Threshold Pion Photoproduction in the A2 Collaboration at MAMI
Precision Hadron Structure

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Newport News, Virginia
USA

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New Brunswick, CANADA

NOT New Jersey!
Where the heck is New Brunswick?

Maritime Province

New Brunswick
Population: c. 750,000
Languages: English and French
Area: 72,908 km²
Time Zone: Atlantic (GMT-4)

Sackville
Population: c. 5,500
Latitude: 45° N

Mount Allison student enrollment: c. 2,000

“Mount” Allison elevation: c. 10 m above sea level (depending on tide...)
Hopewell Rocks, NB – Highest Tides in the World
Outline

1. Introduction
   - Theory Motivation and Context
   - The MAMI Facility

2. Single-Polarization Measurement: $\vec{\gamma}p \rightarrow \pi^0 p$

3. Double-Polarization Measurement: $\vec{\gamma}\vec{p} \rightarrow \pi^0 p$

4. Unpolarized Production on $^3$He to extract $E_{0+}^{\pi^0 n}$
How do we test QCD in the non-perturbative regime?

High-precision measurements with polarization observables.

**Near-Threshold $\pi^0$ Photoproduction**

Can be used to test **Chiral Perturbation Theory (ChPT)**, an effective field-theory of the strong interaction based on the symmetries of QCD.

In its domain of validity, **ChPT** represents predictions of QCD *subject to the errors imposed by uncertainties in the LECs and by neglect of higher order terms.*

Any discrepancy that is significantly larger than the combined experimental and theoretical errors **MUST** be taken seriously!

*Lattice QCD is another technique, and presently great strides are being made...*
Partial-Wave Analysis and Multipoles

How can we compare experimental results to ChPT and other theoretical approaches?

Through partial-wave analysis by extracting multipoles.

- Multipoles are an instructive meeting ground between theory and experiment.
- A **Model-Independent Partial-Wave Analysis** can be used to obtain the multipoles from experiment.
Photoproduction Amplitudes

\[ EL: \pi = (-1)^L \]
\[ ML: \pi = (-1)^{L+1} \]

In the threshold region, \( S \)-, \( P \)- and even \( D \)-waves contribute:

\[
\begin{align*}
  l = 0 & \quad E_{0+} & \quad S\text{-wave} \\
  l = 1 & \quad E_{1+}, M_{1+}, M_{1-} & \quad P\text{-waves} \\
  l = 2 & \quad E_{2+}, E_{2-}, M_{2+}, M_{2-} & \quad D\text{-waves}
\end{align*}
\]

Energy dependence of \( P \)-waves is not totally clear: \( \sim q \), \( \sim qk \) or something completely different?

The \( D \)-waves are small, but non-negligible.
A carefully chosen set of 8 independent observables is enough for a complete description of an experiment using photoproduction.

For a complete partial-wave analysis, one needs fewer observables, and with 4 one can obtain solutions with only discrete sign ambiguities.

Below the $2\pi$ threshold, we only need two observables and unitarity.

<table>
<thead>
<tr>
<th>set</th>
<th>observables</th>
</tr>
</thead>
<tbody>
<tr>
<td>single</td>
<td>$d\sigma/d\Omega$ $\Sigma$ $T$ $P$</td>
</tr>
<tr>
<td>beam-target</td>
<td>$G$ $H$ $E$ $F$</td>
</tr>
<tr>
<td>beam-recoil</td>
<td>$Ox'$ $Oz'$ $Cx'$ $Cz'$</td>
</tr>
<tr>
<td>target-recoil</td>
<td>$Tx'$ $Tz'$ $Lx'$ $Lz'$</td>
</tr>
</tbody>
</table>
Complete PWA in $\pi^0$ photoproduction below $2\pi$ threshold.

Need only two observables, $d\sigma/d\Omega$, $\Sigma$, and unitarity.

How is it done?

