Compton Scattering at the High Intensity Gamma-Ray Source (HIGS)

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Shandong University

The 12th Workshop on Hadron Physics and Opportunities Worldwide

Dalian, August 5-9, 2024

Outline

- **Nucleon polarizabilities**
- **Compton scattering experiments at HIGS**
  - The HIGS facility
  - Experimental apparatus
- **Results for nuclear Compton scattering**
  - from the proton, deuteron, ^{4}He, and ^{3}He
- **Outlook**

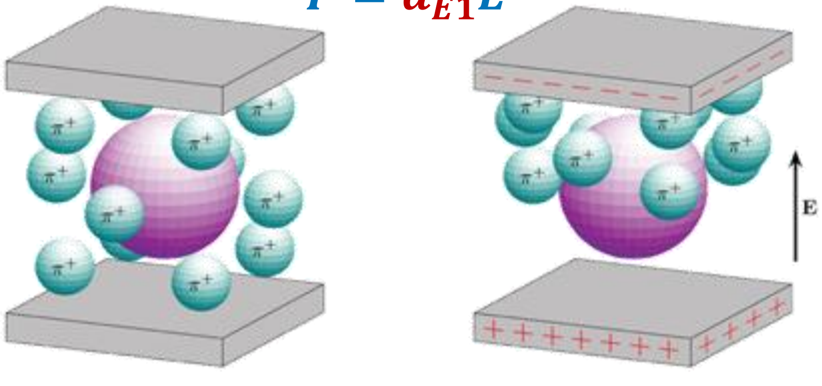
Nucleon Electromagnetic Dipole Polarizabilities

- Nucleon **electromagnetic (EM) structure constants**
- Characterize the **response of the charged constituents of a nucleon to an external EM field**
  - α_{E1} : charged pion-cloud dynamics
  - β_{M1} : pion charge current dynamics (diamaganetic) + constituent quarks dynamics (paramagnetic)
- Primarily accessed via **Compton Scattering**
- Theoretical approaches: **χEFT, LQCD**, DR, models
- Balding sum rule

$$\alpha_{E1} + \beta_{M1} = \frac{1}{2\pi}\int_{\omega_0}^{\infty} \frac{\sigma_{tot}(\omega')}{\omega'^2 - \omega^2} d\omega'$$

Electric polarizability (α_{E1})

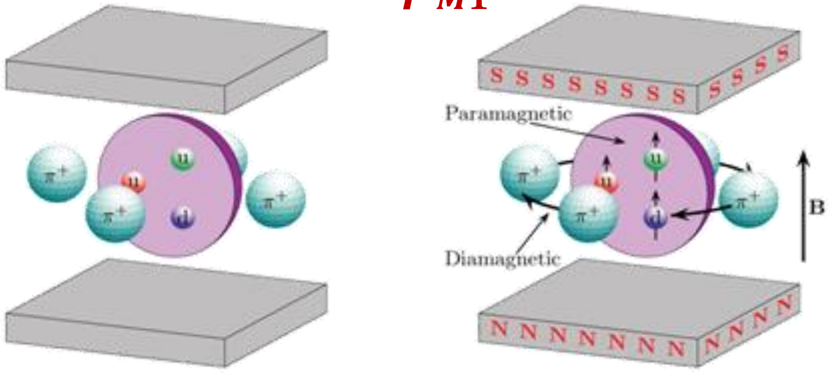
$\vec{P} = \alpha_{E1}\vec{E}$



(a) Electric field off (b) Electric field on

Magnetic polarizability (β_{M1})

$\vec{M} = \beta_{M1}\vec{H}$

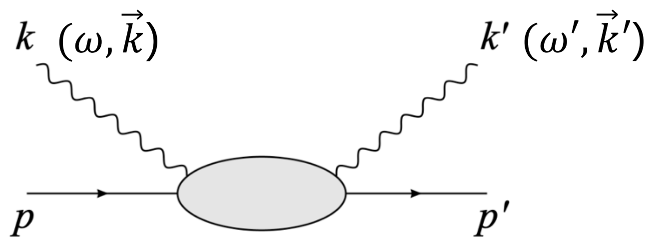


(a) Magnetic field off (b) Magnetic field on

(Graphs credited to P. Martel)

