Photoproduction off Neutrons

Lilian Witthauer

CHIPP Annual Plenary Meeting 2015

Château de Bossey
June 29th 2015
Outline

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   Structure of the Nucleon
   Former Results
   Complete Experiment

2 Experiment
   MAMI and ELSA Accelerators
   A2 and CBELSA/TAPS Setup

3 Analysis
   Concept
   Background Suppression

4 Results
   Unpolarised Cross Sections
   Double Polarisation Observable E

5 Summary

η Photoproduction off Neutrons
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QCD

- QCD: fundamental theory of strong interaction
- pQCD successful at high energies
- Low energies: pQCD not applicable
- Phenomenological descriptions: Quark Models
- Numerical methods: Lattice QCD

S. Bethke, arXiv:hep-ex/0606035
Structure of the Nucleon

Constituent Quark Model | Lattice QCD \( m_\pi \sim 396 \text{ MeV} \)

<table>
<thead>
<tr>
<th>( J^\pi )</th>
<th>( L^2 \tau )</th>
<th>Mass [MeV]</th>
<th>( N=1 )</th>
<th>( N=2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 1/2^+ )</td>
<td>( P_1 )</td>
<td>1061</td>
<td>1.0</td>
<td>2.0</td>
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<tr>
<td>( 3/2^+ )</td>
<td>( P_3 )</td>
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<td>3.0</td>
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<tr>
<td>( 5/2^+ )</td>
<td>( F_{15} )</td>
<td>2200</td>
<td>3.0</td>
<td>4.0</td>
</tr>
<tr>
<td>( 7/2^+ )</td>
<td>( F_{17} )</td>
<td>2900</td>
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<td>5.0</td>
</tr>
<tr>
<td>( 1/2^- )</td>
<td>( S_{11} )</td>
<td>900</td>
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</tr>
<tr>
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<td>( D_{13} )</td>
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<td>2.0</td>
<td>3.0</td>
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<tr>
<td>( 5/2^- )</td>
<td>( D_{15} )</td>
<td>2300</td>
<td>3.0</td>
<td>4.0</td>
</tr>
<tr>
<td>( 7/2^- )</td>
<td>( G_{17} )</td>
<td>3000</td>
<td>4.0</td>
<td>5.0</td>
</tr>
</tbody>
</table>


Mismatch between experiment and models:

- Ordering of states, missing resonances!
- Model effective dof’s or experimental bias?
### Experimental Bias

- Most results only $\pi N$ scattering: **photoproduction**

<table>
<thead>
<tr>
<th>Resonance</th>
<th>PDG 2010</th>
<th>PDG 2012</th>
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<tbody>
<tr>
<td>$N(1860)^{5/2^+}$</td>
<td></td>
<td>★★</td>
</tr>
<tr>
<td>$N(1875)^{3/2^-}$</td>
<td></td>
<td>★ ★ ★</td>
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<tr>
<td>$N(1880)^{1/2^+}$</td>
<td>★★</td>
<td></td>
</tr>
<tr>
<td>$N(1895)^{1/2^-}$</td>
<td>★★</td>
<td></td>
</tr>
<tr>
<td>$N(1900)^{3/2^+}$</td>
<td>★★</td>
<td>★ ★ ★</td>
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<tr>
<td>$N(2060)^{5/2^-}$</td>
<td></td>
<td>★★</td>
</tr>
<tr>
<td>$N(2160)^{3/2^-}$</td>
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<td>★★</td>
</tr>
<tr>
<td>$\Delta(1940)^{3/2^-}$</td>
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<td>★★</td>
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</tbody>
</table>

Experimental Bias

- Most results only $\pi N$ scattering: photoproduction
- Elm. excitation isospin dependent: neutron
Experimental Bias

- Most results only $\pi N$ scattering: photoproduction
- Elm. excitation isospin dependent: neutron
- Resonances broad and overlapping: $\eta$-meson

![Photoproduction of isovector mesons like pions involves all three matrix elements](image1.png)

In summary, an intensive experimental program is currently under way to understand the electromagnetic interaction in the reactions of hadrons. The electromagnetic interaction does not conserve isospin. The electromagnetic interaction can be described by a transition operator $I$ and $\bar{I}$, while only one of these operators is used depending on the reaction.