- Use (1) Empirical Single-Energy and (2) Energy-Dependent Fits to $d\sigma/d\Omega$ and $\Sigma$.
- Extract coefficients and multipoles.
- Compare to ChPT and other theoretical approaches.
(1) Empirical Single-Energy Fits to the Multipoles

$S$- and $P$-waves only

\[
\frac{d\sigma}{d\Omega}(\theta) = \frac{q}{k} \left( a_0 + a_1 \cos \theta + a_2 \cos^2 \theta \right)
\]

\[
\frac{d\sigma}{d\Omega}(\theta)\Sigma(\theta) = \frac{q}{k} \sin^2 \theta b_0
\]

Coefficients

\[
a_0 = |E_{0+}|^2 + P_{23}^2
\]

\[
a_1 = 2\text{Re}E_{0+}P_1
\]

\[
a_2 = P_1^2 - P_{23}^2
\]

\[
b_0 = \frac{1}{2} \left( P_3^2 - P_2^2 \right)
\]

\[
P_1 = 3E_{1+} + M_{1+} - M_{1-}
\]

\[
P_2 = 3E_{1+} - M_{1+} + M_{1-}
\]

\[
P_3 = 2M_{1+} + M_{1-}
\]

\[
P_{23}^2 = \frac{1}{2} (P_2^2 + P_3^2)
\]

4 measured quantities, $a_0, a_1, a_2, b_0$, and 4 unknown real parameters, Re$E_{0+}, P_1, P_2, P_3$. Note that $D$-waves contribute, but they are small. Added using the Born terms.
Including the $D$-waves

### S-, P-, and D-waves

\[
\frac{d\sigma}{d\Omega}(\theta) = \frac{q}{k} \left( a_0 + a_1 \cos \theta + a_2 \cos^2 \theta + a_3 \cos^3 \theta + a_4 \cos^4 \theta \right)
\]

\[
\frac{d\sigma}{d\Omega}(\theta)\Sigma(\theta) = \frac{q}{k} \sin^2 \theta \left( b_0 + b_1 \cos \theta + b_2 \cos^2 \theta \right)
\]

8 coefficients.
Including the $D$-waves

$S$-, $P$-, and $D$-waves

\[ a_0 = |E_{0+}|^2 + P_{23}^2 + \text{Re}E_{0+}D_1 + \frac{1}{4}(D_1^2 + 9D_2^2) \]

\[ a_1 = 2\text{Re}E_{0+}P_1 - P_1D_1 - 3P_2D_2 + 3P_3D_3 \]

\[ a_2 = P_1^2 - P_{23}^2 - \frac{3}{2}(D_1^2 - 3D_2^2 - 3D_3^2 + 3D_4^2) + 3\text{Re}E_{0+}D_1 \]

\[ a_3 = 3(P_1D_1 + P_2D_2 - P_3D_3) \]

\[ a_4 = \frac{9}{4}(D_1^2 - 2D_2^2 - 2D_3^2 + D_4^2) \]

\[ b_0 = \frac{1}{2}(P_3^2 - P_2^2 - 3D_1D_4) + 3\text{Re}E_{0+}D_4 \]

\[ b_1 = 3(P_1D_4 + P_2D_2 + P_3D_3) \]

\[ b_2 = \frac{9}{2}(-D_2^2 + D_3^2 + D_1D_4) \]
Including $D$-waves

Where:

\[
D_1 = E_{2-} - 3M_{2-} + 6E_{2+} + 3M_{2+} \\
D_2 = E_{2-} - M_{2-} - 4E_{2+} + M_{2+} \\
D_3 = 2M_{2-} + 3M_{2+} \\
D_4 = E_{2-} + M_{2-} + E_{2-} - M_{2+}
\]

*It turns out they are pretty small and we add them by hand via the Born terms...*
Multipoles are expanded as a function of $W$

Fit the coefficients using the following ansatz:

**S-wave:**

$$E_{0^+}(W) = E_{0^+}^{(0)} + E_{0^+}^{(1)} \left( \frac{k_{\gamma,\text{lab}}(W) - k_{\gamma,\text{thr}}^{\text{lab}}}{m_{\pi^+}} \right) + i\beta \frac{q_{\pi^+}(W)}{m_{\pi^+}}$$

