Threshold Pion Photoproduction in the A2 Collaboration at MAMI

Precision Hadron Structure

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Newport News, Virginia
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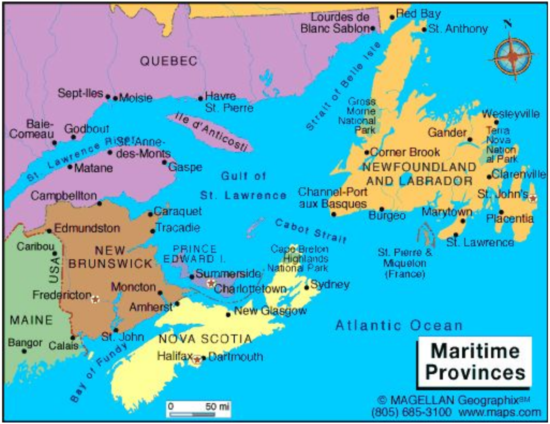
NOT New Jersey!

Where the heck is New Brunswick?

Maritime Province



<u>New Brunswick</u>

Population: c. 750,000

Languages: English and French

Area: 72,908 km^2

Time Zone: Atlantic (GMT-4)

<u>Sackville</u>

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

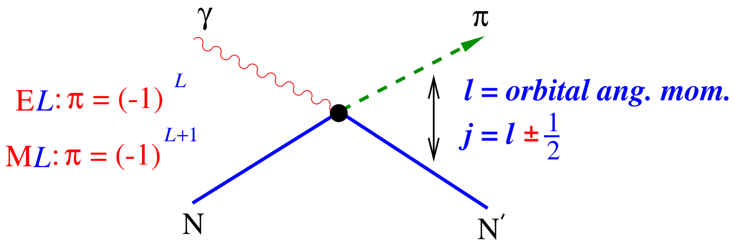
Partial-Wave Analysis and Multipoles

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



In the threshold region, *S*-, *P*- and even *D*-waves contribute:

$l = 0$	E_{0^+}	*S*-wave
$l = 1$	E_{1^+}, M_{1^+}, M_{1^-},	*P*-waves
$l = 2$	E_{2^+}, E_{2^-}, M_{2^+}, M_{2^-}	*D*-waves

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.

Partial-Wave Analysis

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 2π threshold, we only need two observables and unitarity.

set	observables			
single	$\boldsymbol{d\sigma/d\Omega}$	$\boldsymbol{\Sigma}$	**T**	P
beam-target	G	H	E	**F**
beam-recoil	Ox'	Oz'	Cx'	Cz'
target-recoil	Tx'	Tz'	Lx'	Lz'

Model-Independent Partial-Wave Analysis

With help from:

L. Tiator, M. Hilt, C. Fernández Ramírez, A.M. Bernstein

Complete PWA in π^0 photoproduction below 2π threshold.

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

How is it done?

- Use (1) Empirical Single-Energy *and* (2) Energy-Dependent Fits to $d\sigma/d\Omega$ and Σ.
- 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

$$a_0 = |E_{0+}|^2 + P_{23}{}^2 \qquad P_1 = 3E_{1+} + M_{1+} - M_{1-}$$

$$a_1 = 2\mathrm{Re}E_{0+}P_1 \qquad P_2 = 3E_{1+} - M_{1+} + M_{1-}$$

$$a_2 = P_1{}^2 - P_{23}{}^2 \qquad P_3 = 2M_{1+} + M_{1-}$$

$$b_0 = \frac{1}{2}\left(P_3{}^2 - P_2{}^2\right) \qquad P_{23}{}^2 = \frac{1}{2}(P_2{}^2 + P_3{}^2)$$

4 measured quantities, a_0, a_1, a_2, b_0, and 4 unknown real parameters, $\mathrm{Re}E_{0+}, P_1, P_2, P_3$.

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

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

$$a_1 = 2\mathrm{Re}E_{0^+}P_1 - P_1D_1 - 3P_2D_2 + 3P_3D_3$$

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

$$a_3 = 3(P_1D_1 + P_2D_2 - P_3D_3)$$

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

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

$$b_1 = 3(P_1D_4 + P_2D_2 + P_3D_3)$$

$$b_2 = \frac{9}{2}(-D_2{}^2 + D_3{}^2 + D_1D_4)$$

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...

(2) Empirical Energy-Dependent Fits to the Multipoles

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.

