Neutron Polarizabilities

MAMI PAC 2020 - Proposal A2-02

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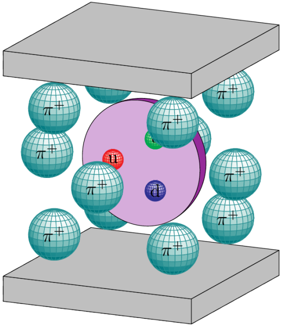
Nucleon Polarizabilities



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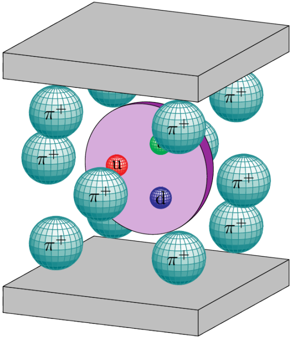

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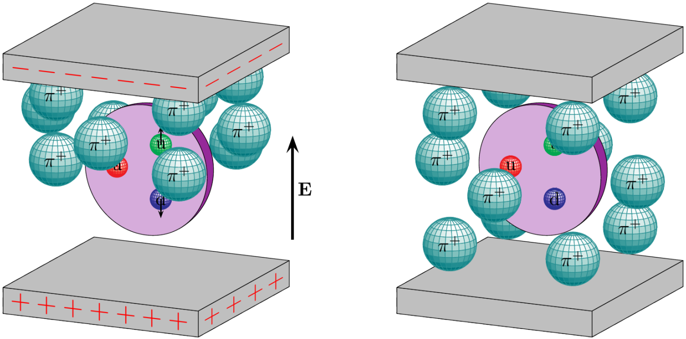
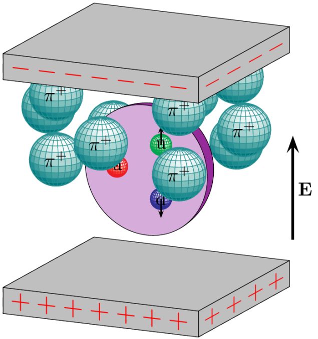
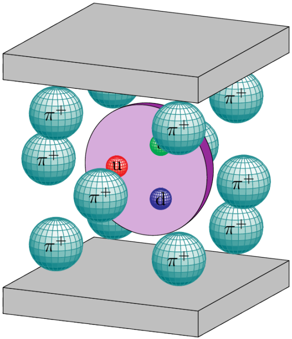
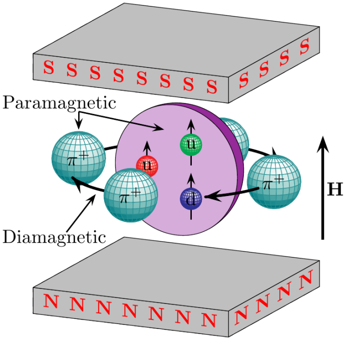


Electric polarizability α_{E1}



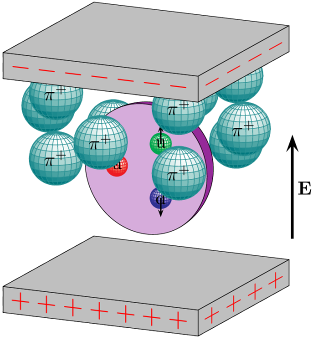




Electric polarizability α_{E1}

Magnetic polarizability β_{M1}

Nucleon Polarizabilities



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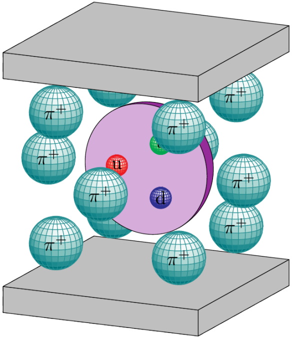
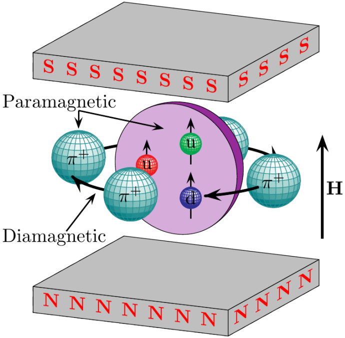


Compton Scattering!



Magnetic polarizability β_{M1}

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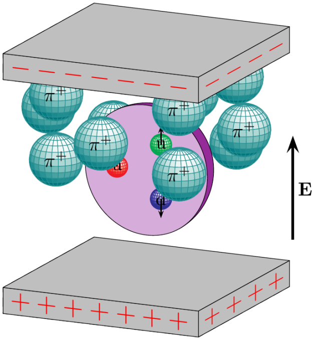

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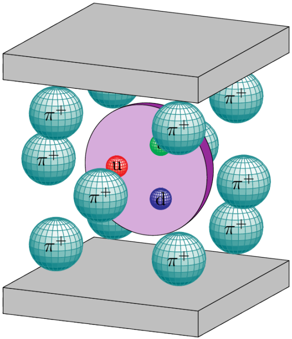

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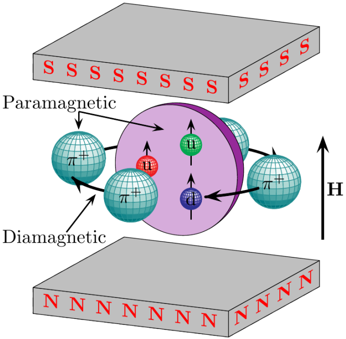

Magnetic polarizability β_{M1}

- In addition to scalar ↑, also have spin polarizabilities → γ_{E1E1}, γ_{M1M1}, γ_{E1M2}, γ_{M1E2}
- Scalar polarizabilities uncertain, spin polarizabilities unknown

Present Status

Proton

- Scalar polarizabilities: 1000 hours on two observables ($d\sigma/d\Omega$ and Σ_3)
  - Unprecedented precision from single experiment
- Spin polarizabilities: 1250 hours on three observables (Σ_{2x}, Σ_{2z}, and Σ_3)
  - Analyses finished: Σ_{2x} published, Σ_{2z} submitted, Σ_3 being written
  - First extraction of the individual spin polarizabilities from data

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Neutron

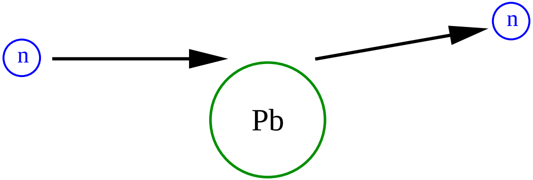
- Even less well known than the proton polarizabilities
  - No free neutron target
  - Neutron is uncharged
  - Small existing data set

Low-Energy Neutron Scattering: $n + X \rightarrow n + X$

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

For $k < 100$ keV

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



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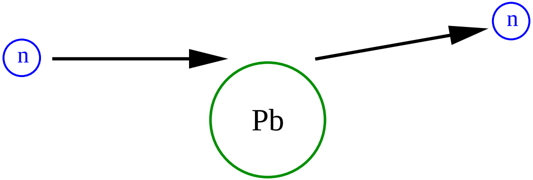

Data	α_{E1} $(10^{-4}\mathrm{fm}^3)$
Schmiedmayer et al.	$12.0 \pm 1.5 \pm 2.0$
Koester et al.	0 ± 5
Enik et al. reanalysis	$7 - 19$

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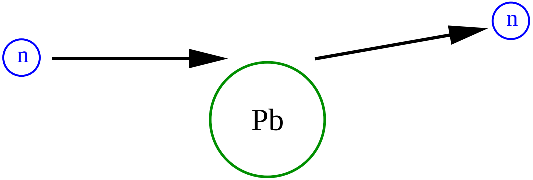

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Unsatisfactory situation

No info. on magnetic polarizability

Quasi-free Compton Scattering from Deuterium: $\gamma + d \rightarrow \gamma + n + p$

A2

- In certain kinematic regions, proton $\rightarrow$ spectator and neutron $\rightarrow$ scatterer
- Model dependence and nuclear effects should be minimized (at least at lower energies)
- Measurements at both Saskatoon and Mainz.

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

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

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Still three times larger than those of the proton! But what are these Elastic results?

Elastic Compton Scattering from Deuterium: $\gamma + d \to \gamma + d$

- Interference between proton and neutron increases sensitivity.
- Higher cross section.
- Nuclear effects are much bigger than one might naively expect!