**P-wave:**

$$P_i(W) = \frac{q_{\pi^0}(W)}{m_{\pi^+}} \left\{ P_i^{(0)} + P_i^{(1)} \left[ \frac{k_{\gamma,\text{lab}}(W) - k_{\gamma,\text{thr}}^{\text{lab}}}{m_{\pi^+}} \right] \right\}$$

Superscripts $(0),(1)$ denote intercept and slope, respectively.

Obtain smooth function of incident photon energy.
Mainz, Germany

- Situated Southwest Germany
- Population ≈210,000
- At the confluence of the Rhine and Main rivers.
Institut für Kernphysik

Johannes Gutenberg-Universität

≈35,000 students
The Mainzer Mikrotron (MAMI)

Johannes Gutenberg-Universität
Mainz, Germany

3 Race-Track Microtrons (882 MeV)
HDSM in Production Mode (1.6 GeV)
High-Quality 100% Duty Factor (CW) Beam

Polarized electron source
Polarized and unpolarized Targets
Race-Track Microtron (RTM)

Key point is that you recirculate the electrons, obviating the need for a long LINAC, reducing the amount of power required.
Maximum electron-beam energy 855 MeV.
Dipole from RTM3

World’s biggest RTM. Each magnet weights 450 t. Field of 1.28 T.
MAMI-C

Includes the HDSM
Maximum energy of 1.6 GeV
Uses 90° dipoles, 250 t each
1.54 T

85% polarization
Up to 100 μA
Harmonic Double-Sided Microtron

Impossible to make magnets for a conventional RTM big enough. Use 4 magnets instead of 2!
Polarized Electron Source

- GaAs photocathode and laser system.
- Trade-off between quantum efficiency and degree of polarization.
- Produces electron polarization up to about 85%.
The A2 Hall

[Diagram of the A2 Hall showing Electron Beam from MAMI, Tagger, Crystal Ball, TAPS + Electronics, Pb Glass, Photon Beam Dump, Deflected Electrons, and Electron Beam Dump.]
Incident Photon Beam – Glasgow-Mainz Photon Tagger

- 352 channels
- $\Delta E = 4 \text{ MeV at } 1.6 \text{ GeV}$
- Up to $\sim 10^8 \gamma / s$
- Refurbished to work at 1.6 GeV
- 5–94% of Bremsstrahlung spectrum

- electron beam
- radiator
- dipole magnet
- collimator
- focal plane
- plastic scintillators
- coincidence
- TAPS
- target
- photon beam
- beam dump

D. Hornidge (Mount Allison University)
Polarized Photons

Circular Polarization

- Helicity transfer of polarization from electron to bremsstrahlung photon.
- Maximized for photon energies close to the electron beam energy.

Linear Polarization

- Created via coherent bremsstrahlung. Entire diamond lattice coherently contributes to producing photons.
- Maximized for high electron beam energies and low photon energies.
Cryogenic LH$_2$/LD$_2$: unpolarized protons/deuterons
Cryogenic L$^4$He/L$^3$He
Butanol Frozen Spin: polarized protons/deuterons
Solid Targets: C, Pb, and many more...
Polarized $^3$He gas
Active Targets: H and He, under development
Cryogenic Targets LH$_2$/LD$_2$

2-cm, 5-cm, and 10-cm Kapton ($C_{22}H_{10}N_2O_5$) cells, 100 $\mu$m thick

1080 mBar, 20.5 Kelvin

$\approx 2 \times 10^{23}$ nuclei/cm$^2$ for 5-cm cell
Detector System: CB-TAPS

A2 Standard Configuration from 2003–present
Detector System: CB-TAPS

- CB: 672 NaI detectors
- TAPS: 384 BaF$_2$ detectors with individual vetoes
- 24-scintillator PID barrel
- 96% of $4\pi$ sr!
- Cylindrical Wire Chamber
- Čerenkov Detector

A2 Standard Configuration from 2003–present
$\vec{\gamma}p \rightarrow \pi^0 p$

PRL 111, 062004 (2013). Analysis done by S. Prakhov (UCLA) and DLH.