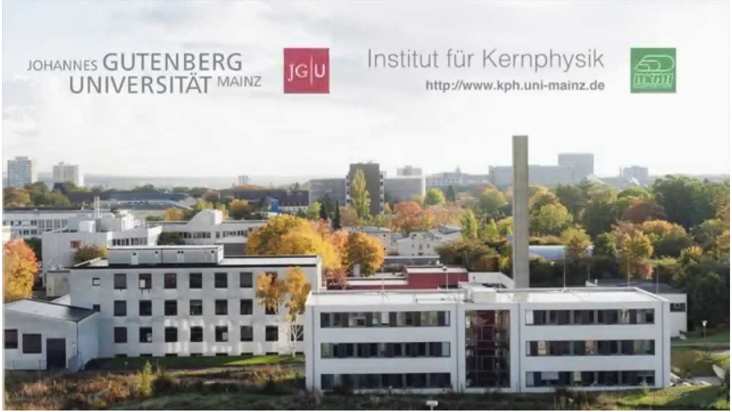
Mainz, Germany

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

Institut für Kernphysik

Johannes Gutenberg-Universität

≈35,000 students



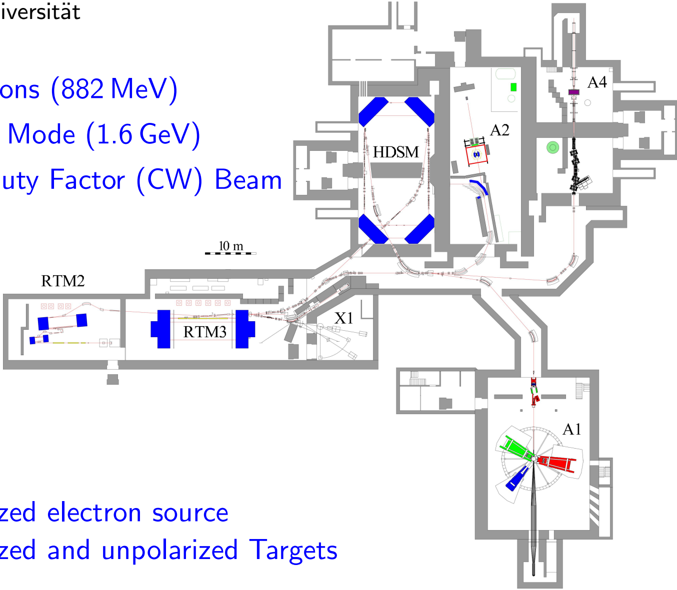
The Mainzer Mikrotron (MAMI)

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



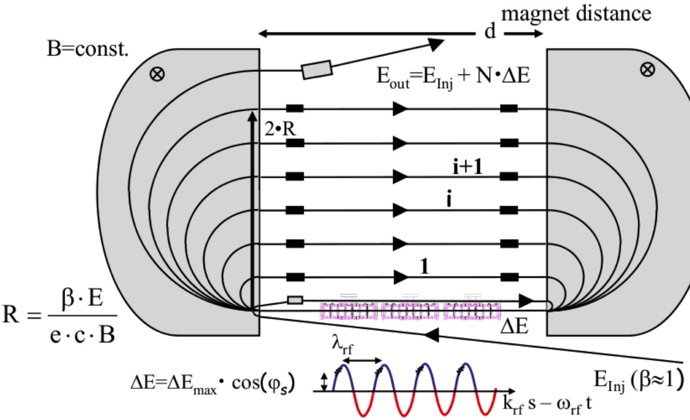
THE LOW-ENERGY FRONTIER
OF THE STANDARD MODEL

Polarized electron source

Polarized and unpolarized Targets

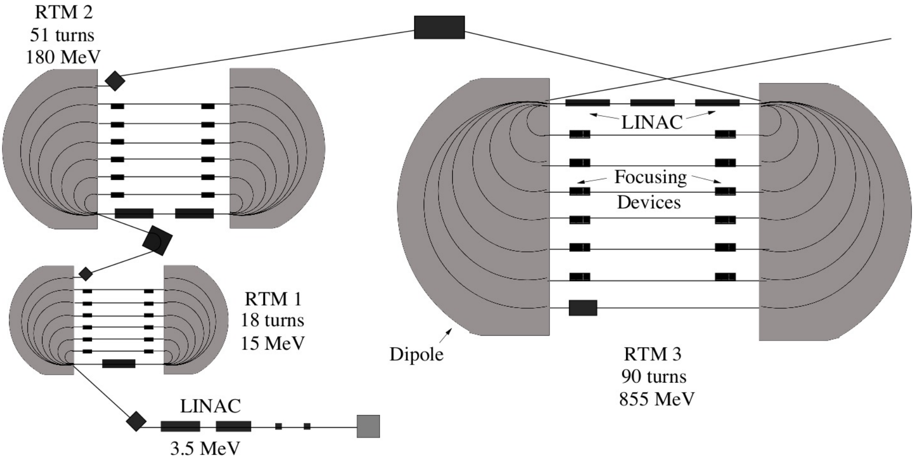
Race-Track Microtron (RTM)

Key point is that you recirculate the electrons, obviating the need for a long LINAC, reducing the amount of power required.



MAMI-B

Maximum electron-beam energy 855 MeV.



Dipole from RTM3

World's biggest RTM. Each magnet weights 450 t. Field of 1.28 T.