For a unique isospin decomposition of the multipole amplitudes (see e.g. Section 3), a substantial decay of the isoscalar mesons like the $D_1(1520)$ and $S_1(1535)$ has been studied, which has the notation $\gamma p \rightarrow p\pi^0$ and $\gamma p \rightarrow p\eta$. Typical decays are $D_1(1520)$ and $S_1(1535)$ with a photon energy of 1.5 GeV. The isospin is determined by the following notation: $\Delta(I=3/2)$, $S_1(1535)$, $D_1(1520)$, $P_1(1440)$, $P_{11}(1600)$, $S_{11}(1535)$, $F_{15}(1680)$, $D_{13}(1700)$. The isospin is determined by the following notation: $\eta$, $\pi$, $\pi$. Notation: $\Lambda(I=3/2)$. The experiments are performed at the Crystal Ball/TAPS experiment at MAMI to measure differential cross sections.
Former Results $\gamma + d \rightarrow \eta + n + (p)$

narrow structure: $W = 1.66$ GeV

- Seen by GRAAL, LNS Sendai and CBELSA/TAPS collaborations
- **Unusual** properties compared to other nucleon resonances ($\Gamma \sim 150$ MeV)
- Various explanations

Various Explanations

Interference of known resonances:

- BnGa: interference effects from $S_{11}(1535)$ and $S_{11}(1650)$ (Anisovich et al.)
- Giessen Model: Interference effect from $S_{11}(1650)$ and $P_{11}(1710)$ (Shklyar et al.)
- $\eta$-MAID: $D_{15}(1675)$ resonance (Chiang et al.)

Coupled channel effects:

- s-wave model: $K\Lambda$, $K\Sigma$ loops (Döring et al.)

New narrow resonance:

- Reggeized $\eta$-MAID: narrow $P_{11}(1670)$ (Fix et al.)
- Chiral quark soliton model: narrow $P_{11}$ state, N(1680) (Diakonov et al.)

Multipole analysis needed to identify quantum numbers!
Complete Experiment

Model independent multipole analysis (Chiang & Tabakin):

- 4 single observables: $\sigma_0$, $\Sigma$, $T$, $P$
- 4 carefully chosen double polarisation observables

<table>
<thead>
<tr>
<th>photon</th>
<th>target</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>$\sigma_0$</td>
</tr>
<tr>
<td>linearly</td>
<td>$\Sigma$</td>
</tr>
<tr>
<td>circularly</td>
<td>-</td>
</tr>
</tbody>
</table>

$$E = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} = \frac{\sigma_{1/2} - \sigma_{3/2}}{2\sigma_0}$$

circularly polarised photons + longitudinally polarised target
MAinzer MIicrotron (Mainz)

- harmonic double-sided microtron
  - 1.6 GeV
- racetrack microtrons
  - 855 MeV
- LINAC
  - 3.97 MeV
- Source

Photoproduction off Neutrons

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ELectron Stretcher Accelerator (Bonn)

Motivation

Experiment

Analysis

Results

Summary

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Experimental Setup

**A2 @ MAMI**
- Continuous beam
- $E_{\gamma} \leq 1.6$ GeV
- CB: 672 NaI
- TAPS: BaF$_2$ & PbWO$_4$
- PID

**CBELSA/TAPS @ ELSA**
- Quasi-continuous beam
- $E_{\gamma} \leq 3.2$ GeV
- CBB: 1230 CsI
- MiniTAPS: 216 BaF$_2$
- Inner Detector
Bremsstrahlung Tagging