Theory support from L. Tiator, M. Hilt, S. Scherer, C. Fernández Ramírez, and A.M. Bernstein.

- Data taken in December 2008.
- CB-TAPS detector system.
- Improvement over previous result (TAPS 2001, Schmidt et al.)
\( \vec{\gamma} p \rightarrow \pi^0 p \) – Experimental Details

**Equipment:**

- A2 Hall.
- Glasgow-Mainz photon-tagging spectrometer.
- CB-TAPS.
- Cryogenic LH\(_2\) “snout” target.

**Run Parameters:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron Beam Energy</td>
<td>855 MeV</td>
</tr>
<tr>
<td>Target</td>
<td>10-cm LH(_2)</td>
</tr>
<tr>
<td>Radiator</td>
<td>100 (\mu)m Diamond</td>
</tr>
<tr>
<td>Tagged Energy Range</td>
<td>100 – 800 MeV</td>
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<tr>
<td>Channel Energy Resolution</td>
<td>2.4 MeV</td>
</tr>
<tr>
<td>Polarization Edge</td>
<td>(\sim) 190 MeV</td>
</tr>
<tr>
<td>Degree of Polarization</td>
<td>40 – 70%</td>
</tr>
<tr>
<td>Beam on Target</td>
<td>90 h Full + 20 h Empty</td>
</tr>
</tbody>
</table>
Comparison with TAPS 2001

Advantage CB-TAPS 2008

- Efficiency for $\pi^0$ detection: 90% vs. 10%.
- Target-empty data taken.
- Higher polarization.
- Smaller systematic errors.

Advantage TAPS 2001

- 40% less target-window material due to target and scattering-chamber design.
- Better incident photon energy resolution.
Disagreement for $\Sigma$ with TAPS 2001

**Serious disagreement** between CB-TAPS 2008 and TAPS 2001 for $\Sigma$

Source? $\Rightarrow$ Target windows in TAPS 2001 measurement.
- $0^+$ nuclei ($C$ and $O$) have $\Sigma = 1$ and thus contribute *significantly* to the measured asymmetry.
- $d\sigma/d\Omega$ was corrected for target windows but $\Sigma$ was NOT!

Erratum for TAPS 2001 has been published [PRL 110, 039903(E) (2013)].

**NOTE:** TAPS 2001 extraction of energy dependence of $\text{Re}E_{0+}$ still the best one to date. *Depends on $d\sigma/d\Omega$ and not $\Sigma$.***
Excellent statistics in both $d\sigma/d\Omega$ and $\Sigma$, and for the first time, energy dependence of $\Sigma$.

Good agreement with HBChPT (black) and ChPT (blue). Empirical fit is also shown with statistical error band (green).

Plots courtesy of C. Fernández Ramírez.
Sample Results at $E_\gamma = 163$ MeV

Good agreement with HBChPT (black) and ChPT (blue). Empirical fit is also shown with statistical error band (green).

Plots courtesy of C. Fernández Ramírez.
Multipoles: $E_{0+}$ and $P_1$

Plots courtesy of C. Fernández Ramírez
Multipoles: $P_2$ and $P_3$

Plots courtesy of C. Fernández Ramírez
Energy Dependence of the Multipoles

- \( \text{Re}E_{0+}, P_1/q, P_2/q, P_3/q \).
- Single-energy fits (points) along with the empirical fits (green band).
- Theory curves are HBChPT (black) and ChPT (blue).
- Systematic uncertainties in the single-energy extraction are the grey-shaded bands.

Plots courtesy of C. Fernández Ramírez.
Energy Region of Agreement

Fit range from $150 \text{ MeV} - E_{\gamma}^{\text{max}}$

Covariant BChPT deviates at $\approx 167 \text{ MeV}$ and HBChPT at $\approx 170 \text{ MeV}$.