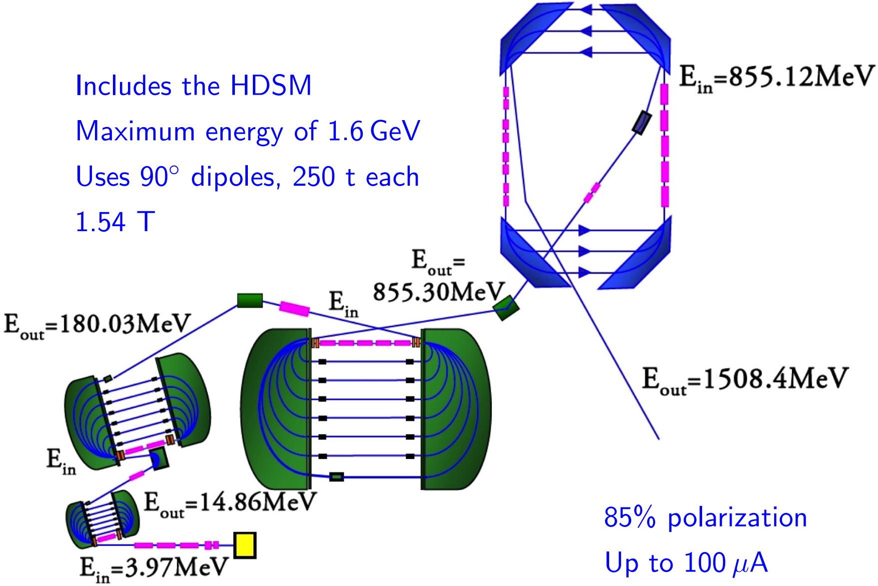
MAMI-C

Includes the HDSM

Maximum energy of 1.6 GeV

Uses 90° dipoles, 250 t each

1.54 T



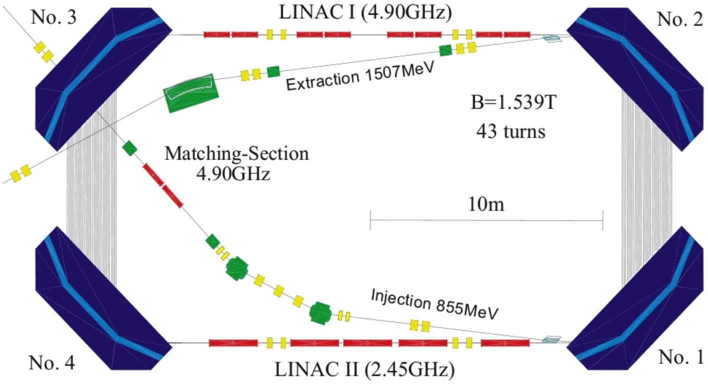
85% polarization

Up to 100 μA

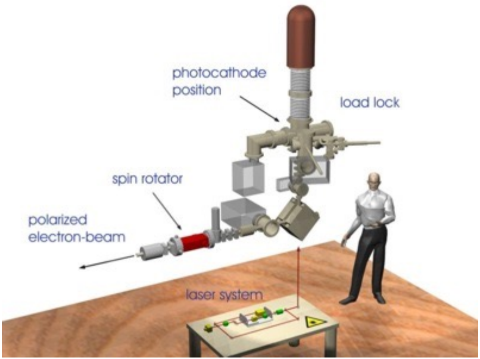
Harmonic Double-Sided Microtron

Impossible to make magnets for a conventional RTM big enough.

Use 4 magnets instead of 2!

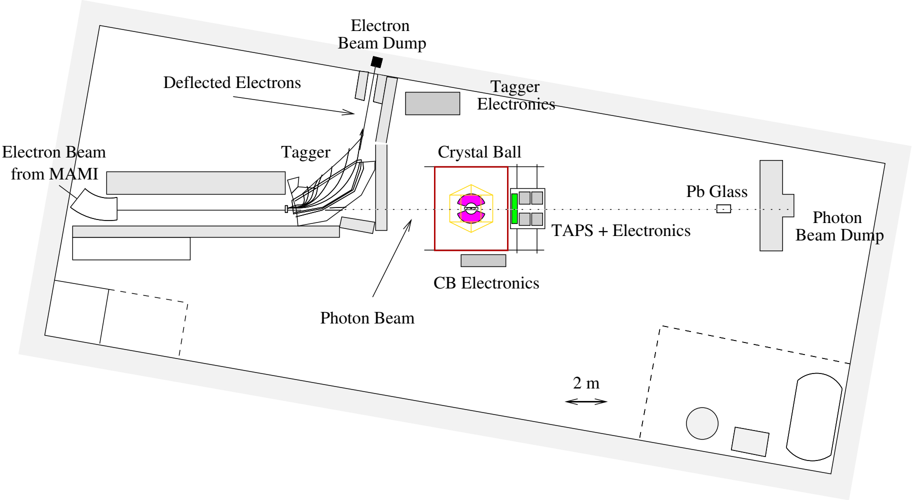


Polarized Electron Source



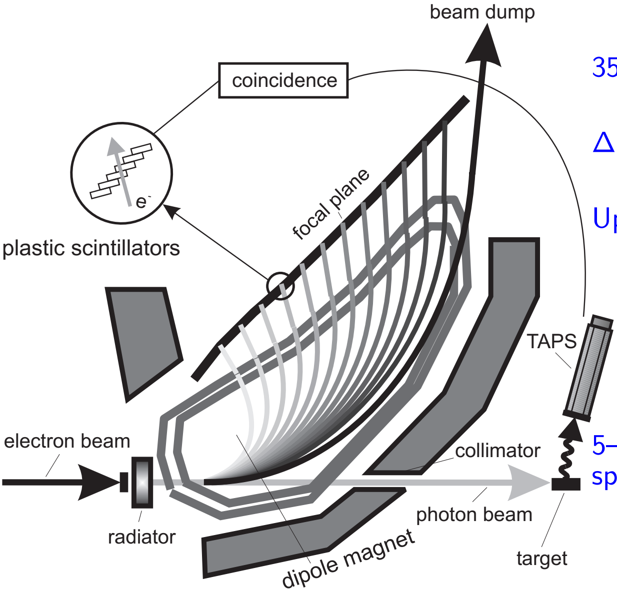
- GaAs photocathode and laser system.
- Trade-off between quantum efficiency and degree of polarization.
- Produces electron polarization up to about 85%.

