Hadron Polarizability Measurements

What do they tell us about hadron structure?

David Hornidge, *Mount Allison University*

58th International Winter Meeting on Nuclear Physics
Bormio, Italy

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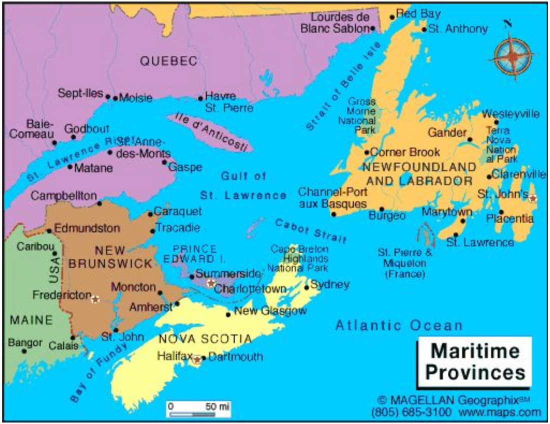
THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

New Brunswick, CANADA

Where the heck is New Brunswick?

Maritime Province



New Brunswick

Population: c. 750,000

Languages: English and French

Area: 72,908 km^2

Time Zone: Atlantic (GMT-4)

Sackville

Population: c. 5,500

Latitude: 46° N

Mount Allison student enrolment: c. 2,000

"Mount" Allison elevation: c. 10 m above sea level (depending on tide. . .)

Hopewell Rocks, NB – Highest Tides in the World

Outline

Non-Perturbative QCD

- Regime where the coupling is too strong and perturbative QCD (pQCD) is not appropriate.
- Very important for a thorough understanding of QCD.
- An understanding of the transition from non-pQCD (confinement) to pQCD (asymptotic freedom) is integral to the overall understanding of QCD.

Fundamental Question:

"Can the theory of quark and gluon confinement quantitatively describe the detailed properties of hadrons?"

Perspectives on Subatomic Physics in Canada 2006–2016.

- Theory: QCD describes the strong force in terms of quarks and gluons.
- Nobel Prize in 2004 for **Asymptotic Freedom** in the pQCD regime. . .
- However, in the non-perturbative region, QCD is still unsolved.

One of the top ten challenges for all of physics!

How do we test QCD in the non-perturbative regime?

High-precision measurements with polarization observables.

Hadron Polarizabilities

- Fundamental structure constants
- Response of internal structure to external fields
- Fertile meeting ground between theory and experiment
- Best measured via **Compton scattering**, both real and virtual

Theoretical Approaches

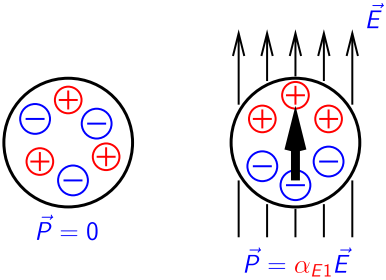
- Dispersion Relations (both subtracted and unsubtracted)
- Chiral Perturbation Theory
- Lattice QCD

Why else do we care about the nucleon polarizabilities?

Limit precision in other areas of physics:

- Lamb shift and hyperfine structure (proton radius)
- EM contribution to $n - p$ mass difference
- Neutron star properties

Electric Dipole Polarizability

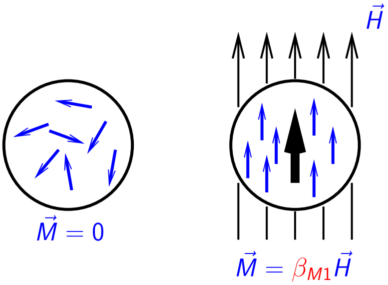


- Apply an electric field to a composite system
- Separation of Charge, or **"Stretchability"**
- Proportionality constant between electric dipole moment and electric field is the electric dipole polarizability, α_{E1}.

Provides information on force holding system together.

Scalar Polarizabilities – Conceptual

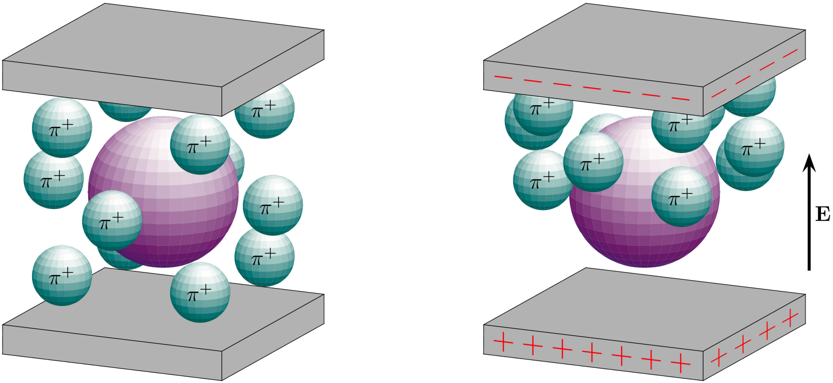
Magnetic Dipole Polarizability



- Apply a magnetic field to a composite system
- Alignment of dipoles or **"Alignability"**
- Proportionality constant between magnetic dipole moment and magnetic field is the magnetic dipole polarizability, β_{M1}.
- Two contributions, paramagnetic and diamagnetic, and they cancel partially, giving $\beta_{M1} < \alpha_{E1}$.

Provides information on force holding system together.

Proton – Toy Model

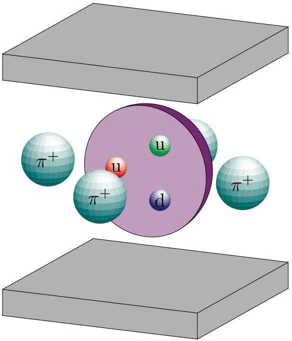


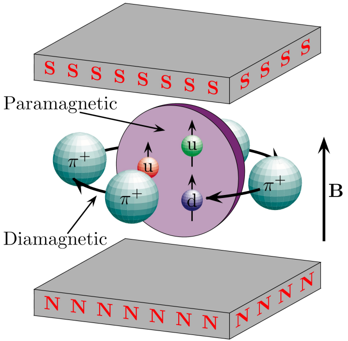
Electric Polarizability: proton between charged parallel plates.

$$\boxed{\alpha_{E1} \simeq 11 \times 10^{-4}\,\text{fm}^3} \approx 3 \times 10^{-4}\,V$$

Proton is VERY stiff! Not so easy to polarize.

