - Additional cuts
Appendix

Acceptance $\epsilon$

\[ \epsilon = \frac{N_{\text{rec}}}{N_{\text{gen}}} (\cos \theta, E_{\gamma}) \]
Appendix

Determination through differences

- Different settings can be combined in such a way that only terms including $\Sigma_B$ or $G$ remain

$$ f(\theta, \phi) = A \sin 2\phi \text{ with } A = -\delta_l \Sigma_B $$

$$ g(\theta, \phi) = B \cos 2\phi \text{ with } B = D\delta_l \Lambda_z G $$

Combination of $\phi$-asymmetries for different settings

$E_\gamma = (464-497) \text{ MeV and } -0.22 < \cos \theta_\pi \leq -0.11$
Dynamic Nuclear Polarization

1. Butanol target is doped with paramagnetic radicals
2. Electrons polarized with a 2.5 T magnetic field at a temperature of 1K
3. Electron polarization can be transferred to the nucleons by microwave irradiation
4. “Freeze” the spin ($\approx 25 mK$) and combine it with a holding coil $\rightarrow$ long relaxation time
• **Incoherent bremsstrahlung:** only one single atom of the crystal absorbs the recoiling momentum $\mathbf{q} \rightarrow$ no preferred plane between incoming electron and outgoing photon $\rightarrow$ no favored orientation of the electric field vector of the photon $\rightarrow$ no polarized photons

• **Coherent bremsstrahlung:** if $\mathbf{q} = n\mathbf{g}$ with $\mathbf{g} = \sum_{i=1}^{3} \mathbf{b}_i \cdot h_i \rightarrow$ single atoms can interfere constructively! $\rightarrow$ preferred plane between incoming electron and outgoing photon $\rightarrow$ orientation of the field vector of the photon $\rightarrow$ polarized photons
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
Appendix

Illustrative presentation of the beam asymmetry $\Sigma$

$\vec{L}$ = orbital angular momentum of baryon (B) and meson (M)
$\vec{S}$ = spin of baryon
$\vec{E}$ = electric field
$\vec{B}$ = magnetic field
Appendix

Ambiguity studies - Comparison MAID- and BnGA-PWA

overall solution, without $P_{11}(1770)$, without $D_{15}(1560)$
1 bump in the cross section

2 maximum in imaginary part of the multipole and zero-crossing in real part! (Problem: not unambiguous due to background)

3 **Solution:** scattering amplitude solution can be expanded into the complex energy plane

- \( E \rightarrow E = E_R + E_I \)
- ”mass” of a resonance = real part of the pole position
- ”width” of a resonance = imaginary part via \( \Gamma = -2 \text{Im}E \)