The A2 Hall



Electron
Beam Dump
Deflected Electrons
Tagger
Electronics
Electron Beam
from MAMI
Tagger
Crystal Ball
Pb Glass
Photon
Beam Dump
TAPS + Electronics
CB Electronics
Photon Beam
2 m

Incident Photon Beam – Glasgow-Mainz Photon Tagger



352 channels

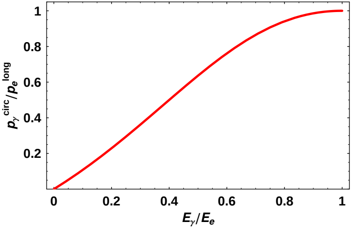
$\Delta E = 4\,\text{MeV}$ at 1.6 GeV

Up to $\sim 10^8 \gamma/\text{s}$

Refurbished to work at 1.6 GeV

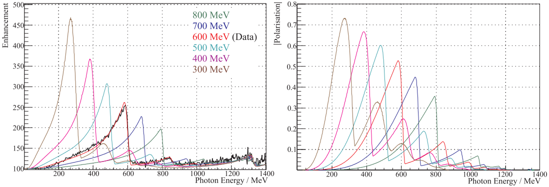
5–94% of Bremsstrahlung spectrum

Circular Polarization



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

Linear Polarization

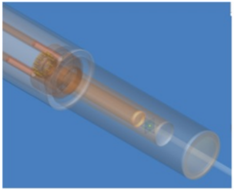


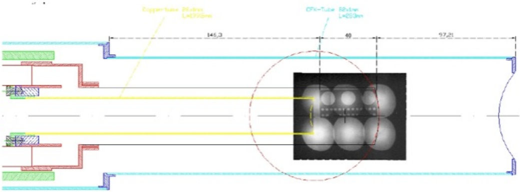
- Created via coherent bremsstrahlung. Entire diamond lattice coherently contributes to producing photons.
- Maximized for *high electron beam energies and low photon energies.*

Reaction Targets in A2

- Cryogenic LH_2/LD_2: unpolarized protons/deuterons
- Cryogenic L^4He/L^3He
- 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





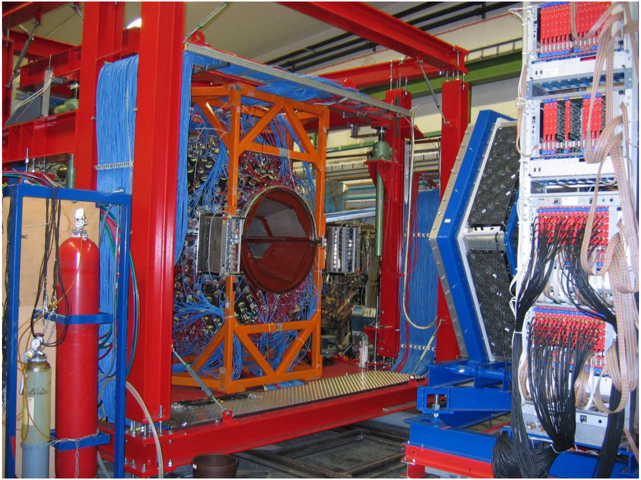
2-cm, 5-cm, and 10-cm Kapton ($C_{22}H_{10}N_2O_5$) cells, 100 μm thick

1080 mBar, 20.5 Kelvin

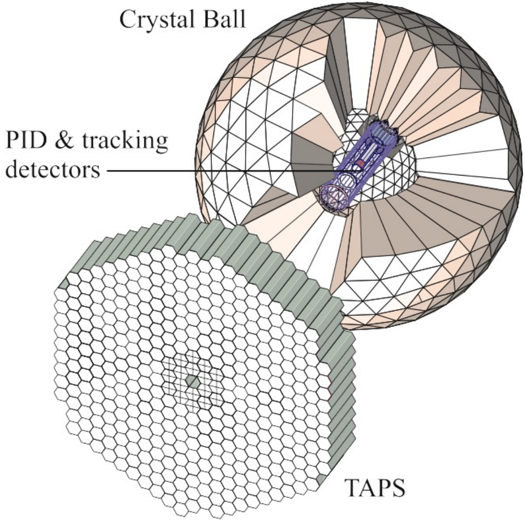
$\approx 2 \times 10^{23}$ nuclei/cm^2 for 5-cm cell

Detector System: CB-TAPS

A2 Standard Configuration from 2003–present



Detector System: CB-TAPS



- A2 Standard Configuration from 2003–present
- CB: 672 NaI detectors
- TAPS: 384 BaF_2 detectors with individual vetoes
- 24-scintillator PID barrel
- 96% of 4π sr!
- Cylindrical Wire Chamber
- Čerenkov Detector

$\vec{\gamma} p \to \pi^0 p$

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.)

$\vec{\gamma} p \to \pi^0 p$ – Experimental Details

Equipment:

- A2 Hall.
- Glasgow-Mainz photon-tagging spectrometer.
- CB-TAPS.
- Cryogenic LH_2 "snout" target.

Run Parameters:

Electron Beam Energy	855 MeV
Target	10-cm LH_2
Radiator	100 μm Diamond
Tagged Energy Range	100 – 800 MeV
Channel Energy Resolution	2.4 MeV
Polarization Edge	$\sim$ 190 MeV
Degree of Polarization	40 – 70%
Beam on Target	90 h Full + 20 h Empty

Comparison with TAPS 2001

Advantage CB-TAPS 2008

- Efficiency for π^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 $\mathbf{\Sigma}$ with TAPS 2001

Serious disagreement between CB-TAPS 2008 and TAPS 2001 for Σ

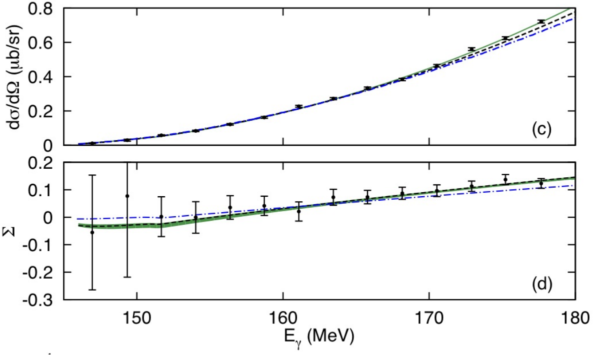
Source? $\Rightarrow$ Target windows in TAPS 2001 measurement.