- longitudinal polarised electrons
- Møller radiator
- circularly polarised photons

\[ E_\gamma = E_{e^-}^{\text{beam}} - E_{e^-}^{\text{tagged}} \]
**Targets**

**Neutron Targets**
- light nuclei: deuterium, $^3$He

**Polarised Target**
- deuterated Butanol

$^3$He: $p_{MPV} = 71$ MeV
d: $p_{MPV} = 40$ MeV
Challenges of Quasi-Free Nucleons (Bound)

Detection of recoil nucleons:
- neutrons: 10-30% efficiency
- deposited energy $\ne$ kinetic energy
- but: kinematics completely defined without measuring energy: use only angular information

Fermi Motion:
- momentum of the initial state nucleon not known
- smears out structures
- solution: use final state particles

FSI:
- meson-nucleon, nucleon-nucleon
- compare quasi-free to free proton results!
Basic Analysis Concept

- neutral and charged particles:
  use information from charge sensitive detectors

- event classes:

<table>
<thead>
<tr>
<th></th>
<th>$\sigma_p$</th>
<th>$\sigma_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma p \rightarrow \eta p$</td>
<td>$\eta \rightarrow 2\gamma$</td>
<td>$2n &amp; 1c$</td>
</tr>
<tr>
<td>$\eta \rightarrow 3\pi^0 \rightarrow 6\gamma$</td>
<td>$6n &amp; 1c$</td>
<td>$3n$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$7n$</td>
</tr>
</tbody>
</table>

- best solution from $\chi^2$-test:
  for events with $>2$ neutral hits to find $\eta$ and recoil neutron
**Kinematical Cuts**

**Coplanarity:**
\[ \Delta \phi = \phi_N - \phi_\eta \]

**Missing Mass:**
\[ \Delta M = |P_{Beam} + P_N^l - P_\eta| - m_N \]

**Invariant Mass:**
\[ M_{\gamma\gamma} = \sqrt{E_{\gamma_1} E_{\gamma_1} (1 - \cos \psi_{12})} \]
Other Identification Possibilities (TAPS)

**Pulse Shape Analysis:**
- Protons and photons have different ToF, since heavier particles are generally slower.

**ToF versus energy:**
- Neutrons, protons, and photons have been used to check the event selection as shown in the subsequent sections.

**Results**
- Summary

Due to the properties of BaF₂ and the large distance from the target (around 1.5 m for Mainz and 2.1 m for Bonn), TAPS/MiniTAPS is ideally suited to perform a Time-of-Flight measurement. The ToF analysis exploits that particles of different masses have different ToF, since heavier particles are generally slower.
via electromagnetic showers, neutrons make elastic or inelastic scattering and nuclear banana-like structure. The spectrum is completely uncorrelated for the neutrons due all their energy in the crystals, at least up to the punch-through limit, and thus build a energetic nucleons is longer than the ToF of the ones with more energy. Protons deposit an energy independent ToF of around 3.3 ns/m. On the other hand, the ToF of low en-

\[ \text{ToF} = \frac{1}{\text{CB/FP}} \]

Since during the calibration procedure all photon times are aligned to zero, Tagger was used as reference because it provides a better time resolution than the Where one meter:

Since the flight path of every detected particle is different, the ToF is normalised to 7.4. FURTHER CHECKS

Since the flight path s of every detected particle is different, the ToF is normalised to one... class, no further analysis cuts have

95

reactions producing secondary particles (photons, protons, deuterons, to different interactions that occur in the crystals. Whereas protons mainly interact

\[ \eta \text{ Photoproduction off Neutrons} \]

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Extraction of Unpolarised Cross Sections

\[
\frac{d\sigma}{d\Omega}_{\text{unpol}}(E, \cos \theta^*) = \frac{N(E, \cos \theta^*)}{\epsilon(E, \cos \theta^*) \cdot N_\gamma(E) \cdot n_t \cdot \Gamma_i / \Gamma \cdot \Delta\Omega}
\]