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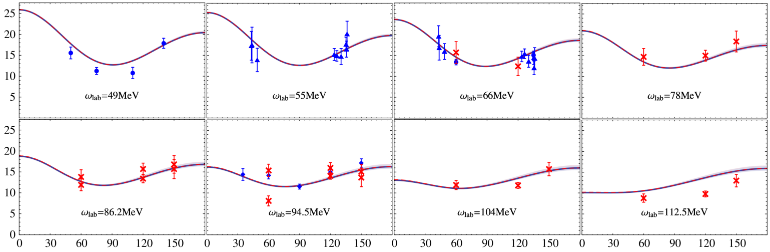

Myers et al. PRL **113**, 262506 (2014)

Still sparse compared to proton data

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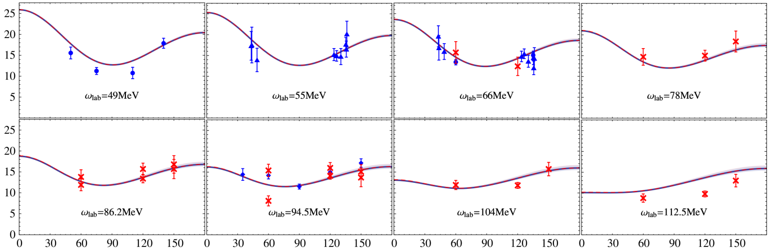

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Still sparse compared to proton data

$$\alpha^n_{E1} = 11.55 \pm 1.25_{\text{stat}} \pm 0.2_{\Sigma} \pm 0.8_{\text{th}} \qquad \beta^n_{M1} = 3.65 \mp 1.25_{\text{stat}} \pm 0.2_{\Sigma} \mp 0.8_{\text{th}}$$

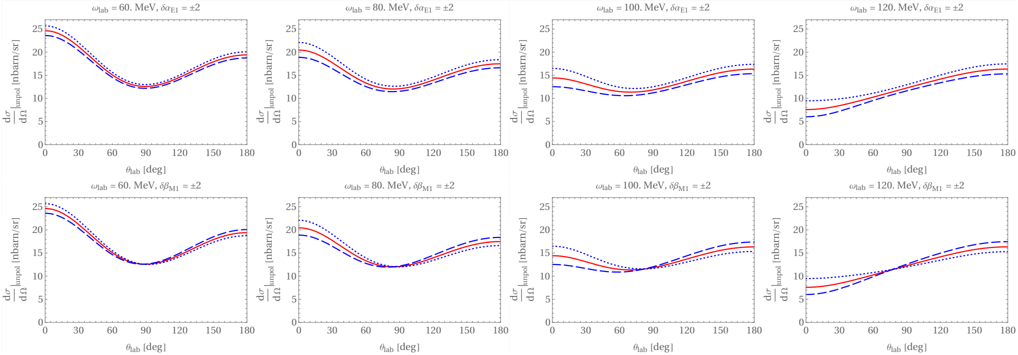
Driver of current PDG numbers. Room for improvement!

Elastic Compton Scattering from Deuterium: $\gamma + d \to \gamma + d$

- Grießhammer, McGovern, Phillips, Feldman, PPNP **67**, 841 (2012)
- Sensitive to iso-scalar polarizabilities $[\alpha_{E1} = (\alpha^p_{E1} + \alpha^n_{E1})/2]$

α_{E1}

β_{M1}



60 MeV **80 MeV** **100 MeV** **120 MeV**

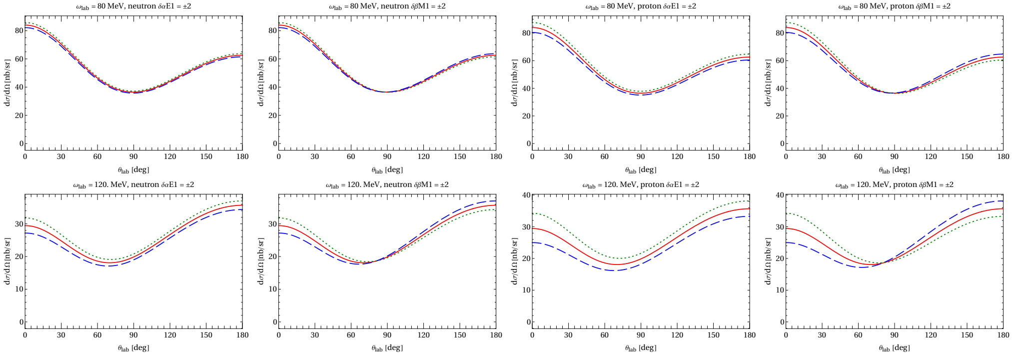
Use knowledge of α^p_{E1} and β^p_{E1} to extract neutron polarizabilities

Elastic Compton Scattering from Helium: $\gamma + {}^3\mathrm{He} \to \gamma + {}^3\mathrm{He}$

- Margaryan, Strandberg, Grießhammer, McGovern, Phillips, Shukla, EPJA **54**, 125 (2018)
- Sensitive to both proton and neutron polarizabilities

80 MeV

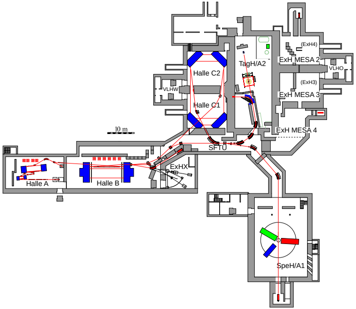
120 MeV



α^n_{E1} β^n_{M1} α^p_{E1} β^p_{M1}

Efforts to extend to ^{4}He are underway

Compton at MAMI



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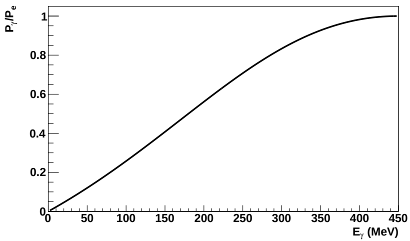

$$P_\gamma = P_e \frac{4E_\gamma E_e - E_\gamma^2}{4E_e^2 - 4E_\gamma E_e + 3E_\gamma^2}$$

- $P_e \approx 80\%$
- Helicity flipped every second

Polarized Photon Beam

A high energy electron can produce Bremsstrahlung ('braking radiation') photons when slowed down by a material.

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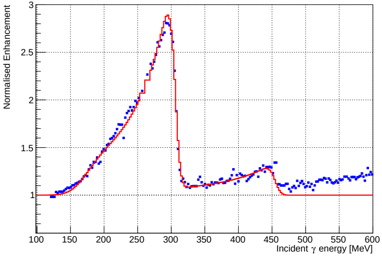
- Diamond radiator produces linearly polarized photons (coherent Bremsstrahlung).



- Coherent edge is tunable
- Polarization plane can be flipped (usually every hour)

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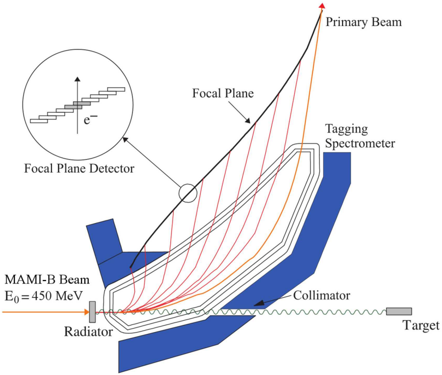
- Residual electron paths bent in a spectrometer magnet.



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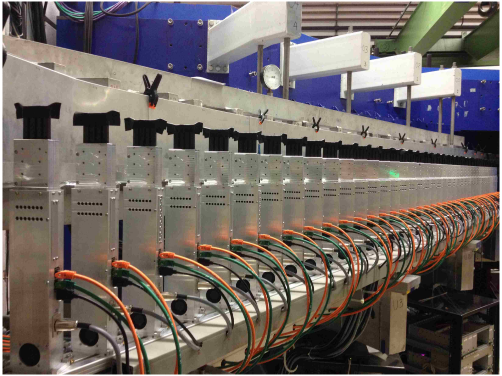
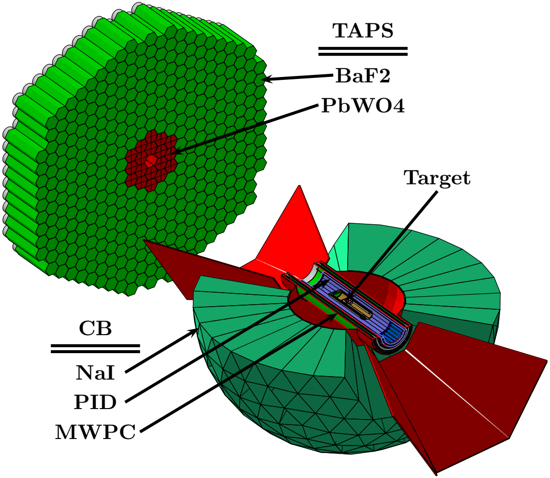
- Residual electron paths bent in a spectrometer magnet.
- Detector array determines the e^- energy, and 'tags' the photon energy by energy conservation.