Proton – Toy Model



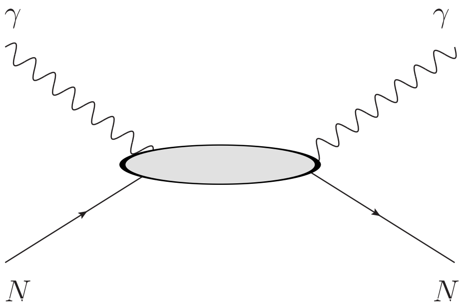


Magnetic Polarizability: proton between poles of a magnet.

$$\beta_{M1} \simeq 3 \times 10^{-4}\,\mathrm{fm}^3$$

Two contributions: paramagnetic and diamagnetic, and they partially cancel out.

Real Compton Scattering from the Nucleon



Low-energy outgoing photon *plays the role of the applied EM field*.

$\Rightarrow$ Nucleon Response

$\Rightarrow$ **POLARIZABILTIES!**

Global response to internal degrees of freedom.

Real Compton Scattering – Hamiltonian

Expand the Hamiltonian in incident-photon energy.

0th order $\longrightarrow$ charge, mass

1st order $\longrightarrow$ magnetic moment

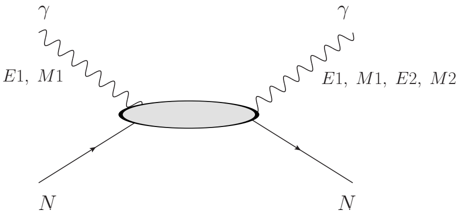
2nd order $\longrightarrow$ **scalar polarizabilities**:

$$H_{\text{eff}}^{(2)} = -4\pi \left[\frac{1}{2}\alpha_{E1}\vec{E}^2 + \frac{1}{2}\beta_{M1}\vec{H}^2 \right]$$

3rd order $\longrightarrow$ **spin (or vector) polarizabilities**:

$$H_{\text{eff}}^{(3)} = -4\pi \left[\tfrac{1}{2}\gamma_{E1E1}\vec{\sigma}\cdot(\vec{E}\times\dot{\vec{E}}) + \tfrac{1}{2}\gamma_{M1M1}\vec{\sigma}\cdot(\vec{H}\times\dot{\vec{H}}) \right.$$
$$\left. -\gamma_{M1E2}E_{ij}\sigma_i H_j + \gamma_{E1M2}H_{ij}\sigma_i E_j \right]$$

where $E_{ij} = \frac{1}{2}(\nabla_i E_j + \nabla_j E_i)$ and $H_{ij} = \frac{1}{2}(\nabla_i H_j + \nabla_j H_i)$



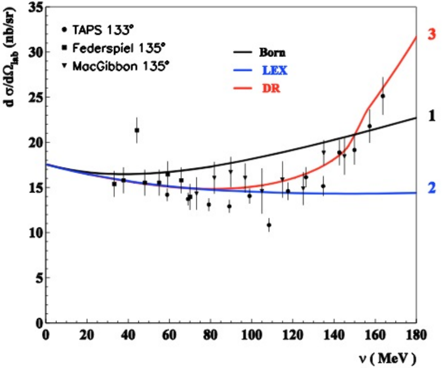
quantity	incident γ	scattered γ
α_{E1}	$E1$	$E1$
β_{M1}	$M1$	$M1$
γ_{E1E1}	$E1$	$E1$
γ_{M1M1}	$M1$	$M1$
γ_{M1E2}	$M1$	$E2$
γ_{E1M2}	$E1$	$M2$

Nucleon has $J^\pi = \frac{1}{2}^+$. Photons have parity given by

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

The usual QM selection rules for angular momentum and parity apply.

Low-Energy Expansion in Proton Compton Scattering



1 — Born (anomalous magnetic moment)

2 — LEX (polarizabilities at leading order)

3 — Dispersion relations (full calculation)

LEX:

$$\frac{d\sigma}{d\Omega}(\nu,\theta) = \frac{d\sigma}{d\Omega}^{Born}(\nu,\theta) - \nu\nu'\left(\frac{\nu'}{\nu}\right)\frac{e^2}{2m}\left[(\alpha_{E1}+\beta_{M1})(1+z)^2 + (\alpha_{E1}-\beta_{M1})(1-z)^2\right]$$

Measure low energies and precise cross sections/asymmetries!

Proton – Fit with DRs

Baldin Sum Rule:

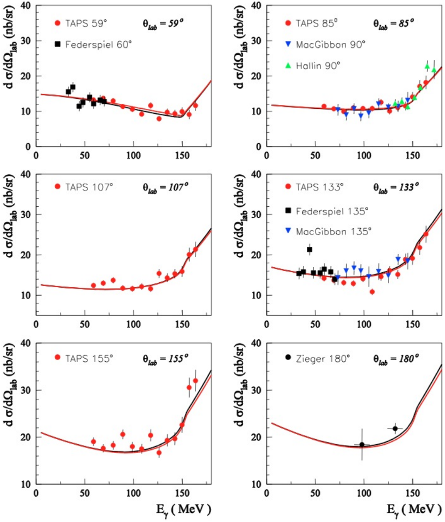
$$\alpha_{E1} + \beta_{M1} = (13.8 \pm 0.4) \times 10^{-4}\,\mathrm{fm}^3$$

Unsubtracted DRs:
Olmos de Leon et al., EPJA **10**, 207 (2001).

$$\alpha_{E1} - \beta_{M1} = (10.5 \pm 0.9) \times 10^{-4}\,\mathrm{fm}^3$$

Subtracted DRs:
Drechsel et al., Phys. Rep. 378 (2003).

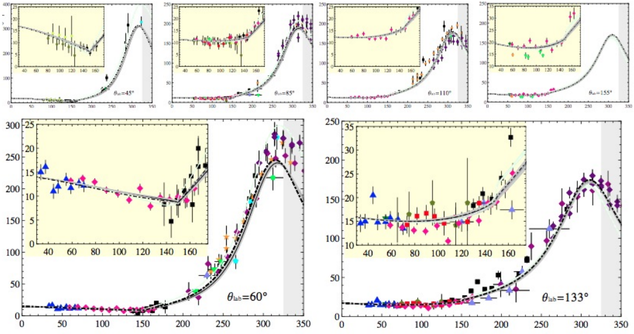
$$\alpha_{E1} - \beta_{M1} = (11.3 \pm 1.1) \times 10^{-4}\,\mathrm{fm}^3$$



Proton – BChPT with Δ

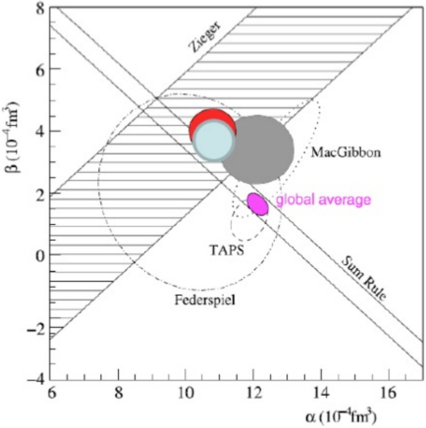
McGovern, Phillips, Grießhammer, EPJA **49**, 12 (2013)

Key Point: Statistically consistent database is used!