Plot courtesy of C. Fernández Ramírez.
Conclusions

- Target-window contributions are very important near threshold, even for the asymmetry.
- HBChPT and Relativistic ChPT are in agreement, with good $\chi^2$/dof values up to around 167 MeV.
- Reasonable agreement with DMT and Lutz-Gasparyan predictions.
- Energy dependence is obviously a big improvement.
$\vec{\gamma}\vec{p} \rightarrow \pi^0 p$

S. Schumann et al., PLB 750, 252 (2015).

Measured the **Transverse target asymmetry**, $T$:

- Sensitive to the $\pi N$ phase shifts
- Provides information for neutral charge states ($\pi^0 p$, $\pi^+ n$) in a region of energies that is not accessible to conventional $\pi N$ scattering experiments
- Hope to test strong isospin breaking due to $m_d - m_u$
Complex Nature of Multipoles

Due to rescattering

\[ \gamma \rightarrow \pi^+ n \rightarrow \pi^0 p \]

there exists a **Unitarity Cusp** in the \( E_{0^+}^{\pi^0 p} \) amplitude:

\[ E_{0^+}^{\pi^0 p} = \text{Re}E_{0^+}^{\pi^0 p} + i \beta \frac{q_{\pi^+}}{m_{\pi^+}} \]

where \( \beta \) is the **cusp function**:

\[ \beta = E_{0^+}^{\pi^+ n} f_{\text{ex}}(\pi^+ n \rightarrow \pi^0 p) \]
Imaginary Part of $E_{0^+}^{\pi^0 p}$

Target Asymmetry, $T$

- Use $T = \text{Im} E_{0^+}^{\pi^0 p} (P_3 - P_2) \sin \theta$ to make a direct determination of $\text{Im} E_{0^+}^{\pi^0 p}$ above the $\pi^+ n$ threshold.
- Never before been done!
- Extract $\beta$.
- Use the known value of $E_{0^+}^{\pi^+ n}$ to find $a_{\text{cex}}(\pi^+ n \rightarrow \pi^0 p)$
- Test **strong isospin breaking** since

  $$a_{\text{cex}}(\pi^+ n \rightarrow \pi^0 p) = a_{\text{cex}}(\pi^- p \rightarrow \pi^0 n)$$

- 2% effect, so precise data with low systematic errors are necessary.
Measuring the Target Asymmetry, $T$

For a transversely polarized target and unpolarized beam, we have

$$\frac{d\sigma}{d\Omega} = \sigma_0 (1 + P_T T \sin \varphi)$$

with the target asymmetry defined as

$$T = \frac{1}{P_T \sin \varphi} \cdot \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

where the $+/-$ denote target polarization parallel/antiparallel to the normal to the scattering plane.

In principle, this can be measured as a counting-rate asymmetry

$$T = \frac{1}{P_T \sin \varphi} \cdot \frac{N_+ - N_-}{N_+ + N_-}$$
\vec{\gamma}\vec{p} \rightarrow \pi^0 p \ - \ \text{Experimental Details}

**Equipment:**

- A2 Hall.
- Glasgow-Mainz photon-tagging spectrometer.
- CB-TAPS with MWPC and Čerenkov detector.
- Circularly polarized photons.
- Butanol frozen-spin target with transverse coil.

**Run Parameters:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron Beam Energy</td>
<td>450 MeV</td>
</tr>
<tr>
<td>Target</td>
<td>Butanol</td>
</tr>
<tr>
<td>Radiator</td>
<td>Møller Foil</td>
</tr>
<tr>
<td>Tagged Energy Range</td>
<td>100 – 400 MeV</td>
</tr>
<tr>
<td>Channel Energy Resolution</td>
<td>1.2 MeV</td>
</tr>
<tr>
<td>Target Polarization</td>
<td>\approx 80%</td>
</tr>
<tr>
<td>Beam on Target</td>
<td>700 h C_4H_9OH and 100 h C</td>
</tr>
</tbody>
</table>
Butanol target is made up of $\text{C}_4\text{H}_9\text{OH}$, and so there are lots of backgrounds. Essentially one heavy nucleus for every 2 protons.