- **yields:**
  - integrate invariant mass
- **photon flux**
- **detection efficiency:** Geant, nucleon detection efficiency correction (hydrogen data)
- **factors:** target density, branching ratio, solid angle

Invariant Mass:

![Invariant Mass Graph]

\(\eta\) Photoproduction off Neutrons

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Extraction of Observable E

\[
E = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} = \frac{1}{P_{\gamma} \cdot P_T} \cdot \frac{N_{1/2} - N_{3/2}}{N_{1/2} + N_{3/2} + 2N_C}
\]
Carbon Subtraction: Missing Mass

\[ \Delta m \text{ [MeV]} \]

Counts [a.u.]

\[ \begin{array}{cccccc}
720 \text{ MeV} & 840 \text{ MeV} & 960 \text{ MeV} & 1080 \text{ MeV} & 1140 \text{ MeV} \\
1310 \text{ MeV} & 1430 \text{ MeV} & 1490 \text{ MeV} & 1550 \text{ MeV} & 1730 \text{ MeV}
\end{array} \]

- [p] Counts [a.u.]
- [n] Counts [a.u.]

\[ \bullet \, dB \]  
\[ \bullet \, C \]  
\[ \bullet \, LD_2 \]  
\[ \bullet \, C + LD_2 \]
Cross Sections $^3$He (A2) and LD$_2$ (CBELSA/TAPS)

- Nucleon system with different momentum distribution and different neutron/proton ratio
- Exclude nuclear effects (re-scattering of mesons, FSI)
- Narrow structure no artefact!
Polarisation Observable E (CBELSA/TAPS & A2)

On Proton

On Neutron

exclusive

inclusive

--- MAID

\( \eta \) Photoproduction off Neutrons

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Polarisation Observable E - Neutron (A2)

— Model predictions by BnGa: constructive interference of $S_{11}(1535)$ and $S_{11}(1650)$
→ change of sign of the electromagnetic coupling of the $S_{11}(1650)$ resonance for the neutron
→ contradictory to Quark Model descriptions!
Summary

Unpolarised cross sections on $^3$He and LD$_2$:

- Confirmed narrow structure
- Exclude nuclear effects
- $^3$He published in PRL and EPJA
- LD$_2$ ready for publication

Double polarisation observable E for quasi-free p & n:

- Narrow structure only visible in $\sigma_{1/2} \rightarrow S_{11}$ or $P_{11}$ state
- Ready for publication
Thanks for your attention!
A2 Experiment
A2 Frozen Spin Target
## Influence of Photoproduction

<table>
<thead>
<tr>
<th>Particle</th>
<th>PDG 2010</th>
<th>PDG 2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>N(1860)5/2⁺</td>
<td>**</td>
<td>**</td>
</tr>
<tr>
<td>N(1875)3/2⁻</td>
<td>*</td>
<td>***</td>
</tr>
<tr>
<td>N(1880)1/2⁺</td>
<td>**</td>
<td>**</td>
</tr>
<tr>
<td>N(1895)1/2⁻</td>
<td>**</td>
<td>**</td>
</tr>
<tr>
<td>N(1900)3/2⁺</td>
<td>**</td>
<td>***</td>
</tr>
<tr>
<td>N(2060)5/2⁻</td>
<td>**</td>
<td>**</td>
</tr>
<tr>
<td>N(2160)3/2⁻</td>
<td>**</td>
<td>**</td>
</tr>
<tr>
<td>Δ(1940)3/2⁻</td>
<td>*</td>
<td>**</td>
</tr>
</tbody>
</table>


- **** Existence is certain, and properties are at least fairly well explored.
- *** Existence is very likely but further confirmation of quantum numbers and branching fractions is required.
- ** Evidence of existence is only fair.
- * Evidence of existence is poor.
Quark Models: Effective degree of freedom

- **3 equivalent Constituent Quarks**
- **Quark-Diquark**
  - $\rightarrow$ 2 dof
  - less states
- **Flux Tubes**
  - $\rightarrow$ more states
  - via rotation or vibration