NLO + Δ	$\alpha_{E1} = 10.7 \pm 0.4_{\text{stat}} \pm 0.2_{\Sigma} \pm 0.3_{\text{th}}$	$\beta_{M1} = 3.2 \mp 0.4_{\text{stat}} \pm 0.2_{\Sigma} \pm 0.3_{\text{th}}$
NLO + Δ	$\alpha_{E1} = 10.8 \pm 0.7$	$\beta_{M1} = 4.0 \pm 0.7$
δ-expansion, Lensky & Pascalutsa EPJC **65** (2010)		
MAMI/TAPS	$\alpha_{E1} = 12.1 \pm 1.2_{\text{stat/mod}} \pm 0.4_{\Sigma}$	$\beta_{M1} = 1.6 \mp 1.2_{\text{stat/mod}} \pm 0.4_{\Sigma}$

EFTs vs. DRs

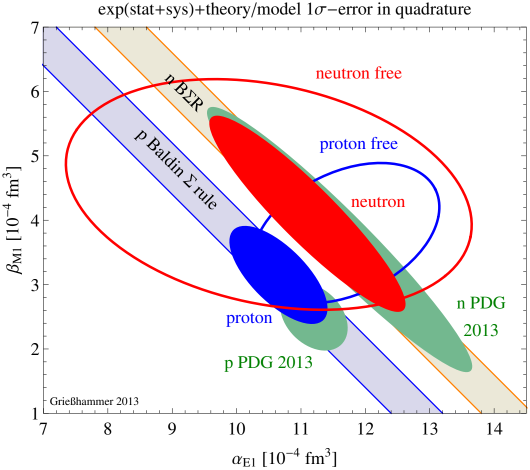


- Old PDG based on DRs
- HBChPT
  Beane et al., NPA **747** (2005)
- BChPT with Δ
  Lensky & Pascalutsa, EPJC **65** (2010)
- Partially Covariant BChPT with Δ
  McGovern et al., EPJA **49**, 12 (2013)

Systematic effect with EFTs consistently higher than DRs!?

New PDG Result and Reanalysis – Proton and Neutron

McGovern, Phillips, Grießhammer, EPJA **49**, 12 (2013)



Situation for both the Proton and (especially) the Neutron could be improved. . .

Re-analysis – Proton Values

Particle Data Group updated their values in 2013:

	2012	Current
α_{E1}	12.0 ± 0.6	11.2 ± 0.4
β_{M1}	1.9 ∓ 0.5	2.5 ∓ 0.4

in units of $10^{-4}\,\mathrm{fm}^3$.

Re-analysis was done *without* any new experimental data!

Need more precise experimental data, and some new observables. . .

Scalar Polarizabilities – Direct Measurement

Linearly Polarized Beam

Different dxs combinations are dependent only on α_{E1} or β_{M1}:

$$\frac{d\sigma^{\perp} - d\sigma^{\parallel}}{d\Omega} = f_1(\mathrm{Born}) - \frac{e^2}{2m}\left(\frac{\nu'}{\nu}\right)^2 \nu\nu'\alpha_{E1}(1 - z^2) + O(\nu^3)$$

$$\frac{z^2 d\sigma^{\perp} - d\sigma^{\parallel}}{d\Omega} = f_2(\mathrm{Born}) - \frac{e^2}{2m}\left(\frac{\nu'}{\nu}\right)^2 \nu\nu'\beta_{M1}z(z^2 - 1) + O(\nu^3)$$

Recent work by Krupina and Pascalutsa [PRL **110**, 262001 (2013)]

At low energies $\Rightarrow$ use beam asymmetry Σ_3 to extract β_{M1}:

$$\Sigma_3 \equiv \frac{d\sigma^{\perp} - d\sigma^{\parallel}}{d\sigma^{\perp} + d\sigma^{\parallel}} = \Sigma_3^{\mathrm{NB}} - f_3(\theta)\beta_{M1}\nu^2 + \mathcal{O}(\nu^4).$$

Spin Polarizabilities of the Proton

- Nucleon has 4 spin or vector polarizabilities:

$$\gamma_{E1E1} \qquad \gamma_{M1M1} \qquad \gamma_{M1E2} \qquad \gamma_{E1M2}$$

- Similar to scalar polarizabilities (α_{E1} and β_{M1}), but higher in order.
- Intimately connected to the nucleon's spin structure. **Fundamental structure constants!**
- Higher order in incident-photon energy, small effect at lower energies.
- Need theoretical help in extracting values.

Predicted Values

	K-mat.	HDPV	DPV	L_χ	HBχPT	BχPT
γ_{E1E1}	-4.8	-4.3	-3.8	-3.7	-1.1 ± 1.8 (th)	-3.3
γ_{M1M1}	3.5	2.9	2.9	2.5	2.2 ± 0.5 (st) ± 0.7 (th)	3.0
γ_{E1M2}	-1.8	-0.02	0.5	1.2	-0.4 ± 0.4 (th)	0.2
γ_{M1E2}	1.1	2.2	1.6	1.2	1.9 ± 0.4 (th)	1.1
γ_0	2.0	-0.8	-1.1	-1.2	-2.6	-1.0
γ_π	11.2	9.4	7.8	6.1	5.6	7.2

- Spin polarizabilities in units of 10^{-4} fm^4
- K-matrix: calculation from Kondratyuk et al., PRC **64**, 024005 (2001)
- HDPV, DPV: dispersion relation calculations, Holstein et al., PRC **61**, 034316 (2000) and Pasquini et al., PRC **76**, 015203 (2007), Drechsel et al., PR **378**, 99 (2003)
- L_χ: chiral lagrangian calculation, Gasparyan et al., NPA **866**, 79 (2011)
- HBχPT and BχPT are heavy baryon and covariant, respectively, ChPT calculations, McGovern et al., EPJA **49**, 12 (2013), Lensky et al., PRC **89**, 032202 (2014)

NO EXPERIMENTAL DATA on the individual spin pols apart from contraints in the form of linear combinations γ_0 and γ_π.