- 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 Σ was NOT!

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

NOTE: TAPS 2001 extraction of energy dependence of $\boxed{\mathrm{Re}E_{0^+}}$ still the best one to date. *Depends on* $d\sigma/d\Omega$ *and not* Σ.

Energy Dependence of $d\sigma/d\Omega$ and Σ at 90°

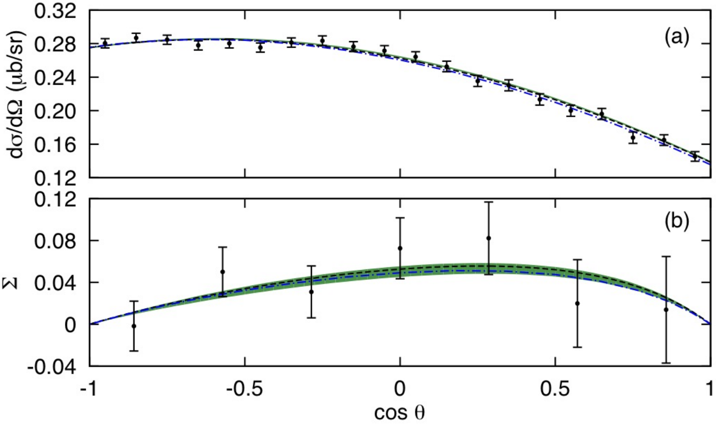


Excellent statistics in both $d\sigma/d\Omega$ and Σ, and for the first time, energy dependence of Σ.

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

Plots courtesy of C. Fernández Ramírez.

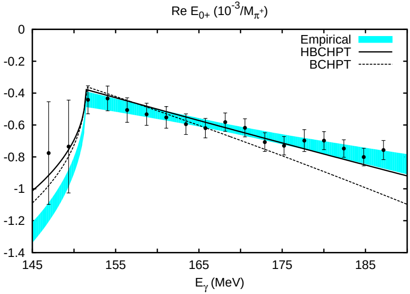
Sample Results at $E_\gamma = \mathbf{163}$ MeV

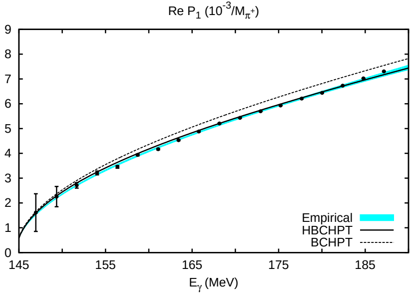


Good agreement with HBChPT (black) and ChPT (blue). Empirical fit is also shown with statistical error band (green).

Plots courtesy of C. Fernández Ramírez.

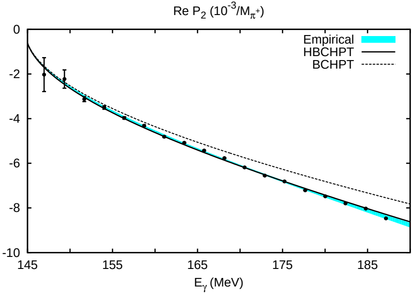
Multipoles: E_{0+} and P_1

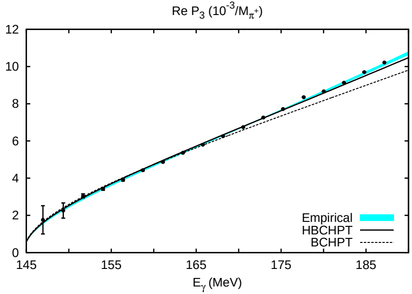




Plots courtesy of C. Fernández Ramírez

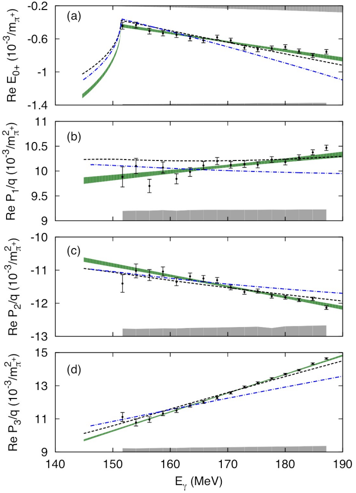
Multipoles: P_2 and P_3





Plots courtesy of C. Fernández Ramírez

Energy Dependence of the Multipoles

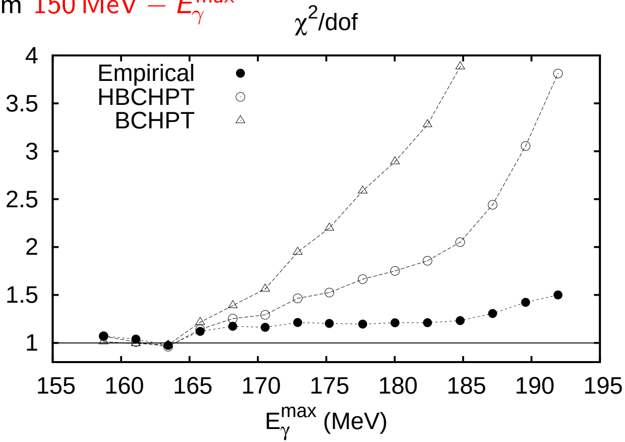


- ReE_{0+}, P_1/q, P_2/q, P_3/q.
- Single-energy fits (points) along with the empirical fits (green band).
- Theory curves are HBChPT (black) and ChPT (blue).
- Systematic uncertainties in the single-energy extraction are the grey-shaded bands.