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Models

- **SAID**: Database for electro and photoproduction, partial wave analysis with energy independent fits
- **MAID**: Unitary isobar model, Partial wave analysis of SAID and additional data. Uses Breit-Wigner distributions and background contributions as Born term and vector meson exchange term in t-channel (effective Lagrangians)
- **BnGa**: Coupled channel approach. Simultaneous fitting of different channels and observables. K-matrix parametrisation at low energies, relativistic Breit-Wigner at energies $> 2.2$ GeV. Non-resonant terms from t- and u-channel amplitudes.
**Appendix**

**Isospin Filter**

The electromagnetic interaction does not conserve isospin. The electromagnetic transition operator \( \hat{A} \) can be split in an isoscalar part \( \hat{S} \) and an isovector part \( \hat{V} \), giving rise to three independent matrix elements \[ \langle I_f, I_f^3 | \hat{A} | I_i, I_i^3 \rangle \]:

\[
A_{IS} = \langle 1/2, \pm 1/2 | \hat{S} | 1/2, \pm 1/2 \rangle, \\
A_{IV} = \langle 1/2, \pm 1/2 | \hat{V} | 1/2, \pm 1/2 \rangle, \\
A_{V3} = \langle 3/2, \pm 1/2 | \hat{V} | 1/2, \pm 1/2 \rangle.
\]

(1)

Photoproduction of isovector mesons like pions involves all three matrix elements, while only \( A_{IS} \) and \( A_{IV} \) contribute in the case of isoscalar mesons like the \( \eta \). Nevertheless, in both cases at least one reaction on a neutron target must be measured for a unique isospin decomposition of the multipole amplitudes (see e.g. [30] for details).

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**Isospin Filter**

[Diagram of isospin resonances and decays]

**Notation:**

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

---

**Photoproduction off Neutrons**

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Narrow Structure: Models

- **etaMAID:**
  - $D_{15}(1675)$ resonance
  - $\Gamma_{\eta N}/\Gamma_{tot} = 17\%$
  - (PDG: $\Gamma_{\eta N}/\Gamma \simeq 0 - 1\%$)
  - (L. Tiator, NSTAR2005)

- **Chiral Soliton Model:**
  - non-strange member of the baryon antidecuplet: $P_{11}$
  - (D. Diakonov et al., arXiv:hep-ph/9703373v2)
Narrow Structure: Fit with BnGa

Narrow $P_{11}(1685)$:

\[
\frac{d\sigma}{d\Omega}, \mu b/sr
\]

<table>
<thead>
<tr>
<th>$z$</th>
<th>0.95</th>
<th>0.85</th>
<th>0.75</th>
<th>0.65</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z$</td>
<td>0.55</td>
<td>0.45</td>
<td>0.35</td>
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<tr>
<td>$z$</td>
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<td>0.05</td>
<td>0.05</td>
<td>0.15</td>
</tr>
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<td>$z$</td>
<td>0.25</td>
<td>0.35</td>
<td>0.45</td>
<td>0.55</td>
</tr>
<tr>
<td>$z$</td>
<td>0.65</td>
<td>0.75</td>
<td>0.85</td>
<td>0.95</td>
</tr>
</tbody>
</table>

$S_{11}(1650)$ Interference:

\[
\frac{d\sigma}{d\Omega}, \mu b/sr
\]

<table>
<thead>
<tr>
<th>$z$</th>
<th>0.95</th>
<th>0.85</th>
<th>0.75</th>
<th>0.65</th>
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<tbody>
<tr>
<td>$z$</td>
<td>0.55</td>
<td>0.45</td>
<td>0.35</td>
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</tr>
<tr>
<td>$z$</td>
<td>0.65</td>
<td>0.75</td>
<td>0.85</td>
<td>0.95</td>
</tr>
</tbody>
</table>

sign change of elm.
$A_{1/2}$ coupling of $S_{11}(1650)$
## Polarisation Observables