Sensitivity to Spin Polarizabilities

#	asymmetry	polarization		E_γ range	spin
		beam	target	(MeV)	polarizability
1	$\mathbf{\Sigma_{2z}}$	circular	longitudinal	200–300	**both**
2	$\mathbf{\Sigma_{2x}}$		transverse	200–300	$\boldsymbol{\gamma_{E1E1}}$
3	$\mathbf{\Sigma_{3}}$	linear	none	200-300	$\boldsymbol{\gamma_{M1M1}}$
4	Σ_{3y}		transverse	200-300	γ_{E1E1}
5	Σ_{1z}		longitudinal	200–300	both
6	Σ_{1x}		transverse	150–250	both

Analysis based on Pasquini et al., PRC **76** 015203 (2007).

Spin Polarizability Extraction

Use known values of γ_0, γ_π, α_{E1}, and β_{M1} along with the three asymmetries.

The various asymmetries respond differently to the individual spin polarizabilities at different energies and angles.

We will conduct an in-depth global analysis, and should be able to extract **all four spin polarizabilities independently** with small statistical, systematic, and model-dependent errors!

Proton RCS Experimental Status – A2 Mainz

Experiment	**Status**	
$\boldsymbol{\Sigma_{2x}}$	February 2011	$\surd$
$\boldsymbol{\Sigma_{3}}$	December 2012	$\surd$
$\boldsymbol{\Sigma_{2z}}$	2014/2015	$\surd$
α_{E1}, β_{M1}	June 2013, 2017/2018	$\surd$

NOTE: Complementary measurements planned for HIGS at the Duke FEL facility!

High-flux, monoenergetic beam, with $\approx$ 100% polarization.

Experimental Set-Up for $\Sigma_{2x}/\Sigma_{2z}/\Sigma_3$ and α_{E1}, β_{M1}

Standard A2 Equipment is required:

- MAMI electrons
- Glasgow-Mainz Tagger
- CB-TAPS detector system
- Cryogenic Targets

Run Parameter	$\boldsymbol{\Sigma_{2x}/\Sigma_{2z}}$	$\boldsymbol{\Sigma_3}$ and $\boldsymbol{\alpha_{E1}, \beta_{M1}}$
Electron Beam Energy	450 MeV	883 MeV
Target	butanol	LH_2
Radiator	Copper	Diamond
Tagged Energy Range	100 – 400 MeV	100 – 400 MeV
Channel Energy Resolution	1 MeV	2 MeV
Beam Polarization	circular	linear
Target Polarization	transverse/longitudinal	none

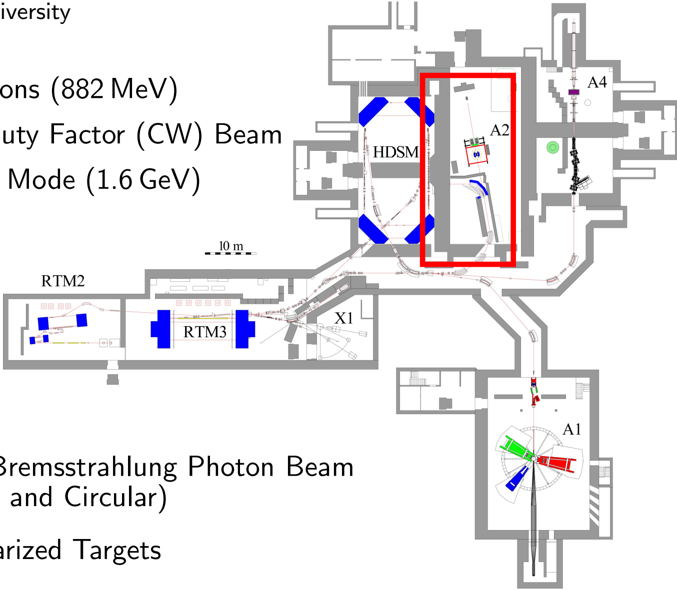
The Mainzer Mikrotron (MAMI)

Johannes Gutenberg University
Mainz, Germany

3 Race-Track Microtrons (882 MeV)

High-Quality 100% Duty Factor (CW) Beam

HDSM in Production Mode (1.6 GeV)

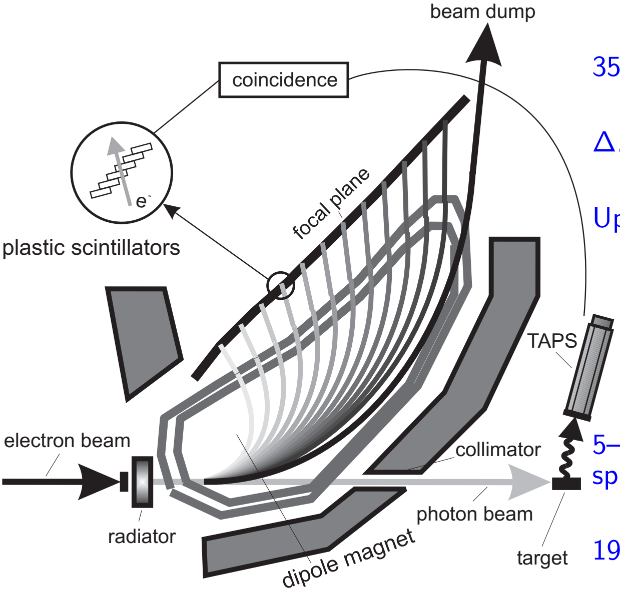


A2 Collaboration:

High-Flux, Tagged, Bremsstrahlung Photon Beam
(Unpolarized, Linear, and Circular)

