Helicity asymmetry measurements for $\pi^0$ photoproduction with FROST

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CLAS Collaboration

The George Washington University
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Outline

1. Motivation
   Study the nucleon resonances and nucleon structure

2. FROST Experiment
   Polarize both beam and target

3. Data Analysis
   Event selection for $\gamma \ p \rightarrow \pi^0 \ p$

4. Results
   Comparison with theoretical models

5. Conclusion
Nucleon Resonance

Mass, width, coupling constants... are not well known

Breit-Wigner (conventional)

masses and overall status
of N and Δ

- estimation by Particle
Data Group (Review of
particle physics 2010)

<table>
<thead>
<tr>
<th>Particle</th>
<th>L_{21,2J}</th>
<th>BW mass</th>
<th>BW width</th>
<th>decay → N π</th>
<th>status</th>
</tr>
</thead>
<tbody>
<tr>
<td>N (1440)</td>
<td>P_{11}</td>
<td>1440</td>
<td>300</td>
<td>0.55 – 0.75</td>
<td>****</td>
</tr>
<tr>
<td>N (1520)</td>
<td>D_{13}</td>
<td>1520</td>
<td>115</td>
<td>0.55 – 0.65</td>
<td>****</td>
</tr>
<tr>
<td>N (1535)</td>
<td>S_{11}</td>
<td>1535</td>
<td>150</td>
<td>0.35 – 0.55</td>
<td>****</td>
</tr>
<tr>
<td>N (1650)</td>
<td>S_{11}</td>
<td>1655</td>
<td>165</td>
<td>0.60 – 0.95</td>
<td>****</td>
</tr>
<tr>
<td>N (1675)</td>
<td>D_{15}</td>
<td>1675</td>
<td>150</td>
<td>0.35 – 0.45</td>
<td>****</td>
</tr>
<tr>
<td>N (1700)</td>
<td>D_{13}</td>
<td>1700</td>
<td>100</td>
<td>0.05 – 0.15</td>
<td>***</td>
</tr>
<tr>
<td>N (1710)</td>
<td>P_{11}</td>
<td>1710</td>
<td>100</td>
<td>0.10 – 0.20</td>
<td>***</td>
</tr>
<tr>
<td>N (1720)</td>
<td>P_{13}</td>
<td>1720</td>
<td>200</td>
<td>0.10 – 0.20</td>
<td>****</td>
</tr>
<tr>
<td>N (1900)</td>
<td>P_{13}</td>
<td>1900</td>
<td></td>
<td></td>
<td>**</td>
</tr>
<tr>
<td>N (2080)</td>
<td>D_{13}</td>
<td>2080</td>
<td></td>
<td></td>
<td>**</td>
</tr>
<tr>
<td>N (2090)</td>
<td>S_{11}</td>
<td>2090</td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Δ (1232)</td>
<td>P_{33}</td>
<td>1232</td>
<td>118</td>
<td>1.00</td>
<td>****</td>
</tr>
<tr>
<td>Δ (1600)</td>
<td>P_{33}</td>
<td>1600</td>
<td>350</td>
<td>0.10 – 0.25</td>
<td>***</td>
</tr>
<tr>
<td>Δ (1620)</td>
<td>S_{31}</td>
<td>1630</td>
<td>145</td>
<td>0.20 – 0.30</td>
<td>****</td>
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<tr>
<td>Δ (1700)</td>
<td>D_{33}</td>
<td>1700</td>
<td>300</td>
<td>0.10 – 0.20</td>
<td>****</td>
</tr>
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<td>P_{31}</td>
<td>1750</td>
<td></td>
<td></td>
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</tr>
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<td>1900</td>
<td>200</td>
<td>0.10 – 0.30</td>
<td>**</td>
</tr>
</tbody>
</table>

****  Existence is certain
***  Existence ranges from very likely to certain.
**  Evidence of existence is only fair.
*  Evidence of existence is poor.
Double polarization experiments are important.
Study of excited nucleon states (N* and Δ*)

For observable E
(case of circularly polarized beam and longitudinally polarized target)

\[
\frac{d\sigma_E}{d\sigma_0} = 1 - P_z P_c E
\]
Experiment for observable $E$

FROST experiment  Nov.3, 2007 ~ Feb. 12, 2008

Photon beam

- Circularly polarized using linearly polarized electron beam
- $E_y = 0.4 \sim 2.4$ GeV (electron beam 1.645 & 2.478 GeV)