Compton Scattering from the Nucleon

Effective probe for nucleon polarizabilities



- Low-energy expansion of the differential cross section:

$$\frac{d\sigma}{d\Omega} = \frac{1}{2}\left(\frac{e^2Z^2}{M_N}\right)^2\left(\frac{\omega'}{\omega}\right)^2[1+g(\omega^2,\kappa)]$$

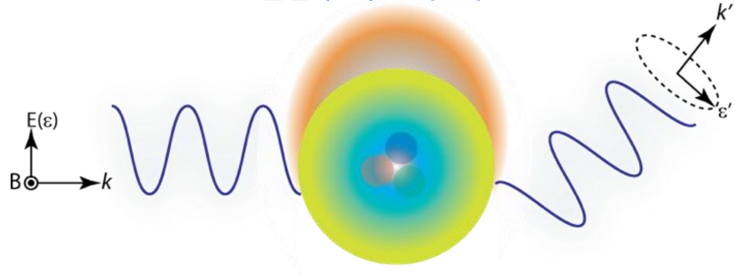
$$-\left(\frac{e^2Z^2}{4\pi M_N}\right)\left(\frac{\omega'}{\omega}\right)^2(\omega\omega')\left[\frac{1}{2}(\alpha+\beta)(1+\cos\theta)^2+\frac{1}{2}(\alpha-\beta)(1-\cos\theta)^2\right]$$

$$+f(\omega^3,\gamma_1,\gamma_2,\gamma_3,\gamma_4)$$

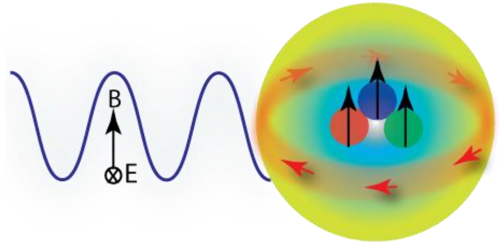
$$+\mathcal{O}(\omega^4)$$

eZ : nucleon charge
M_N : nucleon mass
κ: anomalous magnetic moment

$\vec{P} = \alpha_{E1}(\omega)\vec{E}(\omega)$



$\vec{M} = \beta_{M1}(\omega)\vec{H}(\omega)$



Compton Scattering from the Nucleon

Effective probe for nucleon polarizabilities

- Low-energy expansion of the differential cross section:

$$\frac{d\sigma}{d\Omega} = \frac{1}{2}\left(\frac{e^2Z^2}{M_N}\right)^2\left(\frac{\omega'}{\omega}\right)^2\left[1+g(\omega^2,\kappa)\right]$$

Born term (nucleons are assumed as point-like particles)

$$-\left(\frac{e^2Z^2}{4\pi M_N}\right)\left(\frac{\omega'}{\omega}\right)^2(\omega\omega')\left[\frac{1}{2}(\alpha+\beta)(1+\cos\theta)^2+\frac{1}{2}(\alpha-\beta)(1-\cos\theta)^2\right]$$

Electromagnetic dipole polarizabilities

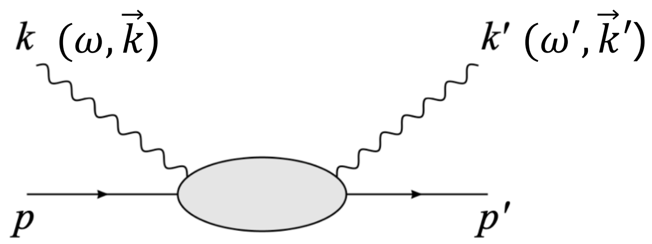
$$+f(\omega^3,\gamma_1,\gamma_2,\gamma_3,\gamma_4)$$