Polarized and Unpolarized Targets

Incident Photon Beam – Glasgow-Mainz Photon Tagger



352 channels

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

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

Refurbished to work at 1.6 GeV

5–94% of Bremsstrahlung spectrum

191-channel microscope

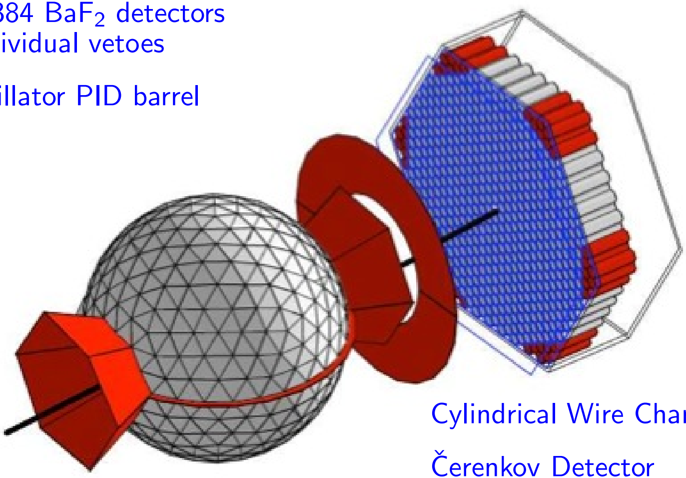
Detector System: CB-TAPS

GEANT4 View

CB: 672 NaI detectors

TAPS: 384 BaF_2 detectors
with individual vetoes

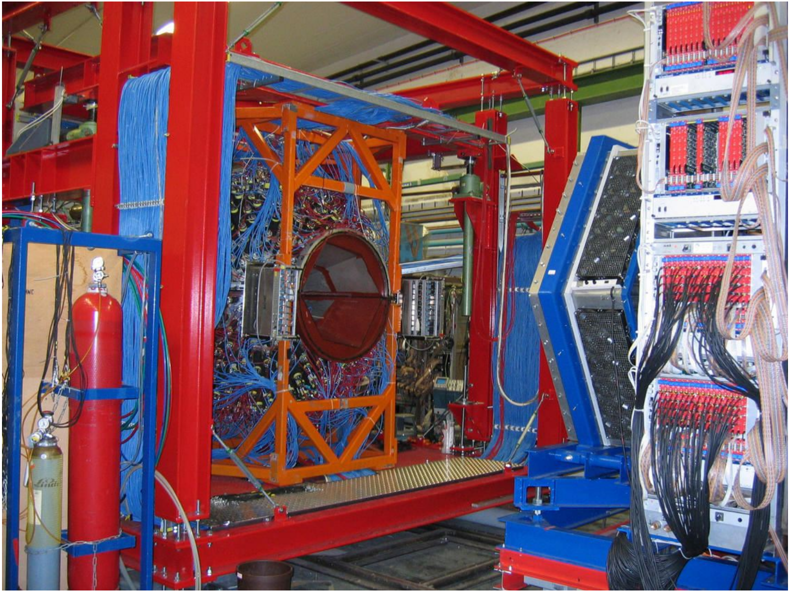
24-scintillator PID barrel



Cylindrical Wire Chamber

Čerenkov Detector

Detector System: CB-TAPS

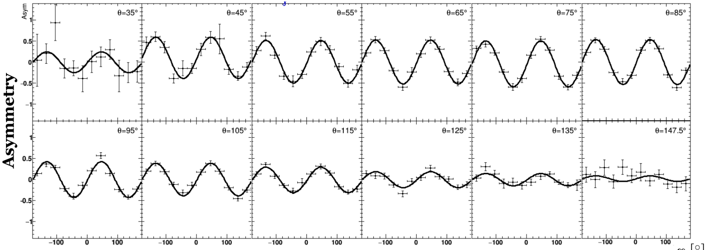


Full Measurement of $\vec{\gamma} p \to \gamma p$

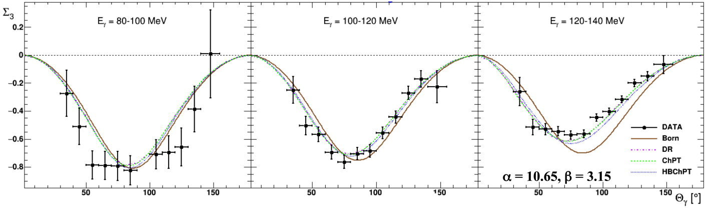
- **Ph.D. work of Edoardo Mornacchi**.
- Data taken in 2017/2018. Similar set up to pilot measurement done in 2013 [Sokhoyan et al., EPJA **53**, 14 (2017)].
- Low-energy Compton scattering.
- Linearly polarized beam, (unpolarized) LH_2 target.
- High-statistics cross sections, $d\sigma/d\Omega$, and beam asymmetry, Σ_3. Most important data are below pion threshold.
- **Upgraded tagger, improved systematic errors:**
  - higher γ-flux with better flux monitoring
  - improved linpol peak stability
  - improved background subtraction
- 1.2×10^6 events, an improvement of $\times 6$ compared to the pilot measurement.
- Approximately $\times 10$ the statistics of the previous world best measurement with TAPS (also A2!) [OdL et al., EPJA **10** 207 (2001)], which make up of about 50% of the existing world data.

Full Measurement of $\vec{\gamma} p \to \gamma p$ – $\mathbf{\Sigma_3}$

$E_\gamma = 120 - 140$ MeV

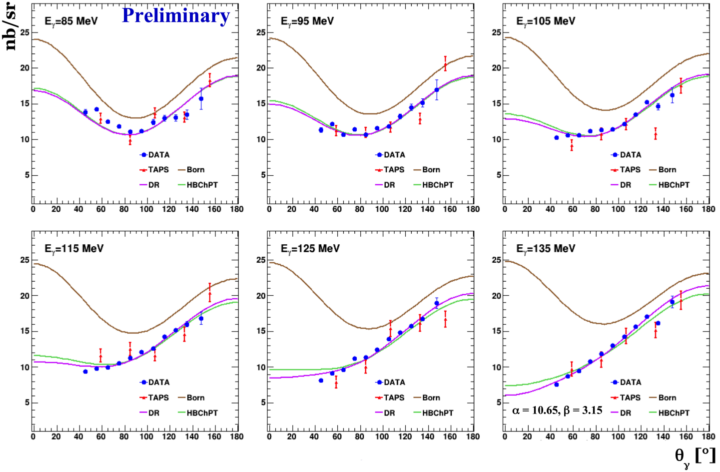


Preliminary



Mornacchi Ph.D.

Full Measurement of $\vec{\gamma} p \to \gamma p$ – $d\sigma / d\Omega$



Mornacchi Ph.D.

Full Measurement of $\vec{\gamma} p \to \gamma p$ – Errors

Fits to both Σ_3 and $d\sigma/d\Omega$!

Preliminary systematic errors included: 3% on the unpolarized cross-section and 5% on the beam asymmetry.