Target

- Butanol ($C_4H_9OH$)
- $P_T = 78 \sim 92\%$ of polarization of free proton

Production

Circularly polarized beam

- 1.645 GeV  1.1 Billion triggers
- 2.478 GeV  2.3 Billion triggers

trigger: at least one charged particle in CLAS
Circularly polarized photon beam

Bremsstrahlung using linearly polarized electron beam

\[ P(\gamma) = P(e) \frac{4x - x^2}{4 - 4x + 3x^2} \]

\[ x = \frac{k}{\epsilon_1} = \frac{(\text{photon energy})}{(\text{incident electron energy})} \]

Circular polarization from 100% longitudinally polarized electron

\[ P(\gamma) \]

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Butanol (C$_4$H$_9$OH)
Dynamic Nuclear Polarization (DNP) technique
Length 52.8 mm / diameter 15 mm
Holding mode (0.5 T, 28 ~ 30 mK)
Relaxation time ~ 2,000 hours
Polarization 78 % ~ 92 %
Event selection and particle ID for $\gamma p \rightarrow \pi^0 p$

**Event selection**

1. Drift chamber track
2. Start counter hit
3. TOF counter hit
4. One positive particle

**Particle ID**

\[ \beta_{\text{mean}} \pm 3\sigma \]

\[ \Delta \beta = \beta_m - \beta_c = \beta_m - \sqrt{\left(\frac{p^2}{m_P^2 + p^2}\right)} \]

Use missing mass technique.
Identify incident photon

Time difference cut

\[ \Delta t = t_2 - t_1 \]

- \( t_1 \): vertex time of proton
- \( t_2 \): vertex time of photon

![Graph showing time difference before and after ID cut](before ID cut)

- Before ID cut: multiple electron beam bunches
- After choosing correct photon: focused data point

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Missing-mass-squared cut

Missing-mass-squared cut depends on the kinematical bin

Cut by mean values ± 3 σ

<table>
<thead>
<tr>
<th>missing mass square for butanol</th>
<th>mmsq butanol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Count</td>
<td>Entries 9.714118e+07</td>
</tr>
<tr>
<td></td>
<td>Mean -0.0397</td>
</tr>
<tr>
<td></td>
<td>RMS 0.3338</td>
</tr>
</tbody>
</table>

![Graph showing missing mass square distribution for butanol with mean and RMS values]
Target selection

### Thickness of targets

- **Butanol**: 52.8 mm
- **Carbon**: 1.5 mm
- **Polyethylene**: 3.5 mm

### Vertex cut

- **Butanol**: $-2.75\, \text{cm} < z\text{-vertex} < +2.75\, \text{cm}$
- **Carbon**: $+5.00\, \text{cm} < z\text{-vertex} < +8.00\, \text{cm}$
- **Polyethylene**: $+14.0\, \text{cm} < z\text{-vertex} < +18.0\, \text{cm}$

---

**C**

$\text{H}_9\text{OH}$

$\text{CH}_2$
Scale factor

Assume the bound nucleon reaction in the butanol target is similar to that in carbon target

Negative missing mass square part → only bound nucleon reaction
Bound nucleon has Fermi motion

Bump and slope in the negative missing mass square region → determine region between -0.2 ~ 0.0 GeV²
Dilution factor for $\gamma p \rightarrow \pi^0 p$

Use scale factor to multiply carbon events
Cut the missing mass square
by sector and by proton momentum

Dilution factor = \frac{\text{Free proton} + \text{Bound nucleon}}{}
Uncertainties

Statistical uncertainties → Use propagation equation

\[ \sigma^2_E = \left[ \left( \frac{\sigma_{D_f}}{D_f} \right)^2 + \left( \frac{\sigma_{P_y}}{P_y} \right)^2 + \left( \frac{\sigma_{P_T}}{P_T} \right)^2 \right] \times E^2 + \frac{4 N_{1/2} N_{3/2}}{N_{tot}^3 (D_f P_y P_T)^2} \]

Systematic uncertainties

Electron beam conditions
- Energy of beam \( \approx 0.1 \% \)
- Beam polarization \( \approx 2 \% \)
- Beam charge asymmetry \( 6 \times 10^{-2} \% \)

Target polarization \( 1.6 \times 10^{-1} \% \)

Fiducial cut \( 2.5 \% \)

Missing mass square cut \( 9.6 \% \)