<table>
<thead>
<tr>
<th>photon</th>
<th>target</th>
<th>recoil</th>
<th>target + recoil</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$x$</td>
<td>$y$</td>
<td>$z$</td>
</tr>
<tr>
<td></td>
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<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$-\sigma_0$</td>
<td>$-\sigma_0$</td>
<td>$-\sigma_0$</td>
<td>$-\sigma_0$</td>
</tr>
<tr>
<td>linearly</td>
<td>$H$</td>
<td>$-P$</td>
<td>$-G$</td>
</tr>
<tr>
<td>circularly</td>
<td>$F$</td>
<td>$-E$</td>
<td>$-E$</td>
</tr>
</tbody>
</table>

### Polarisation Observables Diagram

- $p_T$: transverse momentum
- $\gamma$: photon
- $\eta$: meson
- $\phi$: angle
- $\theta_p$: polar angle
- $\theta_\eta$: polar angle
- $p$: momentum
- $x$, $y$, $z$: coordinates
- $x'$, $y'$, $z'$: transformed coordinates

### Table

<table>
<thead>
<tr>
<th></th>
<th>$x$</th>
<th>$y'$</th>
<th>$z'$</th>
</tr>
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<tr>
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<td>$x'$</td>
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<tr>
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<td>$x'$</td>
<td>$y'$</td>
<td>$z'$</td>
</tr>
<tr>
<td>$z'$</td>
<td>$x'$</td>
<td>$y'$</td>
<td>$z'$</td>
</tr>
</tbody>
</table>

### Equation

\[ \text{Polarisation Observable} = \frac{\text{Observed Quantity}}{\text{Expected Quantity}} \]

### Examples

- **Linearly polarised photon:** $x$, $y$, $z$
- **Circularly polarised photon:** $F$, $E$
- **Target recoil:** $P$
- **Target + Recoil:** $T_x$, $T_y$, $T_z$
Polarisation Observables

\[
\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega} \cdot \left\{ 1 - P_{lin} \Sigma \cos 2\phi 
+ P_x \cdot \left[ -P_{lin} H \sin 2\phi + P_{circ} F \right] 
- P_y \cdot \left[ +P_{lin} P \cos 2\phi - P_{circ} T \right] 
- P_z \cdot \left[ -P_{lin} G \sin 2\phi - P_{circ} E \right] \right\}
\]
## Data Overview

<table>
<thead>
<tr>
<th>beamtime</th>
<th>target material</th>
<th>length [cm]</th>
<th>$E_e$ [GeV]</th>
<th>collimator</th>
<th>photon pol.</th>
<th>current [nA]</th>
<th>trigger</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008 LD</td>
<td>LD$_2$</td>
<td>5.258</td>
<td>2.35</td>
<td>4</td>
<td>circular</td>
<td>0.32</td>
<td>eta3</td>
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<tr>
<td>2008 LH</td>
<td>LH$_2$</td>
<td>5.262</td>
<td>2.35</td>
<td>7</td>
<td>circular</td>
<td>0.32</td>
<td>eta3</td>
</tr>
<tr>
<td>02.03.-22.04.2011 dbutanol</td>
<td>1.88</td>
<td>2.35</td>
<td>circular</td>
<td>0.70</td>
<td>eta4</td>
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<tr>
<td>08.06.-21.06.2011 dbutanol</td>
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<td>2.35</td>
<td>circular</td>
<td>0.70</td>
<td>eta4</td>
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<td>04.12.-10.12.2011 carbon</td>
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<td>2.35</td>
<td>circular</td>
<td>0.70</td>
<td>eta4</td>
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</tr>
<tr>
<td>28.10-17.11.2008  $^3$He</td>
<td>5.08</td>
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<td>M2+ 300 MeV</td>
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<td>M3+ 360 MeV</td>
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<td>08.05-25.05.2009 LD$_2$</td>
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<tr>
<td>28.02.-03.03.2014 carbon</td>
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<td>M2+ 250 MeV</td>
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<tr>
<td>24.03.-30.03.2015 dbutanol</td>
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<td>circular</td>
<td>10.0</td>
<td>M2+ 250 MeV</td>
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</tr>
</tbody>
</table>

Table 3.1: Overview of the data sets used for this work.
$W_B$ versus $W_R$

Cross Sections as function of...