Baldin SR	Yes		No	
γ_π	Fix	Fit	Fix	Fit
α_{E1}	± 0.47	± 0.60	± 0.75	± 0.84
β_{M1}	± 0.29	± 0.46	± 0.31	± 0.48
$\alpha_{E1} + \beta_{M1}$	± 0.32	± 0.32	± 0.59	± 0.59
γ_π	8.00	± 1.29	8.00	± 1.26
χ^2/DOF	1.18	1.15	1.14	1.10

Fits are done by P. Martel, using HDPV code from B. Pasquini

Central values are on their way...

Mornacchi Ph.D.

α_{E1}, β_{M1} Outlook

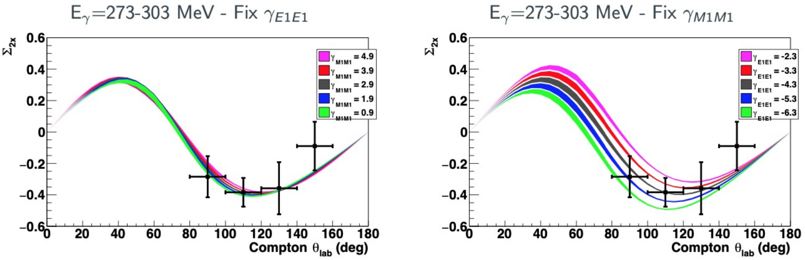
- Finalize data analysis.
- Use a simultaneous fit to unpolarized cross sections and beam asymmetry to achieve precision on β_{M1} **comparable to the current PDG value**, ± 0.4!

Asymmetries in $\Delta(1232)$ Region – Experimental Challenges

Especially for the frozen-spin target, there are many challenges:

- Small Compton scattering cross sections.
- Large backgrounds:
  - π^0 photoproduction cross section is about 100 times that of Compton scattering.
  - Coherent and incoherent reactions off of C, O, and He.
- A source of polarized protons is not easy to come by (or to operate).
- In Δ-region, proton tracks are required to suppress backgrounds, but energy losses in the LH_2 target, frozen-spin cryostat, and CB-TAPS are considerable.

$\boldsymbol{\Sigma_{2x}}$ Results – Martel et al., PRL **114**, 112501 (2015).

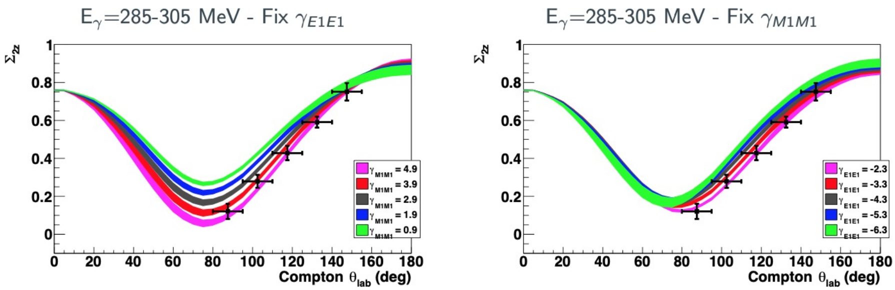


Fix one ($\gamma_{\mathrm{E1E1/M1M1}}$), vary other. Band from γ_0, γ_π, α_{E1}, and β_{M1} errors.

- First measurement of a double-polarized Compton scattering asymmetry on the nucleon, Σ_{2x}.
- Curves are from DR calculation of Pasquini et al.
- Data have sensitivity to the γ_{E1E1} spin-polarizability, with a preliminary estimate of

$$\boxed{\gamma_{E1E1} = (-4.5 \pm 1.5) \times 10^{-4}\ \mathrm{fm}^4}$$

Σ_{2z} Results

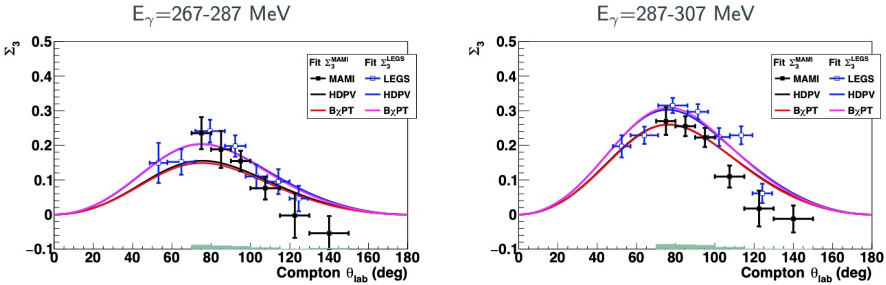


Fix one ($\gamma_{\mathrm{E1E1/M1M1}}$), vary other. Band from γ_0, γ_π, α_{E1}, and β_{M1} errors.

- PhD work of D. Paudyal (Regina).
- There were some issues with ice and target polarization, but we finally solved them.
- D. Paudyal et al. (A2), arXiv:1909.02032 (2019)
- "Preliminary" acceptance to PRC Rapid Communication.

Σ_3 Results

PhD work of C. Collicott



- Recent data (MAMI) and older data (LEGS) are shown along with Dispersion Relation (HDPV) and ChPT (BχPT) predictions.
- Fits have been done.
- Draft in preparation.

Spin Polarizability Fitting Results

	Σ_3^{MAMI}		Σ_3^{LEGS}	
	HDPV	BχPT	HDPV	BχPT
γ_{E1E1}	-3.99 ± 0.66	-3.53 ± 0.58	-3.18 ± 0.52	-2.65 ± 0.43
γ_{M1M1}	3.33 ± 0.45	2.71 ± 0.46	2.98 ± 0.43	2.43 ± 0.42
γ_{E1M2}	0.70 ± 0.82	0.19 ± 0.90	-0.44 ± 0.67	-1.32 ± 0.72
γ_{M1E2}	0.89 ± 0.49	1.56 ± 0.51	1.58 ± 0.43	2.47 ± 0.42
γ_0	-0.93 ± 0.11	-0.93 ± 0.11	-0.93 ± 0.11	-0.94 ± 0.11
γ_π	7.51 ± 1.62	7.61 ± 1.68	8.17 ± 1.60	8.86 ± 1.57
$\chi 2$/DOF	1.11	1.79	1.14	1.36

- Includes all three asymmetries in the $\Delta(1232)$-region: Σ_{2x}, Σ_{2z}, and Σ_3.
- Fitting done with our Σ_3 and the older LEGS data.
- Values for **ALL** spin pols, with relatively small errors!