Spin polarizabilities

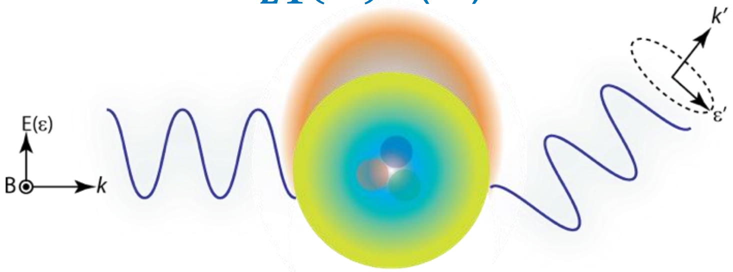
$$+\mathcal{O}(\omega^4)$$

eZ : nucleon charge
M_N : nucleon mass
κ: anomalous magnetic moment

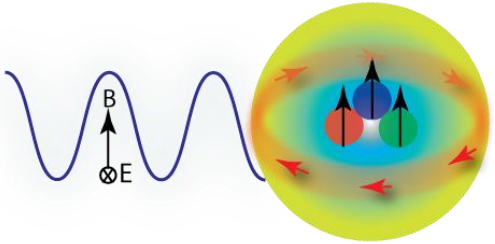
To extract α and β
- ✓ Measure the forward and backward Compton scattering cross sections