Swamped with $\pi^0$s from C and O, both coherent and incoherent.

C and O nuclei are not polarized, but they dilute the asymmetries.

$$A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

$$= \frac{(\sigma_p^+ + \sigma_C) - (\sigma_p^- - \sigma_C)}{(\sigma_p^+ + \sigma_C) + (\sigma_p^- + \sigma_C)}$$

$$= \frac{\sigma_p^+ - \sigma_p^-}{\sigma_p^+ + \sigma_p^- + 2\sigma_C}$$

Need to know the lineshapes very well, and we must be able to eliminate effect of unpolarized, heavy nuclei.
Two main techniques for eliminating backgrounds:

1. Background subtraction:
   - Measure heavy-nucleus lineshape with C target
   - Normalize and subtract contributions
   - Technique used by Ph.D. students P. Hall Barrientos (Edinburgh) and P.B. Otte (Mainz)
   - Very tricky in the threshold region due to huge coherent C cross section.

2. Calculate Polarized Cross Sections
   - Doesn’t use C data
   - Technique pioneered by S. Schumann (Mainz-MIT)
Polarized Cross Section Technique

Poor statistics near threshold, and lots of background from heavy nuclei...

⇒ Polarized Cross sections

Product of unpolarized cross section and asymmetries:

\[ \sigma_T \equiv \sigma_0 T = \frac{\sigma^+ - \sigma^-}{P_T \sin \phi} = \frac{1}{P_{\text{eff}}^y} \frac{N_{\text{but}}^+ - N_{\text{but}}^-}{\epsilon \Phi_{\gamma} \rho_p} \frac{1}{2\pi \sin \phi} \]

No unpolarized contributions in the difference of \( N^+ \) and \( N^- \) count rates:

\[ N_{\text{but}}^+ - N_{\text{but}}^- = N_p^+ + N_C - N_p^- - N_C = N_p^+ - N_p^- \]

⇒ Can obtain polarized cross sections directly from butanol data, meaning no explicit background subtraction from carbon measurement.
Effective Polarization

In order to define the *effective* polarization, we define the following angle:

\[ \phi \equiv \phi_{\pi^0} - \phi_T \]

where \( \sin \phi > 0 \) defines \(+\) and \( \sin \phi < 0 \) defines \( -\).

Thus

\[ P^y_{\text{eff}} \equiv P_T |\sin \phi| \]

Note that we placed a cut \( \phi \) to increase the effective polarization

\[ |\sin \phi| > 0.35 \]

This had the effect of limiting the angular coverage, but increasing the polarization for about 50\% to 60\%. 
## Missing Mass Distributions

### Butanol

<table>
<thead>
<tr>
<th>Points</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dashed curve</td>
<td>Simulated $\pi^0$ production on $^{12}\text{C}$</td>
</tr>
<tr>
<td>Solid curve</td>
<td>Simulated $\pi^0$ production on $p$</td>
</tr>
</tbody>
</table>
Polarized Differential Cross Sections $\sigma_T$

Solid lines are predictions of the DMT model, dashed are Legendre polynomial fits, and dashed-dot are a cross-check from a standard analysis done by P.B. Otte.
Legendre Polynomial Coefficients, $t_0$ and $t_1$

To facilitate comparisons with theory, the following parametrization has been used:

$$\sigma_T = \frac{q}{k} \sin \theta \left[ t_0 P_0(z) + t_1 P_1(z) \right]$$

where $P_0(z)$ and $P_1(z)$ are Legendre polynomials with $z = \cos \theta$.