The "Other" Nucleon – The Neutron

Situation is considerably worse than for the proton:

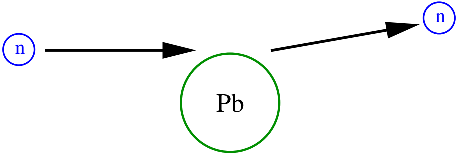
- No free neutron target.
- Neutron is uncharged.
- Small data set!

Techniques:

- Low-energy neutron scattering.
- Elastic Compton scattering from deuterium.
- QF Compton scattering from deuterium.
- Compton scattering from heavier nuclei.

Nuclear Effects are NOT negligible!

Low-Energy Neutron Scattering



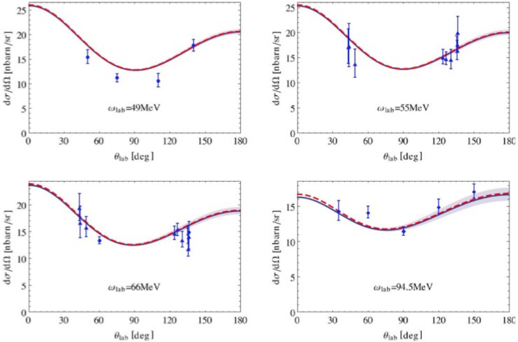
Scatter neutrons in the Coulomb field of a heavy nucleus, i.e. Pb.

For $k < 100\,\text{keV} \Rightarrow \sigma_s(k) = \sigma_s(0) + ak + bk^2 + \mathcal{O}(k^4)$
where a depends **ONLY** on α^n_{E1}.

Results:

Data	α_{E1} $(10^{-4}\,\text{fm}^3)$
Schmiedmayer et al.	$12.0 \pm 1.5 \pm 2.0$
Koester et al.	0 ± 5
Enik et al. reanalysis	$7 - 19$

Unsatisfactory situation.



Interference between proton and neutron increases sensitivity.

Higher cross section.

Nuclear effects are much bigger than one might naively expect!

Amount of data pretty sparse compared to the proton. . .

Estimates of scalar polarizabilities from an NLO analysis of Grießhammer et al.:

$$\alpha^n_{E1} = 11.1 \pm 1.8_{\text{stat}} \pm 0.4_{\Sigma} \pm 0.8_{\text{th}} \qquad \beta^n_{M1} = 4.1 \mp 1.8_{\text{stat}} \pm 0.4_{\Sigma} \pm 0.8_{\text{th}}$$

Big error bars! $\Rightarrow$ Planned measurements at HIGS at 65 MeV and 100 MeV.

QF Compton from Neutron in Deuterium

$d(\gamma, \gamma' n)p$

In certain kinematic regions, proton acts like a spectator and scattering is done primarily from the neutron.

Model dependence and nuclear effects should be minimized, but higher energies mean more model dependence.

Measurements at both Saskatoon and Mainz.

Analysis of M. Schumacher, PPNP **55**, 567 (2005), using theory of Levchuk & L'vov, NPA **674**, 449 (2000):

$$\alpha^n_{E1} = 12.5 \pm 1.8_{\text{stat}} \pm 1.1_{\text{mod}} \qquad \beta^n_{M1} = 2.7 \mp 1.8_{\text{stat}} \pm 1.1_{\text{mod}}$$

Suggested results from same using weighted average of Coulomb, Elastic, and QF:

$$\alpha^n_{E1} = 12.5 \pm 1.7 \qquad \beta^n_{M1} = 2.7 \mp 1.8$$

Error on β^n_{M1} still very large!

Doubts exist about theory...

ChPT for ^{3}He$(\gamma, \gamma)^3$He

Relatively new idea for extraction of scalar polarizabilities for the neutron.

Shukla, Nogga, and Phillips, NPA **819**, 98 (2009).

Theory is promising, but still needs some work to extend it to higher energies. . .

Proposal A2-01-2013 using a high-pressure active helium target (both ^{3}He and ^{4}He).

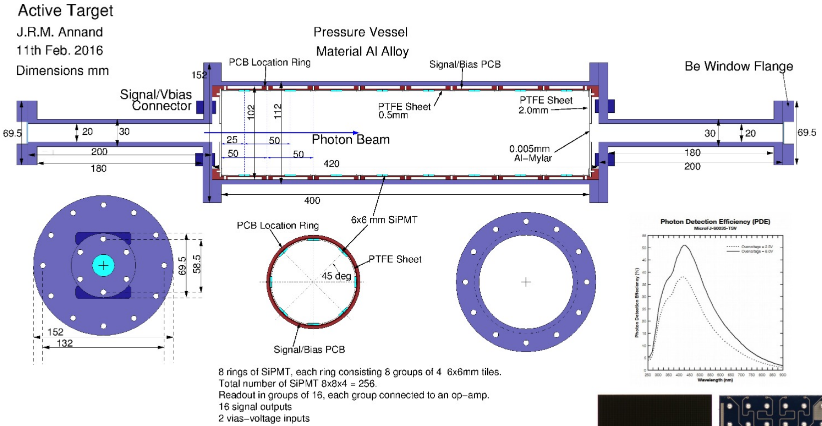
Given a rating of A by the PAC!

Will hopefully run in the next year.

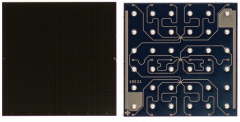
High-pressure, Active He Target

University of Glasgow

The New Active Target

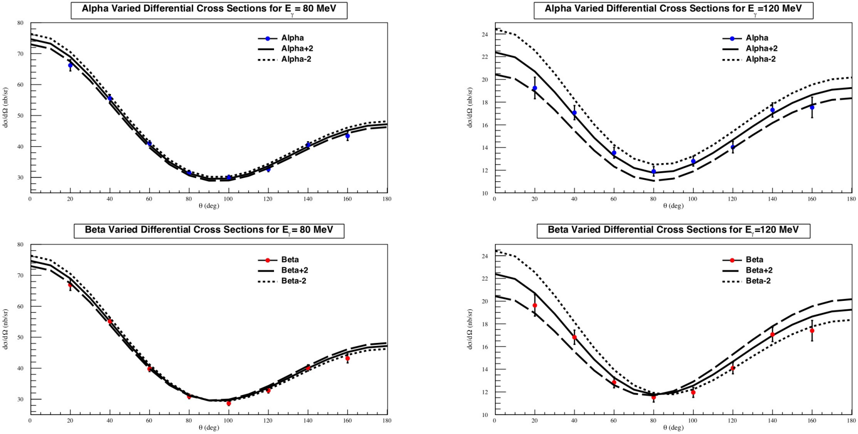


- Al pressure vessel, no welds
- Reuse Be outer windows from original Active Target
- PTFE sheet covers printed circuit board, windows cut for SiPMT



6 x 6mm J-Series SiPMT

Work done by MTA honours student Meg Morris.