$$\vec{P} = \alpha_{E1}(\omega)\vec{E}(\omega)$$



$$\vec{M} = \beta_{M1}(\omega)\vec{H}(\omega)$$

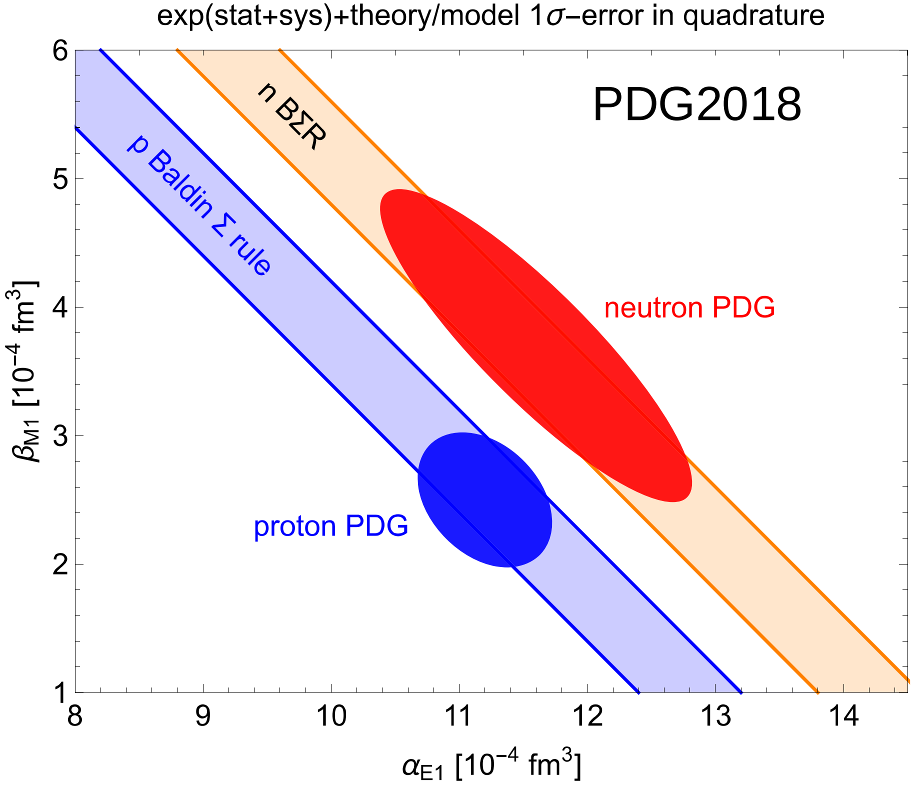


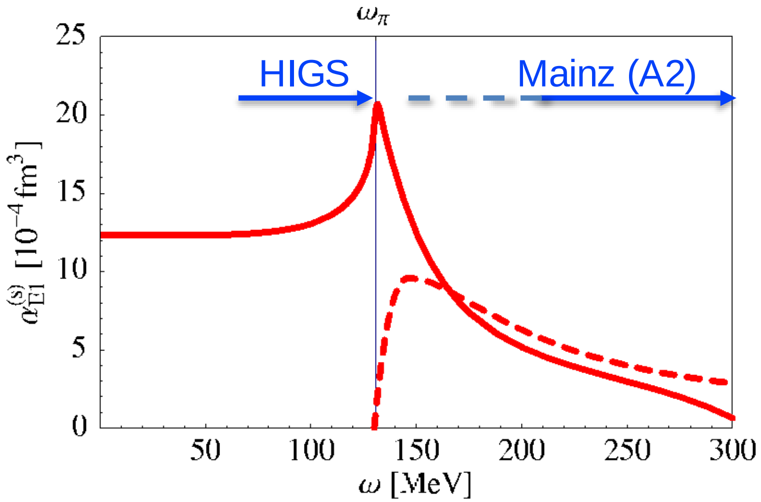
Global Extraction of α_{E1} and β_{M1}

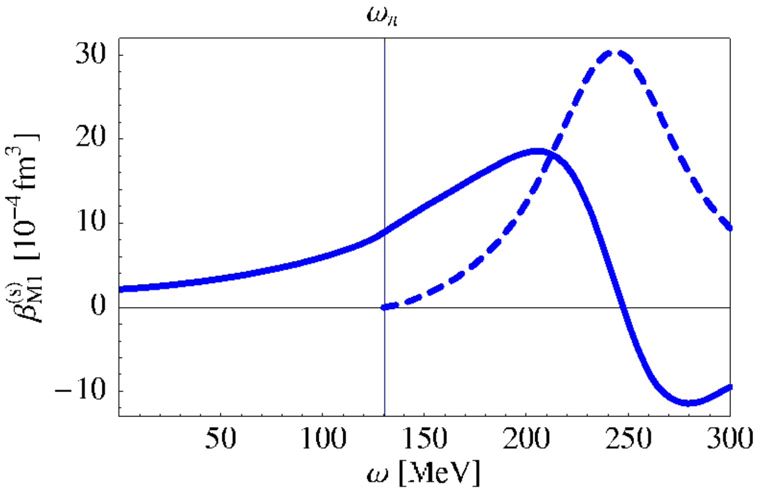
TUNL

- Proton EM polarizabilities relatively well determined using liquid hydrogen targets
- Neutron measurements always harder
  - Charge neutral
    - α_{E1} and β_{M1} appear at the order of ω^4
  - No stable free neutron target
    - use light nuclear targets (D, He, Li,…)
    - model dependent

$$\alpha_{E1}^{(p)} = 11.2 \pm 0.4$$
$$\beta_{M1}^{(p)} = 2.5 \pm 0.4$$
$$\alpha_{E1}^{(n)} = 11.8 \pm 1.1$$
$$\beta_{M1}^{(n)} = 3.7 \pm 1.2$$







Baldin sum rule

$$\alpha_{E1}^{(p)} + \beta_{M1}^{(p)} = 13.8 \pm 0.4$$
$$\alpha_{E1}^{(n)} + \beta_{M1}^{(n)} = 15.2 \pm 0.4$$

R. P. Hildebrandt, H.W. Griesshammer, T.R. Hemmert and B. Pasquini, Eur. Phys. J. A **20**, 293 (2004)

Triangle Universities Nuclear Laboratory (TUNL)

From US 2023 Long Range Plan for Nuclear Science:

A consortium of 13 university-based accelerator laboratories, known collectively as the **Association for Research at University Nuclear Accelerators (ARUNA)**

Figure 9.7. The unique ARUNA facilities are distributed throughout the country in 11 states: Florida, Kentucky, Indiana, Massachusetts, Michigan, New York, North Carolina, Ohio, Texas, Virginia, and Washington [44].

University (Figure 9.7). In addition to providing a high level of hands-on training in every aspect of an experiment, the accelerator facilities at these institutions provide unique beam and research capabilities that are often not available elsewhere. These facilities add an element of agility to US low-energy nuclear physics research by offering flexibility in scheduling and quick response to research developments and challenges. Importantly, ARUNA facilities are cost-effective to operate, enabling beam time to be devoted to a project for a long duration as is often required in nuclear astrophysics, where cross sections are low, and in fundamental symmetries, where high statistics and extensive studies of systematics are required. The diversity of approaches provided by these laboratories is a critical asset of the field, and ARUNA laboratories provide a highly creative, flexible, stimulating, and supportive scientific environment with many opportunities for students to acquire the essential skills necessary for them to become a well-trained nuclear workforce. Scientists at ARUNA facilities pursue research in nuclear astrophysics, low-energy nuclear physics, fundamental symmetries, and a rapidly growing number of nuclear physics applications that build bridges to other research communities.