Multipole Extraction from $\sigma_T$

Decomposition of $\sigma_T$, including the $D$-waves, is given by

$$\sigma_T = \frac{q}{k} \sin \theta \left\{ 3 \text{Im} \left[ E_{0+}^* (E_{1+} - M_{1+}) \right] + 3 \text{Im} \left[ 4 E_{0+}^* (E_{2+} - M_{2+}) - E_{0+}^* (E_{2-} - M_{2-}) \right] \cos \theta \right\}$$

Real parts of the $S$- and $P$-waves were taken from our previous experiment that measured $\Sigma$ and $\sigma_0$.

Imaginary parts of the $P$-waves were assumed to vanish.

$D$-waves were included as fixed Born terms.

$\Rightarrow \text{Im} E_{0+}$ is then the only free parameter.
Imaginary Part of $E_{0^+}$

Single-energy fits are the points, with statistical errors only. Systematic errors are shown by the grey-shaded band.

Lines are DMT (solid), parametrization (short dashed), Lutz-Gasparyan (long dashed), ChPT (dash dotted) and HBChPT (dotted).
Energy Dependence of $\beta$

Using the data and a two-parameter fit

$$\beta(\omega) = \beta_0 (1 + \beta_1 \cdot k_{\pi^+}) \quad \text{with} \quad k_{\pi^+} = \frac{\omega - \omega_{\text{thr}}}{m_{\pi^+}}$$

we obtain

$$\beta_0 = (2.2 \pm 0.2_{\text{stat}} \pm 0.6_{\text{syst}}) \cdot 10^{-3} / m_{\pi^+}$$
$$\beta_1 = (0.5 \pm 0.5_{\text{stat}} \pm 0.9_{\text{syst}})$$

Large uncertainties preclude us from making a reliable determination of the energy dependence. . .
First measurements of $\sigma_T$ in neutral pion photoproduction in the threshold region.
First direct measurement of $\text{Im} E_{0+}$, confirming rapid rise above $n\pi^+$ threshold.
Uncertainties still too large to determine a precise value of $\beta(\omega)$.
More running with transverse coil to improve statistics and therefore even smaller uncertainty in $\sigma_T$.
Continue work on an active, polarized target eliminate heavy-nucleus backgrounds altogether, improving measurement of $\sigma_T$.
Test strong isospin breaking...
Active Polarized Proton Target

Ph.D. Work of M. Biroth (Mainz)

- Polarizable plastic scintillator.
- Capable of standing high rates, with high light output, but low thermal energy input.
- Still in prototyping phase.
What about the Neutron?

The $S$-wave amplitude $E_{0+}^{\pi^0 n}$ represents a crucial test of ChPT.

Predicts $|E_{0+}^{\pi^0 n}| > |E_{0+}^{\pi^0 p}| \Rightarrow$ Faster rise in total cross section!

Convergence of $E_{0+}^{\pi^0 n}$ should be better, making the prediction more reliable.

Also, of the four photoproduction reactions on the nucleon:

\[
\begin{align*}
\gamma p & \rightarrow \pi^0 p \\
\gamma n & \rightarrow \pi^+ n \\
\gamma n & \rightarrow \pi^0 n \\
\gamma n & \rightarrow \pi^- p 
\end{align*}
\]

only the $\pi^0 n$ amplitude has never been measured! With an accurate enough extraction, one could test isospin breaking...
Status of $E_{0^+}^{N\pi}$

Results (in units of $10^{-3}/m_{\pi^+}$):

<table>
<thead>
<tr>
<th>Reaction</th>
<th>ChPT$^1$</th>
<th>DR$^2$</th>
<th>LET</th>
<th>Expt</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^0p$</td>
<td>-1.16</td>
<td>-1.22</td>
<td>-2.47</td>
<td>-1.33 ± 0.08$^3$</td>
</tr>
<tr>
<td>$\pi^+n$</td>
<td>28.2 ± 0.6</td>
<td>28.0 ± 0.2</td>
<td>27.6</td>
<td>28.1 ± 0.3$^4$</td>
</tr>
<tr>
<td>$\pi^0n$</td>
<td>2.13</td>
<td>1.19</td>
<td>0.69</td>
<td>???</td>
</tr>
<tr>
<td>$\pi^-p$</td>
<td>-32.7 ± 0.6</td>
<td>-31.7 ± 0.2</td>
<td>-31.7</td>
<td>-31.5 ± 0.8$^5$</td>
</tr>
</tbody>
</table>