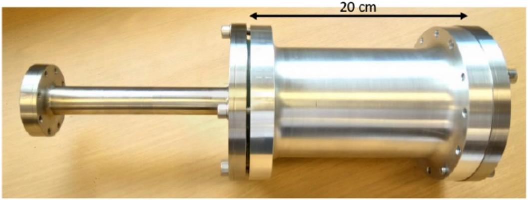


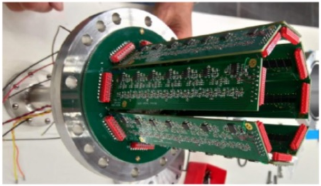
$E_\gamma = 80\,\mathrm{MeV}$ $E_\gamma = 120\,\mathrm{MeV}$

$\delta\alpha_{E1}^{n} \approx \delta\beta_{M1}^{n} \approx 1.0 \times 10^{-4}\ \mathrm{fm}^3$ compared to $1.8 \times 10^{-4}\ \mathrm{fm}^3$!

High-pressure, Active He Target

Prototype has been built and is undergoing testing.





Readout is proving to be a bit tricky.

Matching the scintillation light from the gas to the Si PMs has been challenging...

Work done by MTA honours student Michael Perry.

Polarizabilities – Outlook and Plans

1. Publish high-energy $\boldsymbol{\Sigma_3}$ results with global fits of the spin polarizabilities.
2. Finish analysis for $\boldsymbol{\alpha_{E1}, \beta_{M1}}$.
3. Complementary measurements at HIGS on the proton, deuteron, and helium.
4. An active polarized target is being developed, and we plan to use it for improved measurements of the asymmetries.
5. An active, high-pressure helium target for approved neutron polarizability (and threshold pion) experiments at MAMI.
6. JLab Hall-D LOI was submitted to PAC 47 last June. Proposal to use the Primakoff effect and the Glue-X detector to extract $\alpha_\pi - \beta_\pi$ for the neutral pion to a precision of 10%.

Polarizabilities

1. Important tool for *testing* QCD via ChPT & DRs in the non-perturbative regime.
2. Both theory and experiment are very active at the moment.
3. We can expect lots of new results in the near future.

Special thanks to Edoardo Mornacchi, Philippe Martel, and Vahe Sokhoyan for slides and input.

BACKUP SLIDES

What can we do about subatomic particles?

We obviously can't put a proton between the plates of a capacitor or the poles of a magnet and measure its deformation. What to do?

One answer is, of course, **Compton scattering!**

What kind of fields can we get from high-energy photons?

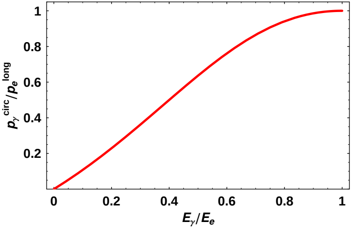
Naively, for a 100-MeV photon:

$$\begin{aligned} E &= \frac{V}{d} \\ &\approx \frac{100\,\mathrm{MV}}{10^{-15}\,\mathrm{m}} \\ &\approx 10^{23}\,\mathrm{V/m} \end{aligned}$$

A HUGE field!

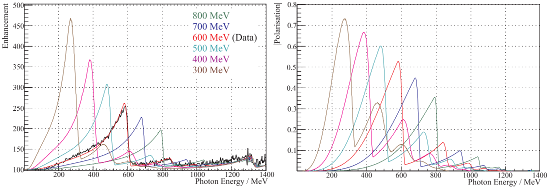
Polarized Photons

Circular Polarization



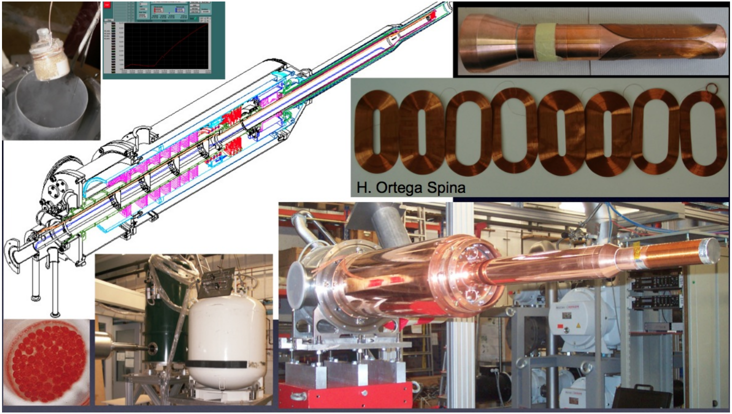
- Helicity transfer of polarization from electron to bremsstrahlung photon.
- Maximized for *photon energies close to the electron beam energy.*

Linear Polarization



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

Polarized Target



Dynamical Nucleon Polarization

Target material is butanol, $C_4H_{10}O$

Dilution cryostat with bath of liquid $^3He/^4He$, $T < 30\,\mathrm{mK}$

$P_p \approx 90\%$ with a relaxation time of $\tau > 1000$ hours.

Asymmetries – Babusci et al., PRC **58** 1013 (1998)

1. Beam: circular
   Target: longitudinal

$$\Sigma_{2z} = \frac{\sigma^R_{+z} - \sigma^L_{+z}}{\sigma^R_{+z} + \sigma^L_{+z}} = \frac{\sigma^R_{+z} - \sigma^R_{-z}}{\sigma^R_{+z} + \sigma^R_{-z}}$$

2. Beam: circular
   Target: transverse

$$\Sigma_{2x} = \frac{\sigma^R_{+x} - \sigma^L_{+x}}{\sigma^R_{+x} + \sigma^L_{+x}} = \frac{\sigma^R_{+x} - \sigma^R_{-x}}{\sigma^R_{+x} + \sigma^R_{-x}}$$

3. Beam: linear, $\parallel$ and $\perp$ to scattering plane
   Target: unpolarized

$$\Sigma_3 = \frac{\sigma^{\parallel} - \sigma^{\perp}}{\sigma^{\parallel} + \sigma^{\perp}}$$