High Intensity Gamma-Ray Source (HIGS)

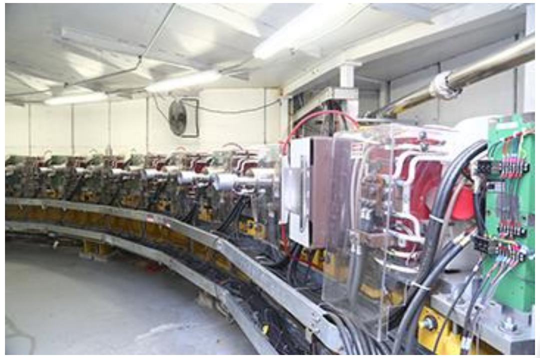
TUNL

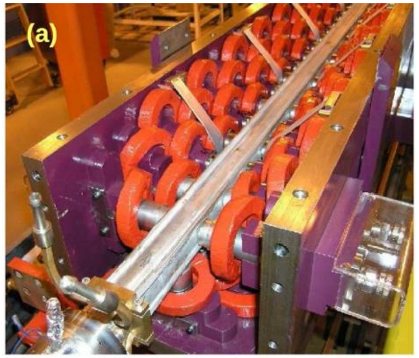
Most intense Compton γ-ray source in the world

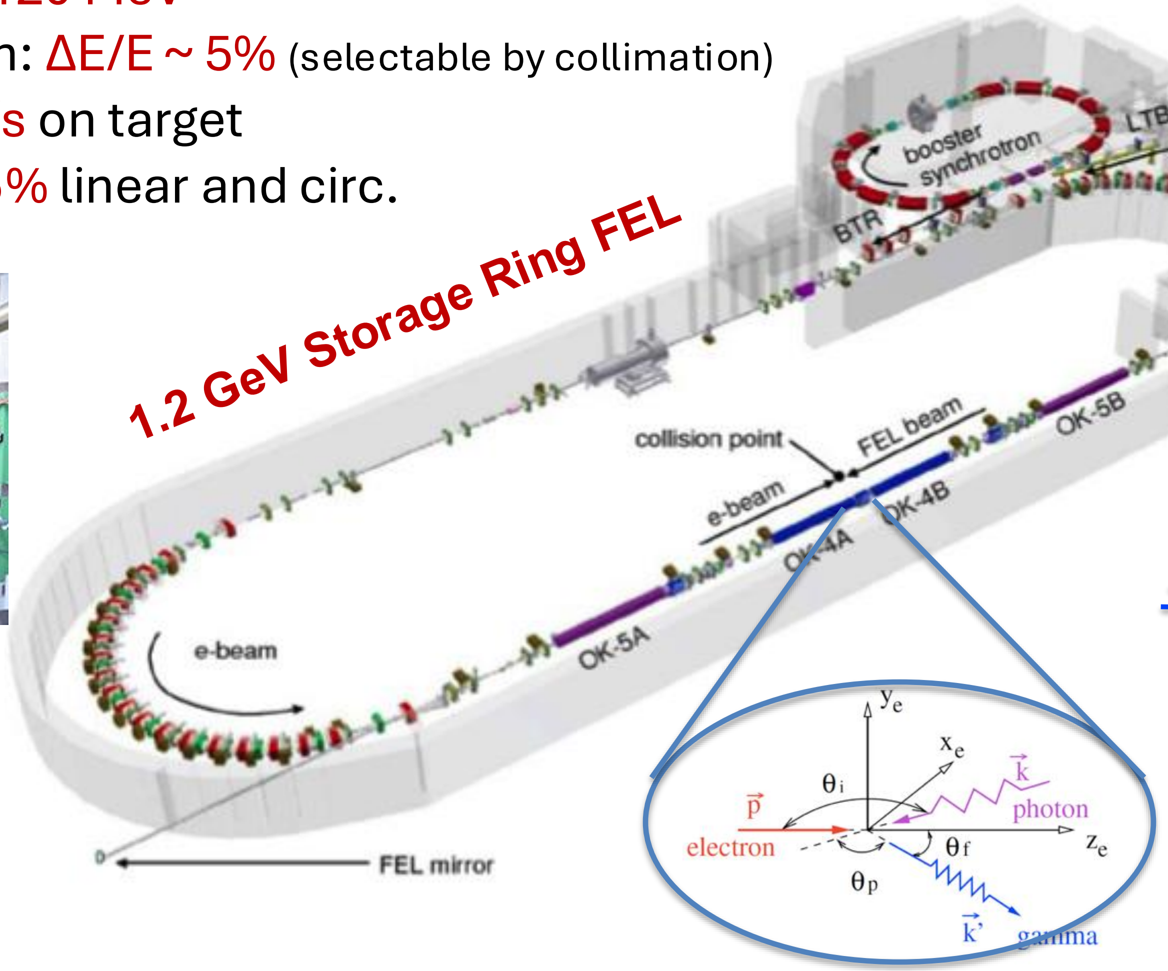
- Energy range: 1-120 MeV
- Energy resolution: ΔE/E ~ 5% (selectable by collimation)
- Intensity: >10^7 γ/s on target
- Polarization: >95% linear and circ.