Plots courtesy of C. Fernández Ramírez.

Energy Region of Agreement

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



Covariant BChPT deviates at ≈ 167 MeV and HBChPT at ≈ 170 MeV.

Plot courtesy of C. Fernández Ramírez.

$\vec{\gamma} p \to \pi^0 p$ — Conclusions

- Target-window contributions are very important near threshold, *even for the asymmetry*.
- HBChPT and Relativistic ChPT are in agreement, with good χ^2/dof values up to around 167 MeV.
- Reasonable agreement with DMT and Lutz-Gasparyan predictions.
- Energy dependence is obviously a big improvement.

$\vec{\gamma}\vec{p} \to \pi^0 p$

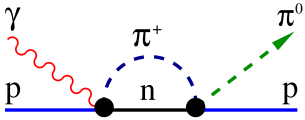
S. Schumann et al., PLB **750**, 252 (2015).

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

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

Complex Nature of Multipoles

Due to rescattering

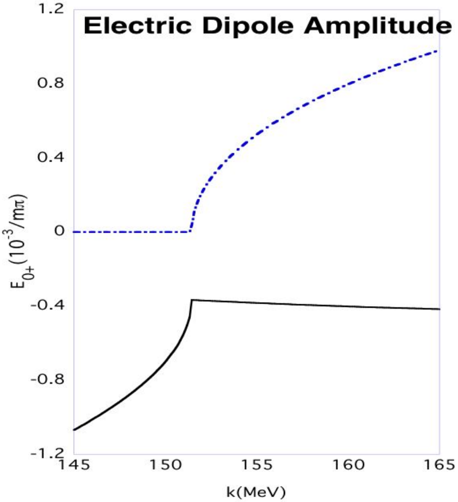


there exists a **Unitarity Cusp**
in the $E_{0+}^{\pi^0 p}$ amplitude:

$$E_{0+}^{\pi^0 p} = \mathrm{Re}E_{0+}^{\pi^0 p} + i\beta \frac{q_{\pi^+}}{m_{\pi^+}}$$

where β is the *cusp function*:

$$\beta = E_{0+}^{\pi^+ n} f_{cex}(\pi^+ n \to \pi^0 p)$$



Imaginary Part of $E_{0^+}^{\pi^0 p}$

Target Asymmetry, T

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

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

- 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

$$\frac{d\sigma}{d\Omega} = \sigma_0 \left(1 + P_{\mathrm{T}}\, T \sin\varphi\right)$$

with the target asymmetry defined as

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

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

$$T = \frac{1}{P_{\mathrm{T}} \sin\varphi} \cdot \frac{N_+ - N_-}{N_+ + N_-}$$

$\vec{\gamma}\vec{p} \to \pi^0 p$ – 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:

Electron Beam Energy	450 MeV
Target	Butanol
Radiator	Møller Foil
Tagged Energy Range	100 – 400 MeV
Channel Energy Resolution	1.2 MeV
Target Polarization	≈80%
Beam on Target	700 h C_4H_9OH and 100 h C

Experimental Challenges

- Butanol target is made up of C_4H_9OH, and so there are lots of backgrounds. Essentially one heavy nucleus for every 2 protons.
- Swamped with π^0s from C and O, both coherent and incoherent.
- C and O nuclei are not polarized, but they dilute the asymmetries.

$$
\begin{aligned}
A &= \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \\
&= \frac{(\sigma_p^+ + \cancel{\sigma_C}) - (\sigma_p^- - \cancel{\sigma_C})}{(\sigma_p^+ + \sigma_C) + (\sigma_p^- + \sigma_C)} \\
&= \frac{\sigma_p^+ - \sigma_p^-}{\sigma_p^+ + \sigma_p^- + 2\sigma_C}
\end{aligned}
$$

- Need to know the lineshapes very well, and we must be able to eliminate effect of unpolarized, heavy nuclei.

Heavy-Nucleus Backgrounds

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...

$\Rightarrow$ Polarized Cross sections

Product of unpolarized cross section and asymmetries:

$$\sigma_T \equiv \sigma_0 T = \frac{\sigma^+ - \sigma^-}{P_T \sin\phi} = \frac{1}{P^y_{\text{eff}}} \frac{N^+_{\text{but}} - N^-_{\text{but}}}{\epsilon\, \Phi_\gamma\, \rho_p} \frac{1}{2\pi \sin\phi}$$

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

$$N^+_{\text{but}} - N^-_{\text{but}} = N^+_p + \cancel{N_C} - N^-_p - \cancel{N_C} = N^+_p - N^-_p$$