5. M. Kovash et al., $\pi N$ Newsletter 12, 51 (1997)

Note the somewhat counter-intuitive ChPT prediction that $E_{0^+}^{n\pi^0}$ is roughly twice that of $E_{0^+}^{p\pi^0}$.
Coherent $\pi^0$ Production from Deuterium?

Results for $E_d$:

<table>
<thead>
<tr>
<th>Method</th>
<th>$E_d$</th>
<th>$E_{p\pi^0}^{0+} + E_{n\pi^0}^{0+}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LET</td>
<td>$-$</td>
<td>-1.78</td>
</tr>
<tr>
<td>ChPT$^1$</td>
<td>-1.8 ± 0.2</td>
<td>0.97</td>
</tr>
<tr>
<td>DR</td>
<td>$-$</td>
<td>-0.03</td>
</tr>
<tr>
<td>Expt$^2$</td>
<td>$-1.45 ± 0.04$</td>
<td>$-$</td>
</tr>
</tbody>
</table>


Obviously FSI and MECs are important.

$\Rightarrow$ Not so easy to extract $E_{0+}^{n\pi^0}$!
Recent Theoretical Work: $^3\text{He}$ Target


Calculation of $^3\text{He}(\gamma, \pi^0)^3\text{He}$ to $\mathcal{O}(q^4)$ in ChPT.

$$a_0 = \left| k \right| \left| q \right| \left| \frac{d\sigma}{d\Omega} \right|_{q=0} = \left| E_{0+} \right|^2.$$

Note that here $E_{0+}$ is for the nucleus!

Valid for $q = 0$ only, i.e. right at threshold.

Measure this reaction with CB-TAPS@MAMI
High-pressure, Active He Target

The New Active Target

- Al pressure vessel, no welds
- Reuse Be outer windows from original Active Target
- PTFE sheet covers printed circuit board, windows cut for SiPMT

8th December 2015

Active Target 3,4He, J.R.M. Annand
Proposal:
- Theory group needs to extend calculation to higher energies.
- Proper rate calculations.
- Signal/background simulations with high-pressure, active He gas target. Especially coherent vs. break-up.
- Estimate expected sensitivity to $E_{0^+}^{n\pi^0}$.

Experiment:
- Find a PhD student.
- Installation and commissioning of high-pressure, active He gas target.
- Set-up, run, analyze, publish.

*Possibly run in parallel with Compton scattering for neutron polarizabilities...*
BACKUP SLIDES
### Active Polarized Target – Specs

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Polystyrene</th>
<th>C&lt;sub&gt;8&lt;/sub&gt;H&lt;sub&gt;8&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scintillator 365 nm</td>
<td>2,5-Diphenyloxazole</td>
<td>C&lt;sub&gt;15&lt;/sub&gt;H&lt;sub&gt;11&lt;/sub&gt;NO</td>
</tr>
<tr>
<td>Wavelength Shifter 430 nm</td>
<td>PPO</td>
<td>C&lt;sub&gt;26&lt;/sub&gt;H&lt;sub&gt;20&lt;/sub&gt;N&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;2&lt;/sub&gt;</td>
</tr>
<tr>
<td>Paramagnetic Free Radical</td>
<td>Dimethyl-POPOP</td>
<td>C&lt;sub&gt;9&lt;/sub&gt;H&lt;sub&gt;16&lt;/sub&gt;NO&lt;sub&gt;2&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td>4-Oxo-TEMPO</td>
<td></td>
</tr>
</tbody>
</table>

**70% polarization** @ 200 mK in Mainz  
**Dilution factor** f<sub>p</sub> = 7.7% (H-Butanol 13.4%)