- $W_B (E_\gamma)$: $\sqrt{s}$ calculated with 4-momenta of initial state particles:

$$W_B^2 = (P_\gamma + P_{N,i})^2 = 2E_\gamma m_N + m_N^2$$

- Structures are smeared out because of Fermi motion
**$W_B$ versus $W_R$**

Cross Sections as function of...

- $W_B (E_\gamma)$: $\sqrt{s}$ calculated with 4-momenta of initial state particles:
  \[ W_B^2 = (P_\gamma + P_{N,i})^2 = 2E_\gamma m_N + m_N^2 \]

  - Structures are smeared out because of Fermi motion

- $W_R$: $\sqrt{s}$ calculated with measured 4-momenta of final state particles ($\eta$, participant nucleon):
  \[ W_R^2 = (P_\eta + P_{N,f})^2 \]

  - No effects from Fermi motion, but experimental resolution for recoil nucleon
Corrections - Monte Carlo Simulation

Requires Event Generator (Pluto, GSI)
- Implementation of Fermi motion
- Fermi Plugin
- Used by other collaborations

Nucleon Detection Efficiency
- Hard to simulate
- Different interaction mechanisms than photons
- Deposited energy \( \neq \) total energy
- Recalculate energy with kinematical considerations
- Additional corrections using hydrogen data.

\[ \eta \text{ Photoproduction off Neutrons} \]
Appendix

Cross Sections Deuterium (CBELSA/TAPS)

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

\[ \gamma n \rightarrow \eta n \]

- Consistent with A2 data
- Deviation from old CBELSA/TAPS data
## Extracted Parameters

<table>
<thead>
<tr>
<th></th>
<th>$W$ [MeV]</th>
<th>$\Gamma$ [MeV]</th>
<th>$b_\eta A_{1/2}^{n}$ [10$^{-3}$ GeV$^{-1/2}$]</th>
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</thead>
<tbody>
<tr>
<td>LD$_2$ (D. Werthmueller)</td>
<td>1670 ± 1</td>
<td>29 ± 3</td>
<td>12.3 ± 0.8</td>
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<tr>
<td>LD$_2$ (this work)</td>
<td>1676 ± 4</td>
<td>30 ± 3</td>
<td>15.3 ± 1.8</td>
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<tr>
<td>$^3$He (this work)</td>
<td>1675 ± 2</td>
<td>46 ± 8</td>
<td>11.9 ± 1.2</td>
</tr>
</tbody>
</table>
Differential Cross Sections LD$_2$, Proton (Bonn)
Differential Cross Sections LD$_2$, Neutron (Bonn)
Fermi Momentum $^3\text{He}$ (A2)

\[ \vec{p}_F = \vec{p}_P^\text{IS} = \vec{p}_P^\text{FS} + \vec{p}_{\eta} - \vec{p}_\gamma \]

- $p_s < 300$ MeV: Long range interactions ratio $\sim N/Z = 0.5$
- $p_s > 300$ MeV: Ratio $\sim 1$ as for deuterium, SRC, high Fermi momenta are produced by isospin singlet pairs!
- Dedicated experiments are planned at JLAB!
Appendix

$\sigma_{1/2} \textbf{ Neutron}$
$\sigma_{3/2}$ Neutron

\begin{figure}
\centering
\includegraphics[width=\textwidth]{neutron_diagram}
\caption{Photoproduction off Neutrons}
\end{figure}
Appendix

$\sigma_{1/2}$ Proton

$\eta$ Photoproduction off Neutrons Lilian Witthauer
$\sigma_{3/2}$ Proton

$\eta$ Photoproduction off Neutrons