Target and Detectors



Liquid Deuterium (Helium) Target

- 10 (5) cm long
- 4.92 (0.95) $\times 10^{23}$ nuclei/cm^2

Crystal Ball (CB)

- 672 NaI Crystals
- 24 Particle Identification Detector (PID) Paddles
- 2 Multiwire Proportional Chambers (MWPCs)

Two Arms Photon Spectrometer (TAPS)

- 366 BaF_2 and 72 $PbWO_4$ Crystals
- 384 Veto Paddles

Background Reactions

$\gamma + d \rightarrow \gamma + d$

- $\gamma + p + n$ (quasi-free)
- $p + n$ (breakup)

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Min $\Delta E_B = 2.2$ MeV

- Unresolvable
- Need theory help
  - Provide Elastic plus Quasi-free
  - Already in progress for HIγS data

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$\gamma + {}^3\mathrm{He} \rightarrow \gamma + {}^3\mathrm{He}$

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Min $\Delta E_B = 4.5$ MeV

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- Need active He target
  - Recoiling energy
  - Event vertex?
  - Track with TPC?

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$\gamma + {}^4\mathrm{He} \to \gamma + {}^4\mathrm{He}$

- $\gamma + n + {}^3\mathrm{He}$ (quasi-free)
- $\gamma + p + t$ (quasi-free)
- $n + {}^3\mathrm{He}$ (breakup)
- $p + t$ (breakup)
- $p + n + d$ (breakup)
- $p + p + n + n$ (breakup)
- $d + d$ (breakup)

Background Reactions

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- $n + {}^3\mathrm{He}$ (breakup)
- $p + t$ (breakup)
- $p + n + d$ (breakup)
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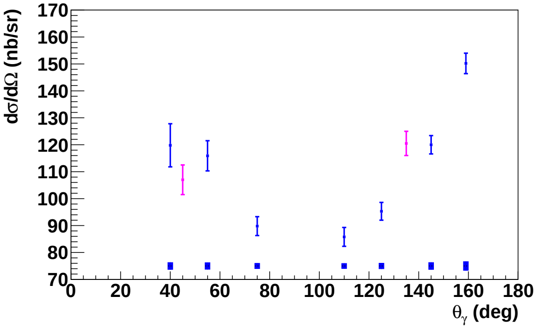
- $d + d$ (breakup)

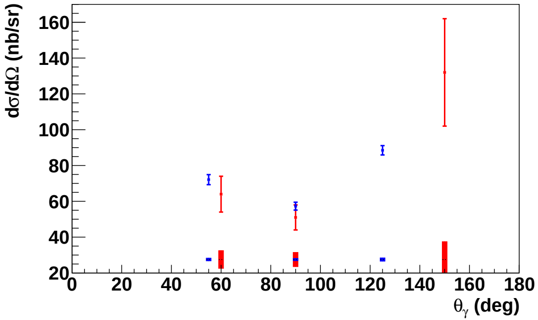
Min $\Delta E_B = 20$ MeV

- Resolvable!

Previous ^{4}He Data



60 MeV



80 MeV

- Magenta points from Illinois [Wells Ph.D. Thesis (1990) unpublished]
- Red points from Lund [Fuhrberg NuclPhysA.591.1 (1995)]
- Blue points from HIγS [Sikora PhysRevC.96.055209 (2017), Li arXiv.1912.06915 (2019)]

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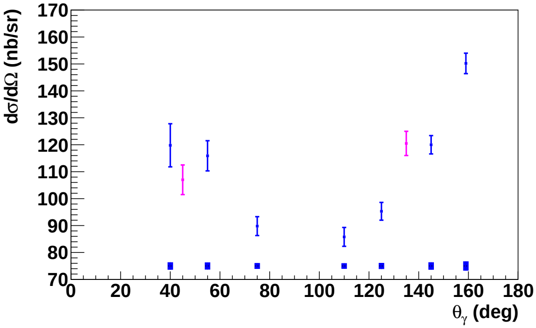

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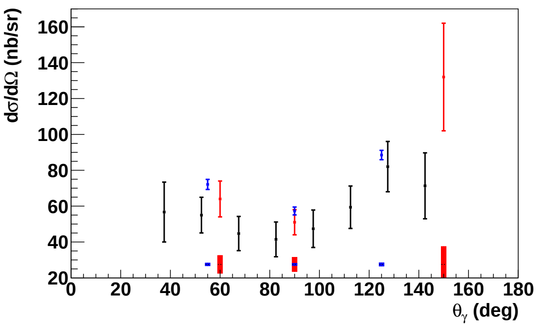

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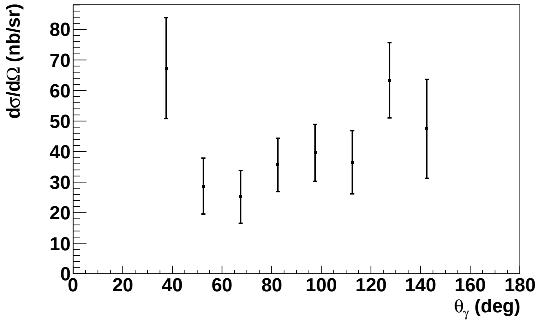
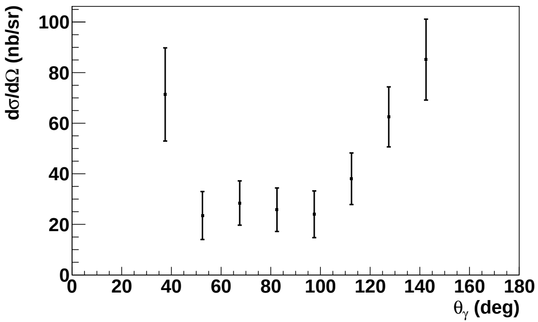
Newer ^{4}He Data



100 MeV



120 MeV

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- Still clear room for improvement (higher ϵ_{tagg}, longer run)

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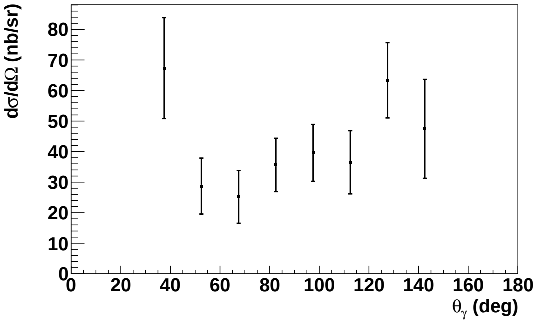
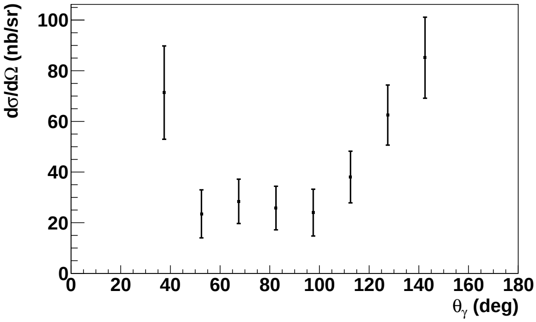


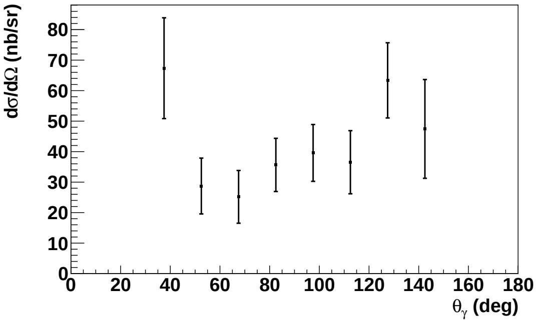
100 MeV



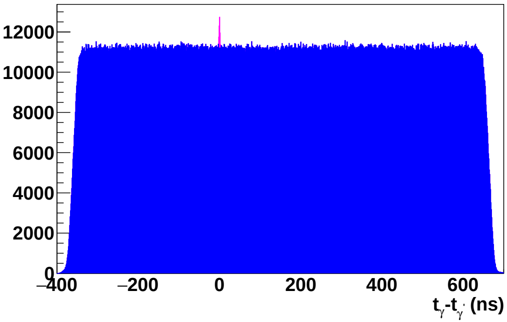
120 MeV

- Black points are preliminary data (statistical) from MAMI (100 hours)
- Still clear room for improvement (higher ϵ_{tagg}, longer run)
- Errors are larger than $\sqrt{N}$ ...