Scale and dilution factor \( 13 \sim 18 \% \)
Helicity asymmetry $E$ for $\gamma p \rightarrow \pi^0 p$ $\cos \theta_{\pi^0}^{cm}$, $\Delta E_{\gamma} = 50$ MeV

$$E = \frac{1}{D_f P_T P_\gamma} \frac{N_{3/2} - N_{1/2}}{N_{1/2} + N_{3/2}}$$

**CLAS**
- SAID2009
- MAID2007
- EBAC

- $D_f$: max $\sim 0.35$
- $P_T$: $0.78 \sim 0.92$
- $P_e$: $0.79 \sim 0.87$

Only statistical uncertainty of asymmetry is shown

**Preliminary**

$600$ MeV $\leq E_{\gamma} \leq 650$ MeV

$0.65 \sim 0.70$ GeV

$0.70 \sim 0.75$ GeV

$0.75 \sim 0.80$ GeV

$0.80 \sim 0.85$ GeV

$0.85 \sim 0.90$ GeV
Helicity Asymmetry (2)

\[
\cos \theta_{\pi^0}^{cm}, \Delta E_\gamma = 50 \text{ MeV}
\]

Preliminary

CLAS

SAID2009

MAID2007

900 \text{ MeV} \leq E_\gamma \leq 950 \text{ MeV}
Helicity Asymmetry (3)

\[
\cos \theta_{\pi^0}^{cm}
\]

\[\Delta E_\gamma = 50 \text{ MeV , 100 MeV}\]

CLAS
SAID2009
MAID2007

Preliminary
Helicity asymmetry $E$ (4) $W, \Delta \cos \theta^{cm}_{\pi^0} = 0.1$

\[0.20 \leq \cos \theta^{cm}_{\pi^0} \leq 0.30\]

Cos theta = 0.15

Cos theta = 0.05
Helicity asymmetry $E(5)$ $W, \Delta \cos \theta^{cm}_{\pi^0} = 0.1$

\[-0.10 \leq \cos \theta^{cm}_{\pi^0} \leq 0.00\]
The helicity asymmetry $E$ is measured for single $\pi^0$ photoproduction with FROST for $E_\gamma = 0.5 - 2.4$ GeV.

At lower $E_\gamma (< 1.35$ GeV), the model predictions describe the data ($\cos \theta_{cm}$-dependence) well.

At higher $E_\gamma (> 1.35$ GeV), there are some deviation between model calculations and the data ($\cos \theta_{cm}$-dependence).

Significant deviation is observed at the backward $\pi^0$ scattering angle, $-0.50 \leq \cos \theta_{cm} \leq 0.0$ and all $W$ values.

Some deviation is also observed at the backward $\pi^0$ scattering angle, $-0.80 \leq \cos \theta_{cm} \leq -0.50$ and $1.4$ GeV $\leq W \leq 1.7$ GeV.

The new results help constrain the parameters of the models, such as coupling constants and weight of partial waves.
Back up
Target selection (2) - helicity states -

- Butanol 1/2
- Carbon (butanol 1/2 state)
- Polyethylene (butanol 1/2 state)

- Butanol 3/2
- Carbon (butanol 3/2 state)
- Polyethylene (butanol 3/2 state)

- Butanol 3/2 - 1/2
- Carbon (3/2 - 1/2)
- Polyethylene (3/2 - 1/2)
Assume the bound nucleon reaction in the butanol target is quite similar to that in carbon target.

Negative missing mass square part $\rightarrow$ only bound nucleon reaction
Bound nucleon has Fermi motion

Bump and slope in the negative missing mass square region $\rightarrow$ determine region between $-0.2 \sim 0.0 \text{ GeV}^2$
Scale factor (2)
Dilution factor for $\gamma p \rightarrow \pi^0 p$ (2)

\[
\text{Dilution factor} = \frac{\text{Free proton reaction}}{\text{Total nucleon reaction}} = 1 - \frac{\text{Scaled carbon}}{\text{Butanol}}
\]

Dilution factor depends on proton momentum

$\rightarrow$ fifth-order polynomial
Missing-mass-squared cut

Missing-mass-squared cut depends on the sector and the proton momentum

**Mean values ± 3 \( \sigma \)**

Low-momentum protons are more sector-dependent

* sector: proton is detected
Protons, especially low-momentum protons, lose energy when they pass through materials surrounding the target.

\[ \Delta E = 2\text{~}60 \text{ MeV} \]
Number of events and polarization

- Helicity state of electron beam changes at rate of 30 Hz
- 7 periods have different direction of target polarization

<table>
<thead>
<tr>
<th>Period</th>
<th>run number</th>
<th>Beam energy</th>
<th>Photon beam polarization (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>55521 ~ 55536</td>
<td>1.645 GeV</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>55537 ~ 55555</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>55556 ~ 55595</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>55604 ~ 55625</td>
<td>2.478 GeV</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>55630 ~ 55678</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>56164 ~ 56193</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>56196 ~ 56233</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For majority of events, photon beam polarization is 15 ~ 65 %.
Fiducial Cuts

Remove events that protons are found in inefficient or inactive region of CLAS (places surrounding the coils of the torus magnet and outside the detectors)

The number of events is reduced to 96.3 %