Gamma Vault

4-paddle flux monitor

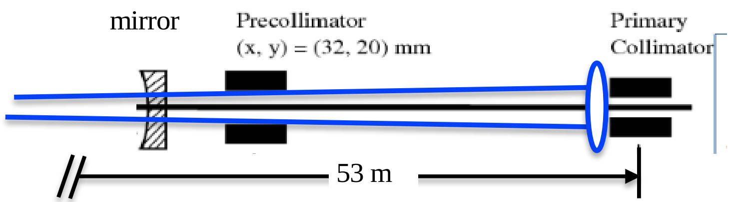


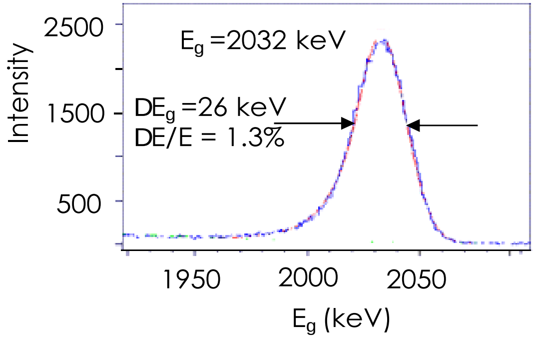




Compton backscattering to produce γ-ray photons

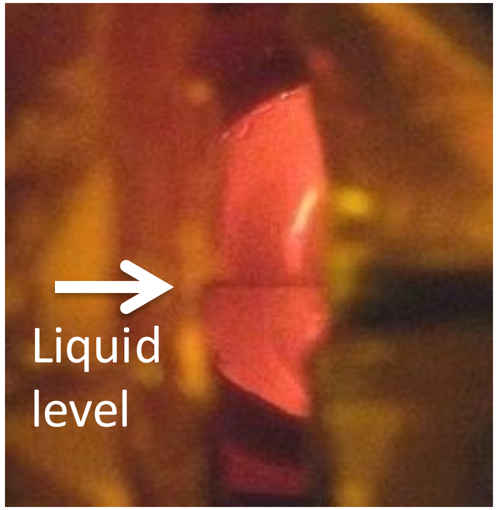
Energy resolution by collimation

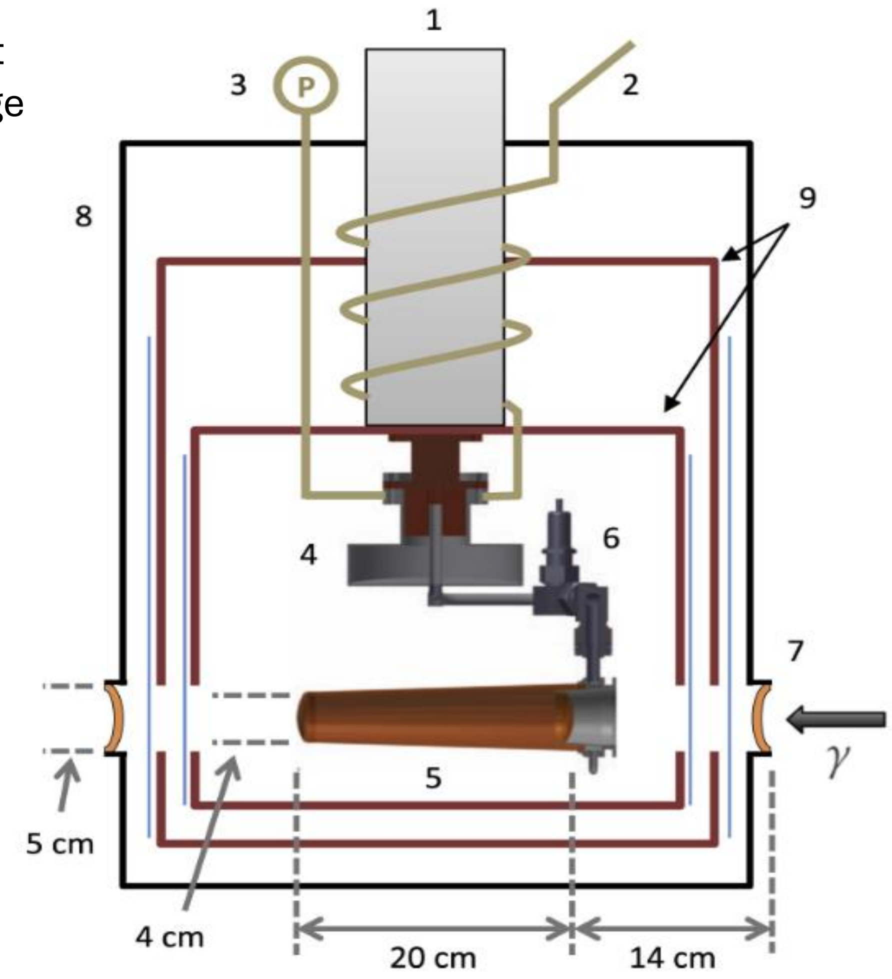