Newer ^{4}He Data



100 MeV



120 MeV

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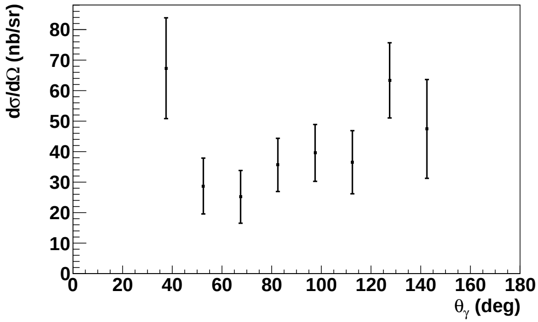
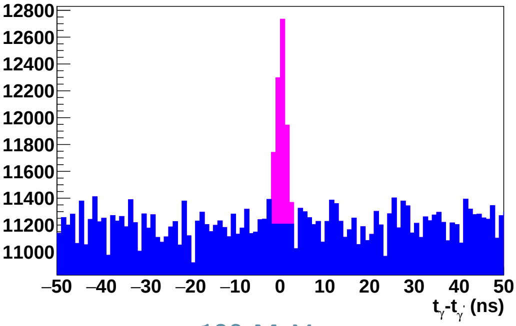
- Still clear room for improvement (higher ϵ_{tagg}, longer run)
- Errors are larger than $\sqrt{N}$ . . . Prompt correlations (P) to random coincidences (R)



100 MeV



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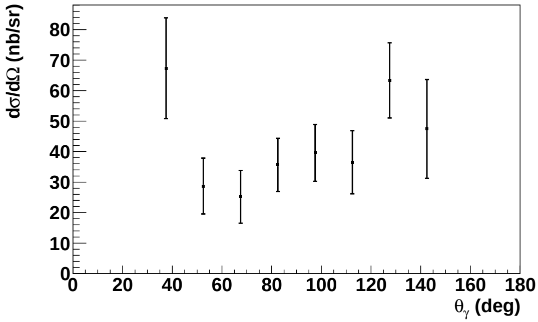
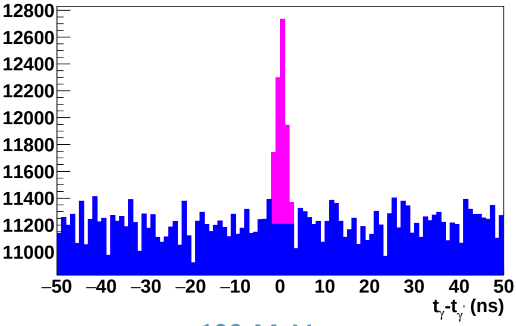


100 MeV



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- Still clear room for improvement (higher ϵ_{tagg}, longer run)
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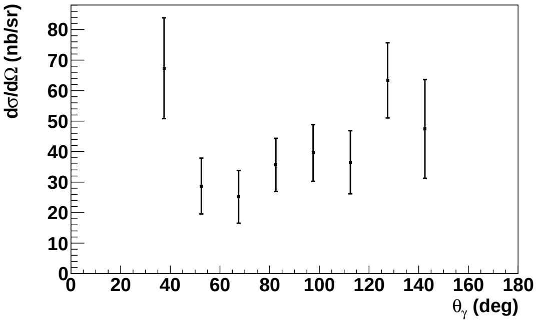
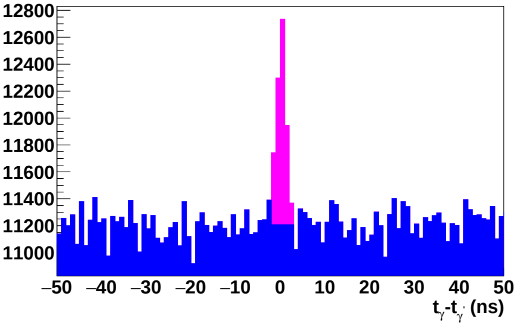
- $\sigma/\sigma_P = \sqrt{1 + R/P} \overset{120\text{MeV}}{=} \sqrt{1 + 13.8} = 3.85!$

Newer ^{4}He Data



100 MeV



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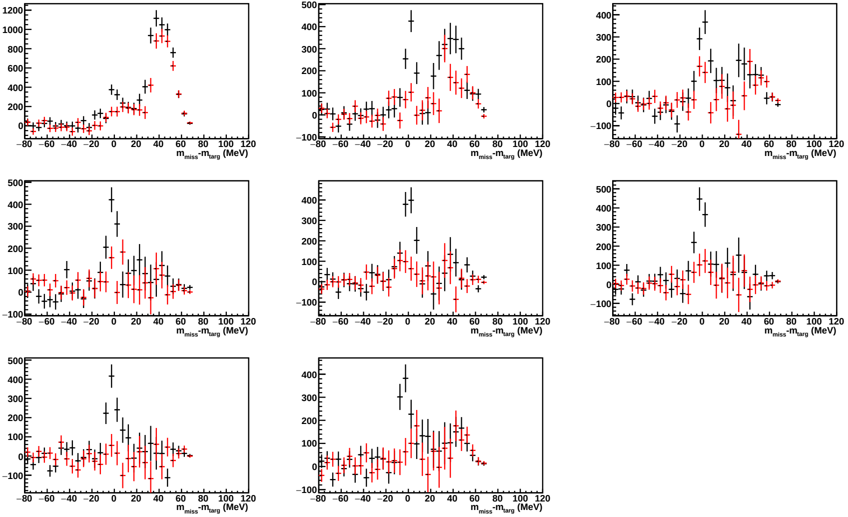
- $\sigma/\sigma_P = \sqrt{1 + R/P} \overset{120\mathrm{MeV}}{=} \sqrt{1 + 13.8} = 3.85!$ Plus background!

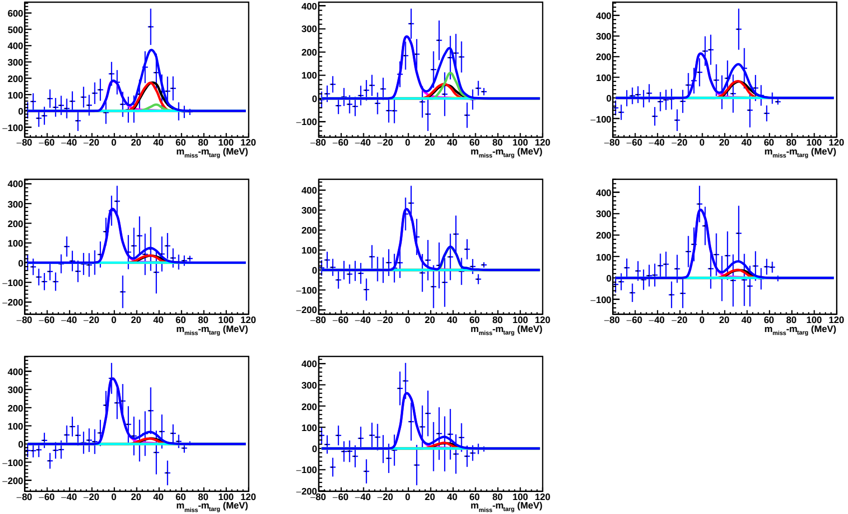
MAMI ^{4}He Data vs Simulation

- 80 MeV
- Full Target
- Empty Target



MAMI ^{4}He Data vs Simulation

- 80 MeV
- Total MC
- $\gamma + {}^4\mathrm{He}$
- $\gamma + n + {}^3\mathrm{He}$
- $\gamma + p + t$
- $n + {}^3\mathrm{He}$



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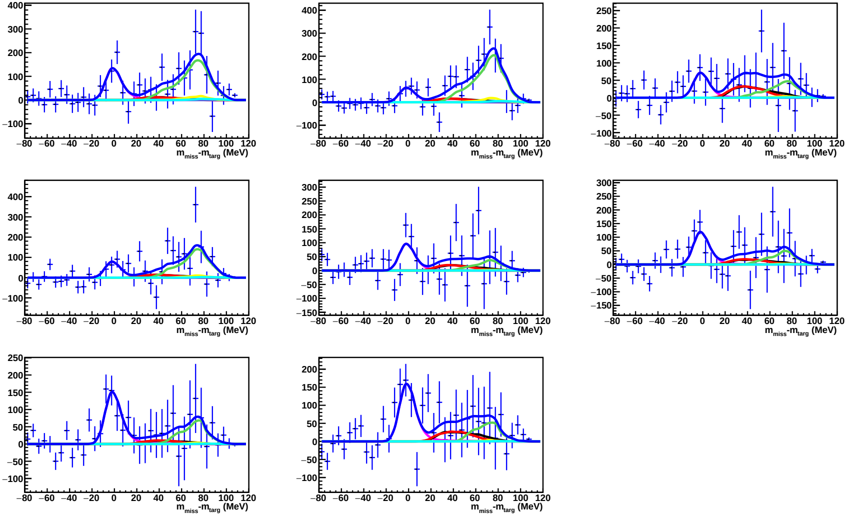
- $\gamma + p + t$
- $n + {}^3\mathrm{He}$
- $p + t$
- $p + n + d$
- $p + p + n + n$