$\Rightarrow$ 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

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

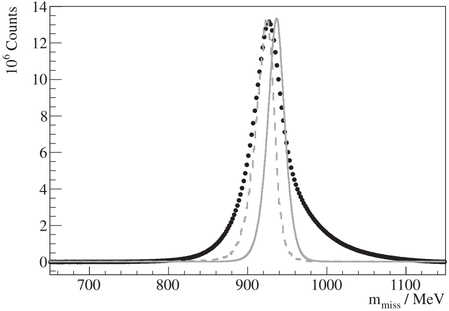
Note that we placed a cut ϕ to increase the effective polarization

$$|\sin\phi| > 0.35$$

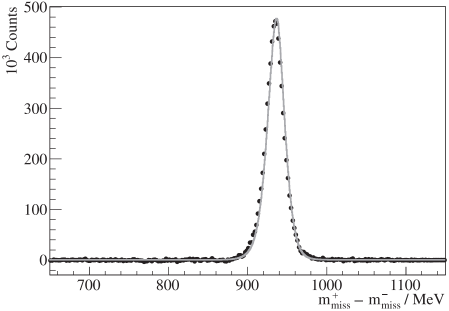
This had the effect of limiting the angular coverage, but increasing the polarization for about 50% to 60%.

Missing Mass Distributions

Butanol

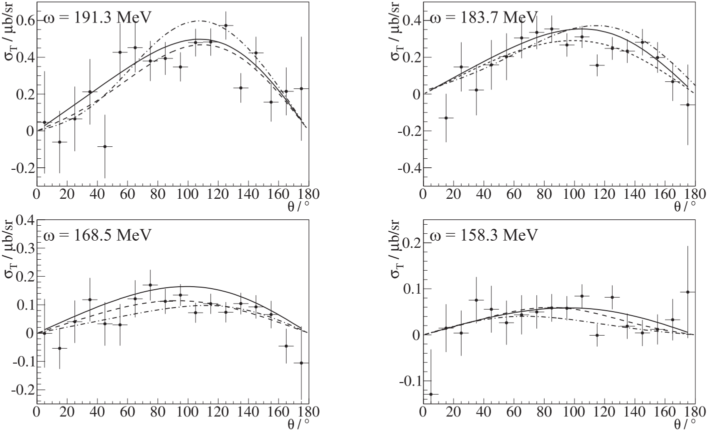


$m^+_{miss} - m^-_{miss}$



Points	Data
Dashed curve	Simulated π^0 production on ^{12}C
Solid curve	Simulated π^0 production on p

Polarized Differential Cross Sections σ_T



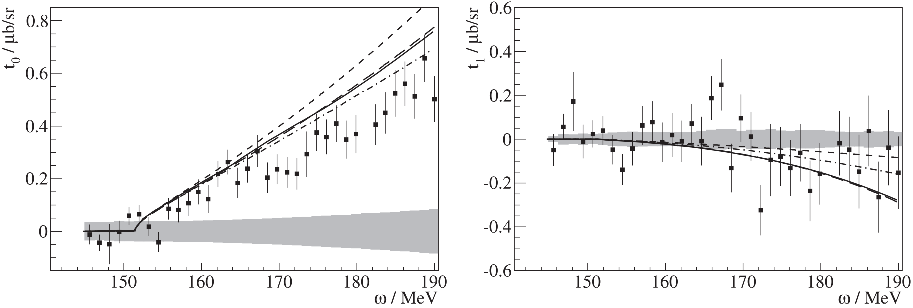
Solid lines are predictions of the DMT model, dashed are Legendre polynomial fits, and dashed-dot are a cross-check from a standard analysis done by P.B. Otte.

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 $z = \cos\theta$.



DMT – Solid, Parametrization – short-dashed, Lutz-Gasparyan – long-dashed, and ChPT – dash-dotted. Systematic errors are the shaded grey bands.

Multipole Extraction from σ_T

Decomposition of σ_T, including the *D*-waves, is given by

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

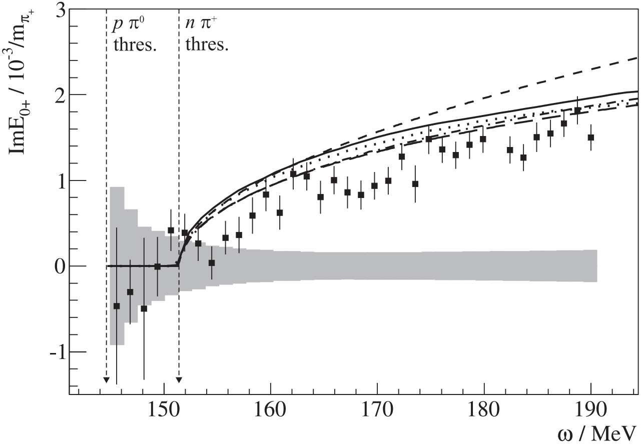
Real parts of the *S*- and *P*-waves were taken from our previous experiment that measured Σ and σ_0.

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

D-waves were included as fixed Born terms.

$\Rightarrow \mathrm{Im}E_{0^+}$ 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 β

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

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

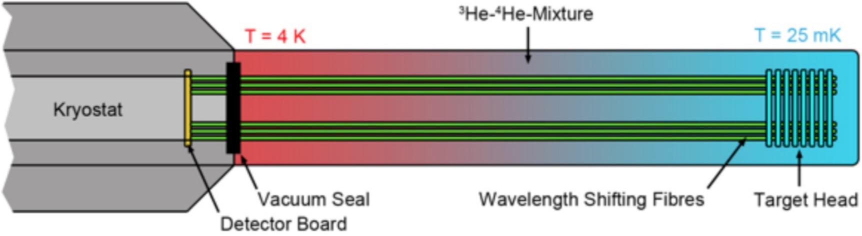
Large uncertainties preclude us from making a reliable determination of the energy dependence...