Next Steps

Optimize Run Conditions

- E_e from 450 to 883 MeV: ϵ_{tagg} from 0.08 to 0.26

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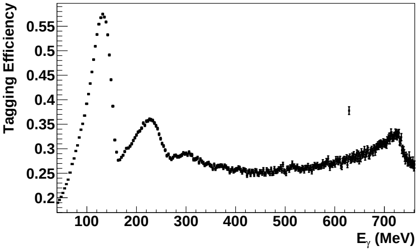

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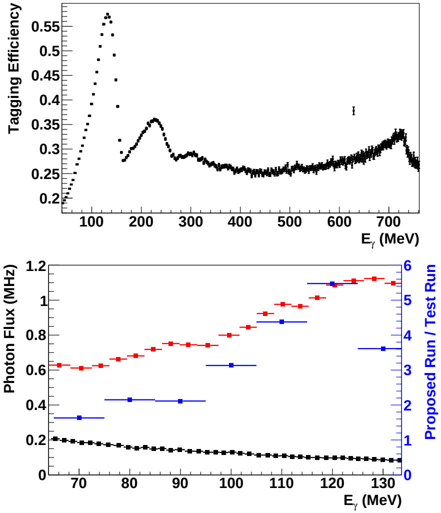
- Photon flux increase (similar energy bins) 1.6–5.5



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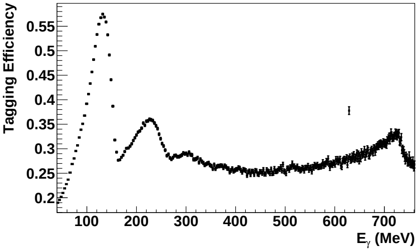

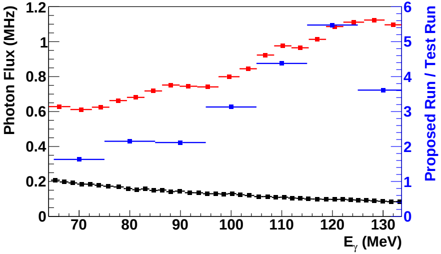

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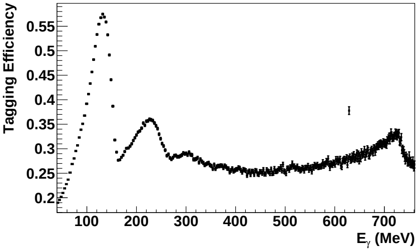
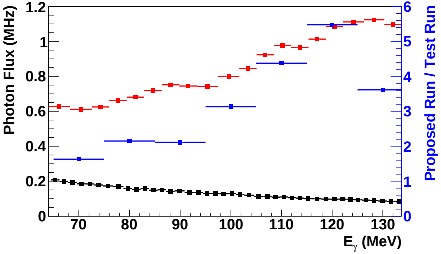
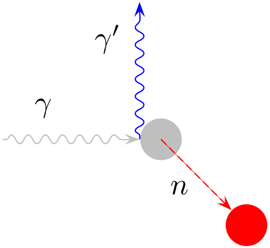


Experiments

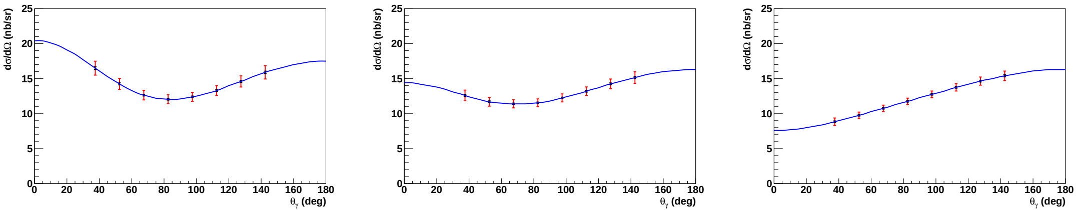
- ^{2}H - 200 hours with liquid target (+150 hours)
- ^{4}He - 300 hours with liquid target (+350 hours)



Proposed Experiments



Projected Deuterium Results (200 h Full + 150 h Empty/Misc)

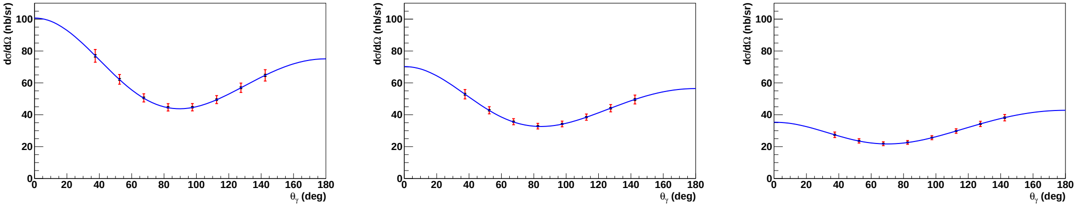


Sample data for $\theta_\gamma = 82.5 \pm 7.5^\circ$ $(\Omega = 1.626$ sr$)$:

E_γ (MeV)	$d\sigma/d\Omega$ (nb/sr)	F_γ (MHz)	R/P	ϵ_{det}	N	σ/N (%)	σ'/N (%)
80	12.05	2.06	16.1	0.85	12127	0.91	5.31
100	11.55	2.39	15.5	0.90	14215	0.84	4.82
120	11.75	3.21	13.8	0.89	19223	0.72	3.92

Expected relative statistical errors 3.8–6.1% (perhaps lower with better prompt/random ratio)

Projected Helium Results (300 h Full + 350 h Empty/Misc)



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E_γ (MeV)	$d\sigma/d\Omega$ (nb/sr)	F_γ (MHz)	R/P	$\epsilon_{\rm det}$	N	σ/N (%)	σ'/N (%)
80	44.67	2.06	16.1	0.85	13014	0.88	5.13
100	32.86	2.39	15.5	0.90	11707	0.92	5.31
120	22.67	3.21	13.8	0.89	10734	0.97	5.25

Expected relative statistical errors 4.7–6.3% (perhaps lower with better prompt/random ratio)

Proposal

Deuterium (200 h Full + 150 h Empty/Misc)

- Expected relative statistical errors 3.8–6.1%

Helium (300 h Full + 350 h Empty/Misc)

- Expected relative statistical errors 4.7–6.3%

Task	^{2}H (h)	^{4}He (h)
Setup	10	10
Tagg. Eff.	40	80
Full Target	200	300
Empty Target	100	260
Subtotal	**350**	**650**
Total	**1000**	

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- Greatly expand ($E_\gamma \geq 90$ MeV) the ^{4}He database $\rightarrow$ both proton and neutron polarizabilities
- Future ^{3}He: needs active target/TPC to identify elastic (or theory support to add quasi-free)

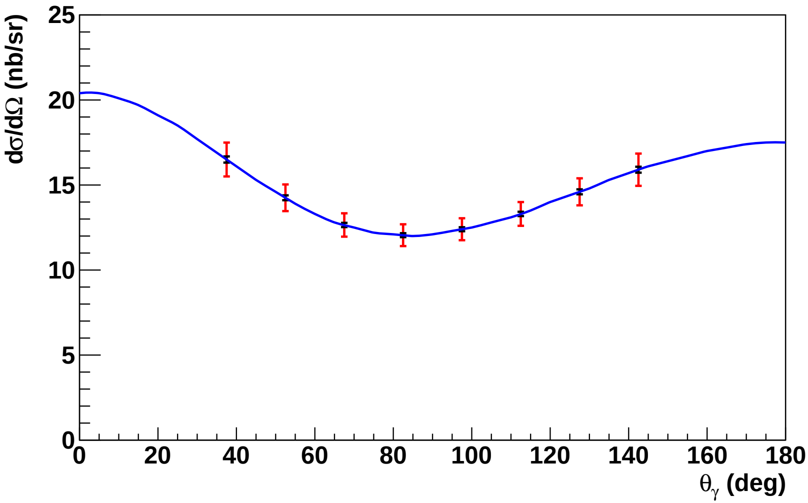
Sensitivities

Target	Polarizability	80 MeV	100 MeV	120 MeV
Deuterium	α_{E1}	2.3–3.5	2.7–5.4	2.7–6.5
	β_{E1}	0.0–3.5	0.0–5.4	0.0–6.5
Helium	α^p_{E1}	1.7–2.1	2.5–3.8	3.4–7.4
	β^p_{E1}	0.0–2.1	0.0–3.8	0.0–7.4
	α^n_{E1}	0.9–1.1	1.4–1.9	1.9–3.6
	β^n_{E1}	0.0–1.1	0.0–1.9	0.0–3.6

Projected Deuterium Results

$\gamma + d \rightarrow \gamma + d$

- 80 MeV



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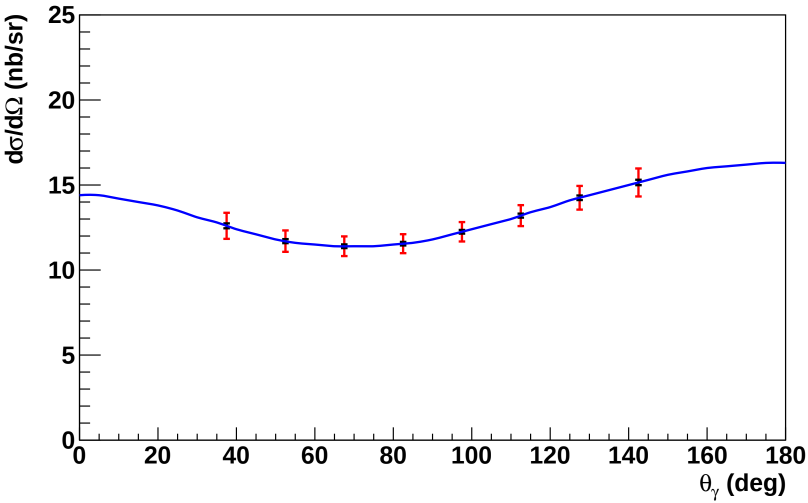

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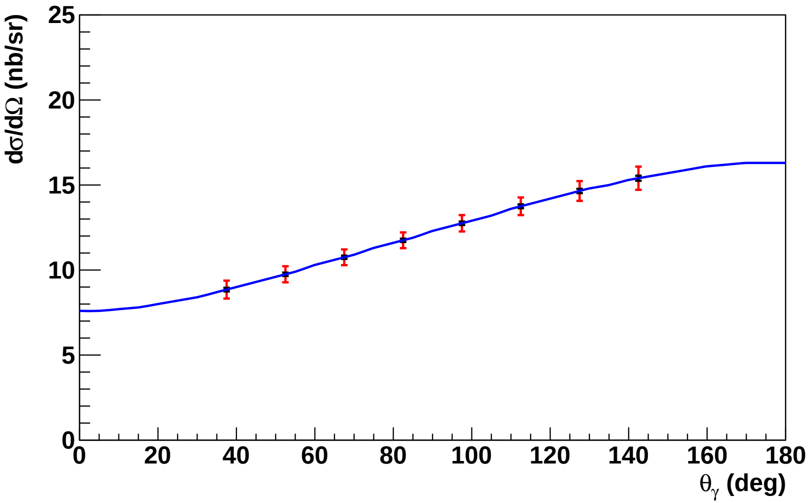
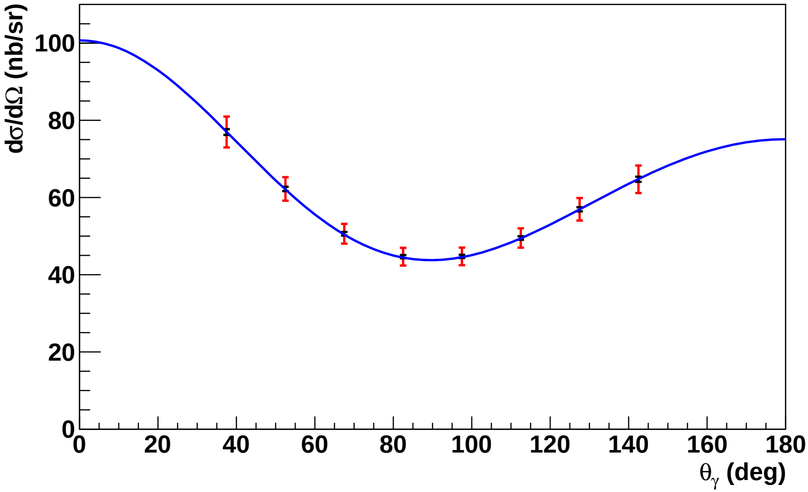


Projected Helium Results

$\gamma + {}^4\mathrm{He} \to \gamma + {}^4\mathrm{He}$

- 80 MeV



Projected Helium Results

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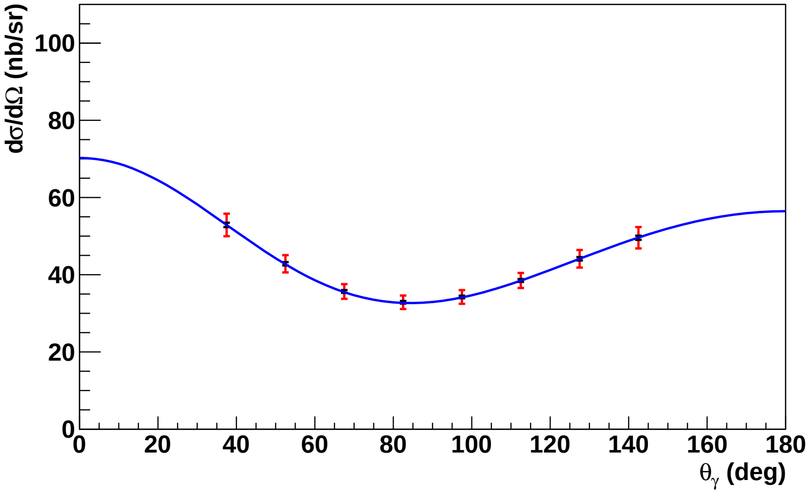
- 100 MeV



Projected Helium Results

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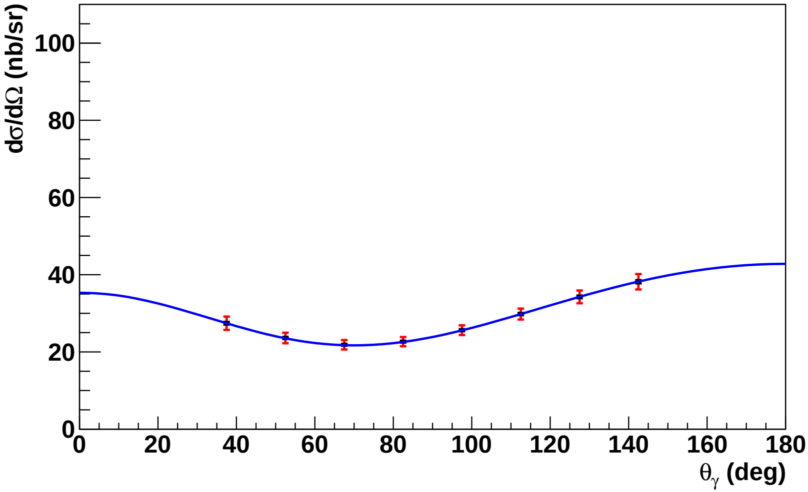
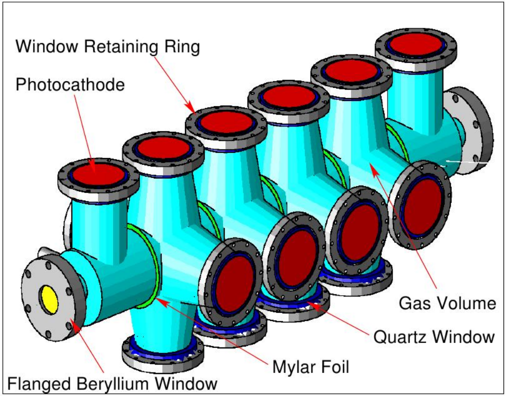
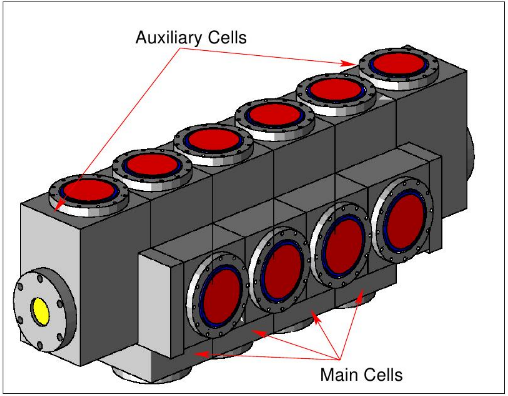
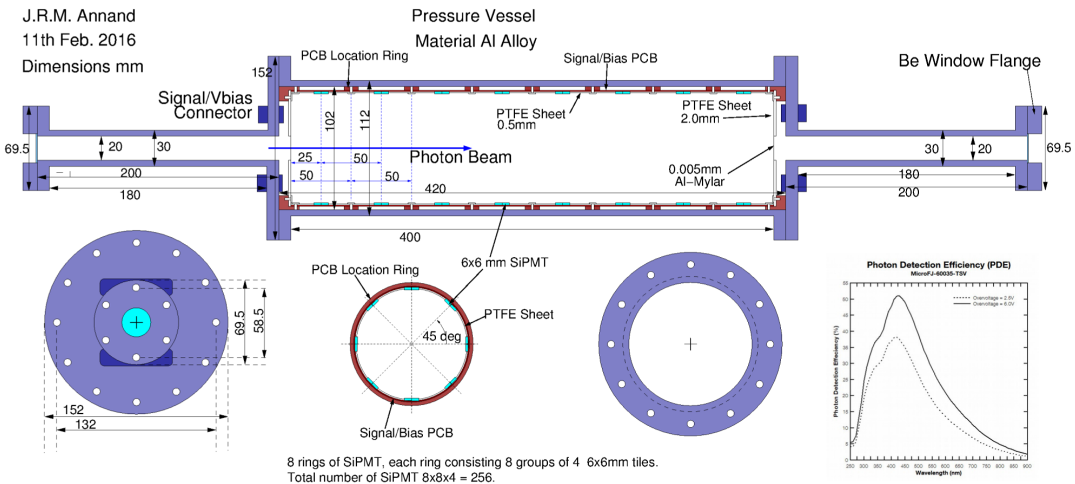