$\vec{\gamma}\vec{p} \to \pi^0 p$ — Conclusions/Outlook

- First measurements of σ_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 σ_T.
- Continue work on an active, polarized target eliminate heavy-nucleus backgrounds altogether, improving measurement of σ_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:

$$\gamma p \to \pi^0 p$$
$$\gamma p \to \pi^+ n$$
$$\boxed{\gamma n \to \pi^0 n}$$
$$\gamma n \to \pi^- p$$

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 $10^{-3}/m_{\pi^+}$):

Reaction	ChPT[1]	DR[2]	LET	Expt
$\pi^0 p$	-1.16	-1.22	-2.47	-1.33 ± 0.08 [3]
$\pi^+ n$	28.2 ± 0.6	28.0 ± 0.2	27.6	28.1 ± 0.3 [4]
$\pi^0 n$	2.13	1.19	0.69	???
$\pi^- p$	-32.7 ± 0.6	-31.7 ± 0.2	-31.7	-31.5 ± 0.8 [5]

1. V. Bernard, N. Kaiser, and U.-G. Meißner, Z. Phys. C **70**, 483 (1996)
2. O. Hanstein, D. Drechsel, and L. Tiator, Phys. Lett. B **399**, 13 (1997)
3. A. Schmidt *et al.*, Phys. Rev. Lett. **87**, 232501 (2001)
4. E. Korkmaz *et al.*, Phys. Rev. Lett. **83**, 3609 (1999)
5. M. Kovash *et al.*, πN 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 π^0 Production from Deuterium?

$$d(\gamma, \pi^0)d$$

Results for E_d:

Method	E_d	$E_{0^+}^{p\pi^0} + E_{0^+}^{n\pi^0}$
LET	–	-1.78
ChPT[1]	-1.8 $\pm$ 0.2	0.97
DR	–	-0.03
Expt[2]	-1.45 ± 0.04	–

1. S.R. Beane *et al.*, Nucl. Phys. A **618**, 381 (1997)
2. J.C. Bergstrom *et al.*, Phys. Rev. C **57**, 3203 (1998)

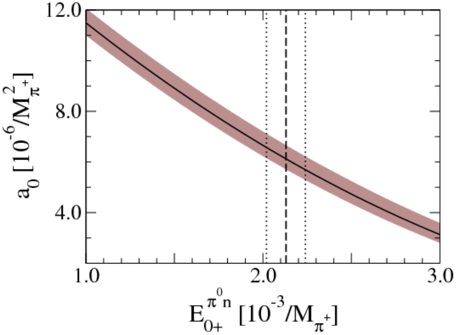
Obviously FSI and MECs are important.

$\Rightarrow$ Not so easy to extract $E_{0^+}^{n\pi^0}$!

Recent Theoretical Work: ^{3}He Target

Lenkewitz et al., PLB **700**, 365 (2011) and EPJA **49**, 20 (2013).

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



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

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

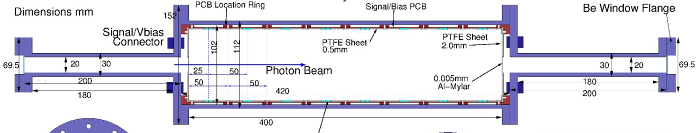
Valid for $q = 0$ only, i.e. right at threshold.

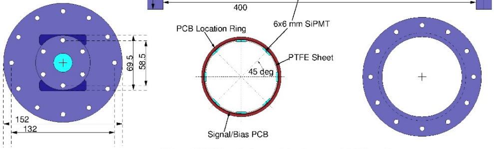
Measure this reaction with CB-TAPS@MAMI

High-pressure, Active He Target

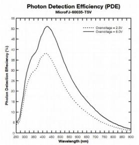
The New Active Target

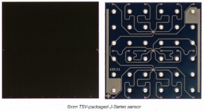
Active Target
J.R.M. Annand
11th Feb. 2016
Dimensions mm





8 rings of SiPMT, each ring consisting 8 groups of 4 6x6mm tiles.
Total number of SiPMT 8x8x4 = 256.
Readout in groups of 16, each group connected to an op–amp.
16 signal outputs
2 vias–voltage inputs





6 x 6mm J-Series SiPMT

- 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 5

$E_{0^+}^{\pi^0 n}$ – Outlook

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.

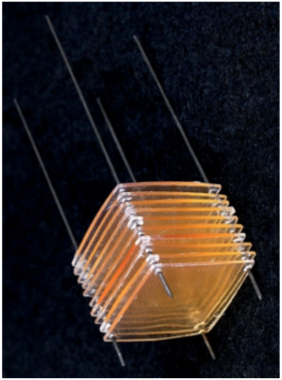
Possibly run in parallel with Compton scattering for neutron polarizabilities. . .

BACKUP SLIDES

Active Polarized Target – Specs

Vehicle	Polystyrene	C_8H_8
Scintillator 365 nm	2,5-Diphenyloxazole PPO	$C_{15}H_{11}NO$
Wavelength Shifter 430 nm	Dimethyl-POPOP	$C_{26}H_{20}N_2O_2$
Paramagnetic Free Radical	4-Oxo-TEMPO	$C_9H_{16}NO_2$

70% polarization @ 200 mK in Mainz
Dilution factor f_p = 7.7% (H-Butanol 13.4%)



D. Von Maluski et al. Polarizable Scintillator for Nuclear Targets. Technical report, Triangle Universities Nuclear Laboratory (TUNL), 2009