Original Active Target



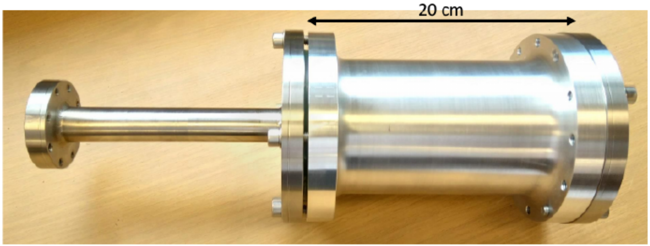


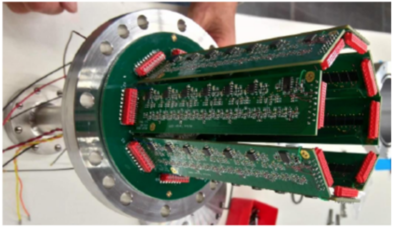
- Concerns over safety for the pressures planned
- Difficult to fit into the Crystal Ball



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

Active Target Prototype





Initial Tests

- Half length with barrel of detachable circuit boards with SiPMs
- Tests with a source proved the concept
- Suffers from low light collection

Improving Light Output

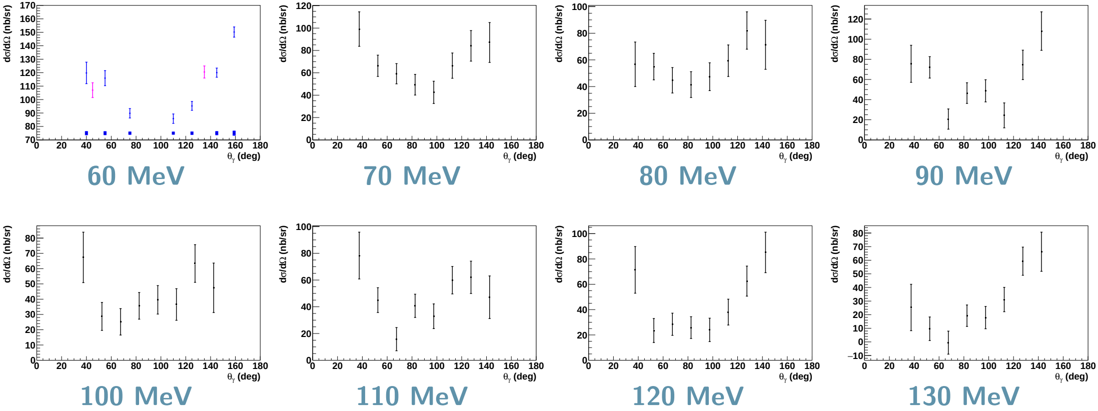
Where did we go wrong?

- Original concept had 18 PMTs covering a large solid angle (signal > noise)
- Current design covers much less solid angle with SiPMs (signal < noise)

Where do we go from here?

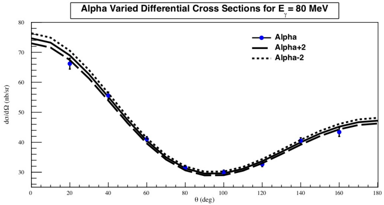
- Larger detectors, 2) more detectors/coincidence, 3) different wavelength shifter (WLS)
- Tetraphenyl-Butadiene (TPB): WLS from VUV (thanks M. Perry)
- Tests with microscope slides coated with TPB doped polystyrene
- Can purchase fibers from St. Gobain (BCF-12-ish) for about $4000, but do we:
  - Wrap thin fibers helically (possibly get vertex reconstruction)
  - Wrap wide fibers longitudinally (possibly better light collection, and easier)

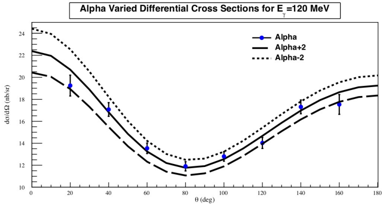
Current ^{4}He Data

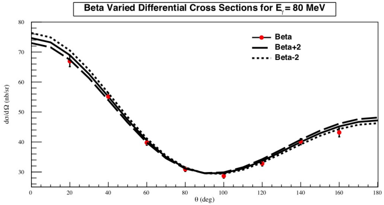


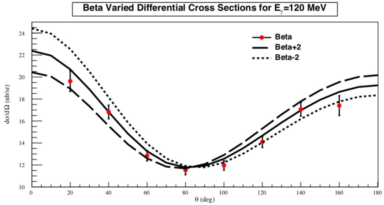
- Obviously preliminary: some points seem off, need to carefully examine
- Clearly also room for improvement

Rate Estimates and Sensitivity - M. Morris and M. Wentland (MTA)







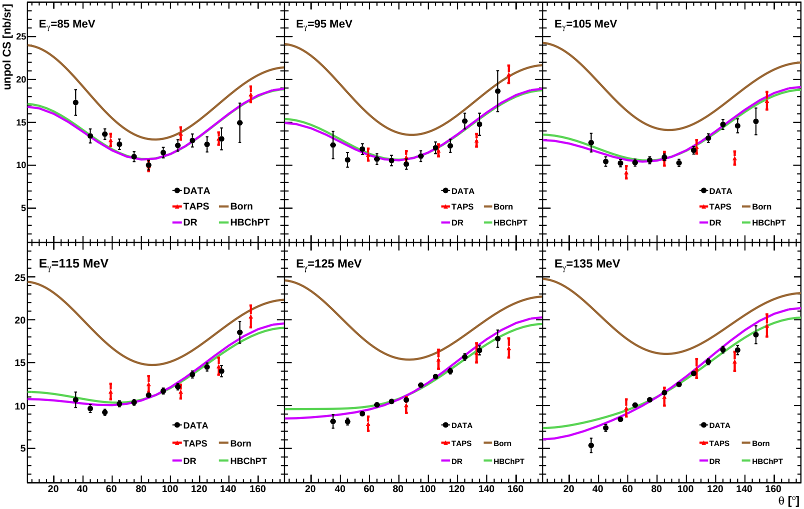


$E_\gamma = 80$ MeV

$E_\gamma = 120$ MeV

$\delta\alpha^n_{E1} \approx \delta\beta^n_{M1} \approx 0.7 \times 10^{-4}\,\mathrm{fm}^3$ compared to $1.15 \times 10^{-4}\,\mathrm{fm}^3$!

Unpolarized Cross Section - $d\sigma/d\Omega$ - Preliminary

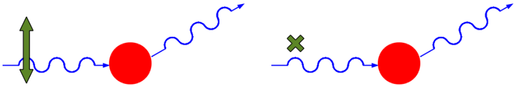


Work by E. Mornacchi (Ph.D. student in A2)

- Nov 2017
- Feb 2018
- Mar 2018
- Jul 2018

Big improvement over previous data

$$\Sigma_3 = \frac{N_{\parallel} - N_{\perp}}{N_{\parallel} + N_{\perp}}$$



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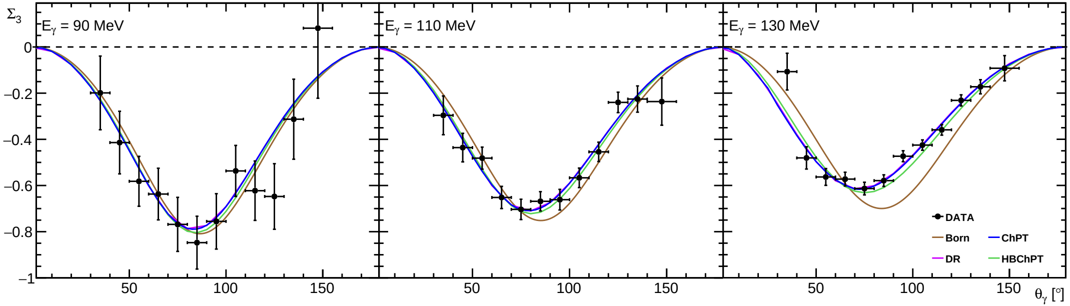


Much higher statistics than June 2013 run, EPJA 53, 14 (2017)

Scalar Polarizability Fitting - Preliminary

Fit low-energy $d\sigma/d\Omega$ and Σ_3 data, with and without Baldin Sum Rule constraint, as well as with and without fixing γ_π, using HDPV calculation:

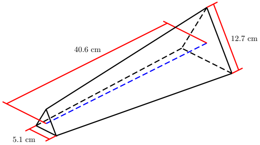
Baldin SR	Yes		No	
γ_π	Fix	Fit	Fix	Fit
α_{E1}	12.66 ± 0.47	13.40 ± 0.60	14.01 ± 0.75	14.82 ± 0.84
β_{M1}	1.68 ± 0.29	0.97 ± 0.46	1.46 ± 0.31	0.70 ± 0.48
$\alpha_{\mathrm{E1}} + \beta_{\mathrm{M1}}$	14.38 ± 0.32	14.36 ± 0.32	15.47 ± 0.59	15.52 ± 0.59
γ_π	8.00	10.66 ± 1.29	8.00	10.73 ± 1.26
S_Σ	0.96	0.94	0.95	0.92
S_σ	0.94	0.94	0.91	0.91
χ^2/DOF	1.18	1.15	1.14	1.10

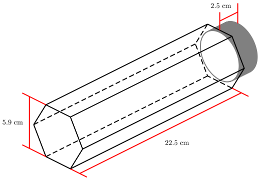
Spin Polarizability Fitting - Preliminary

Fit either newer Σ_3^{MAMI} data or older Σ_3^{LEGS} data, using either HDPV or BχPT calculations:

	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
χ^2/DOF	1.11	1.79	1.14	1.36

Neutral vs Charged Particle Detection

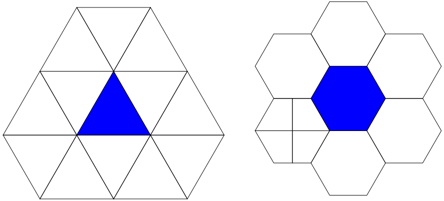




NaI/BaF_2/$PbWO_4$ Crystal Scintillators

- Produce light from charged particles
- Large crystals → full energy deposition

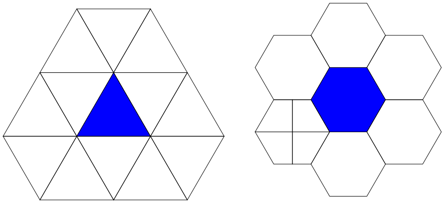
Neutral vs Charged Particle Detection



$NaI/BaF_2/PbWO_4$ Crystal Scintillators

- Produce light from charged particles
- Large crystals $\rightarrow$ full energy deposition
- Electromagnetic showers ($\gamma \rightarrow e^+e^-$)
  Many crystals
- Hadronic showers (lose E bumping around)
  Few crystals

Neutral vs Charged Particle Detection



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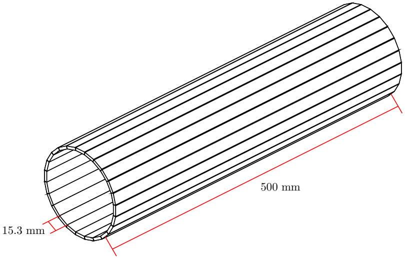
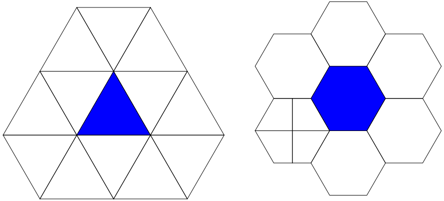


Particle Identification Detector (PID)

- Barrel of 24 plastic paddles
- Each covers $15 < \theta < 159^\circ$, and 15° in ϕ

Neutral vs Charged Particle Detection



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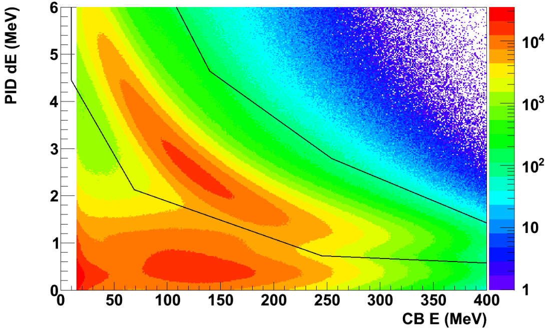
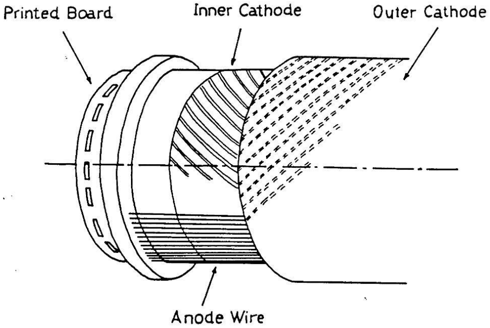


Particle Identification Detector (PID)

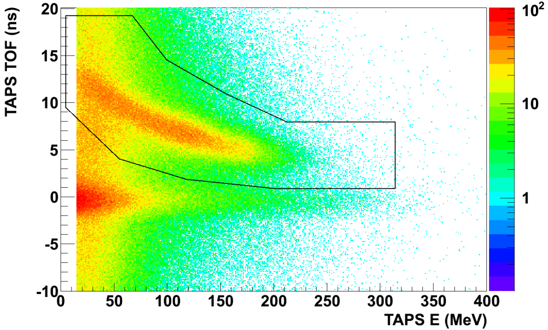
- Barrel of 24 plastic paddles
- Each covers $15 < \theta < 159°$, and $15°$ in ϕ
- Plot ΔE in PID vs E in NaI

Additional Charged Particle Detection



Multiwire Proportional Chamber (MWPC)

- Two chambers: anode wires sandwiched by two layers of cathode strips
- Voltage between wires and strips increases when gas is ionized



Time of Flight

- Given its increased distance from the target, massive particles take longer to reach TAPS
- Plot time vs E, identify nucleons

Measure Compton Scattering Cross Section

Probability for a reaction to happen at a given energy and angle

$$\frac{d\sigma}{d\Omega}(E_\gamma, \theta_\gamma) = \frac{N_{\gamma'}}{N_\gamma \times N_p} = \frac{N(E_\gamma, \theta_\gamma)}{\epsilon(E_\gamma, \theta_\gamma) \times \Delta\Omega(\theta_\gamma)} \times \frac{1}{F(E_\gamma)} \times \frac{M}{\rho \times L \times N_A}$$

- N - Number of events at a given energy and angle
- ϵ - Detection efficiency at a given energy and angle
- $\Delta\Omega$ - Solid angle at a given angle (sr)
- F - Incoming photon flux at a given energy
- M - Molar mass of the target (g/mol)
- ρ - Target density (g/cm^3)
- L - Target length (cm)
- N_A - Avogadro constant - 6.022e23 (1/mol)