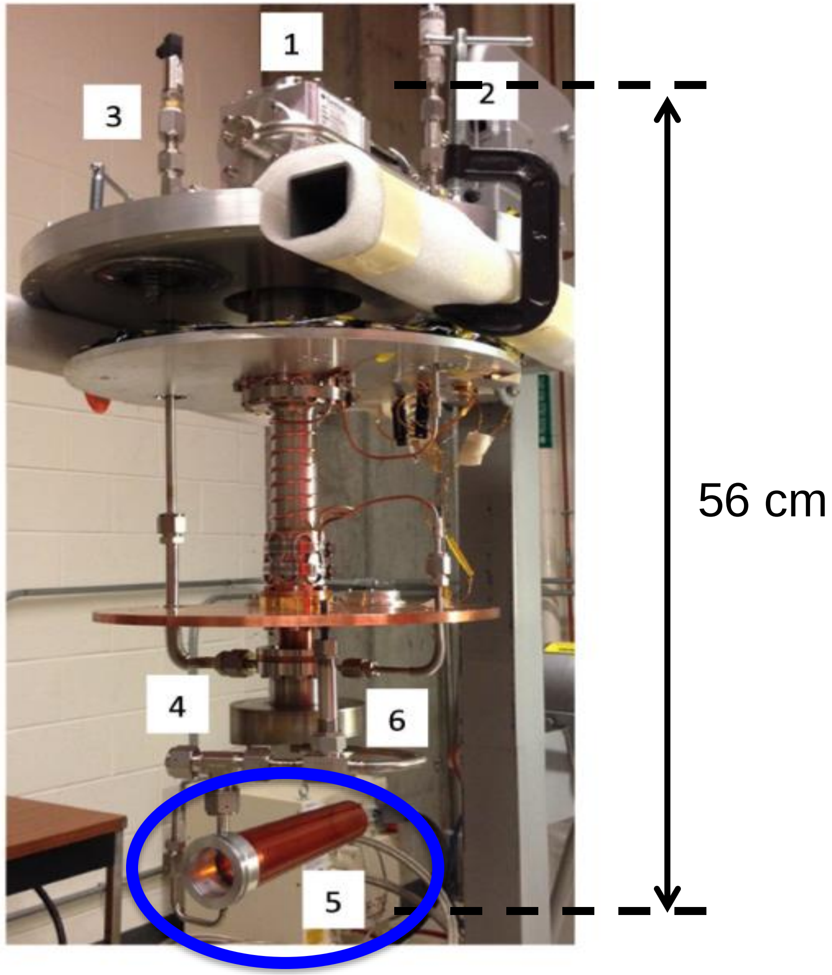


Cryogenic Target for Liquid H, D and ^{4}He

1. Cryocooler
2. Room-temperature gas inlet
3. Vent line with pressure gauge
4. Condenser
5. Target cell
6. Outlet valve
7. Kapton window
8. Aluminum can
9. Thermal shield





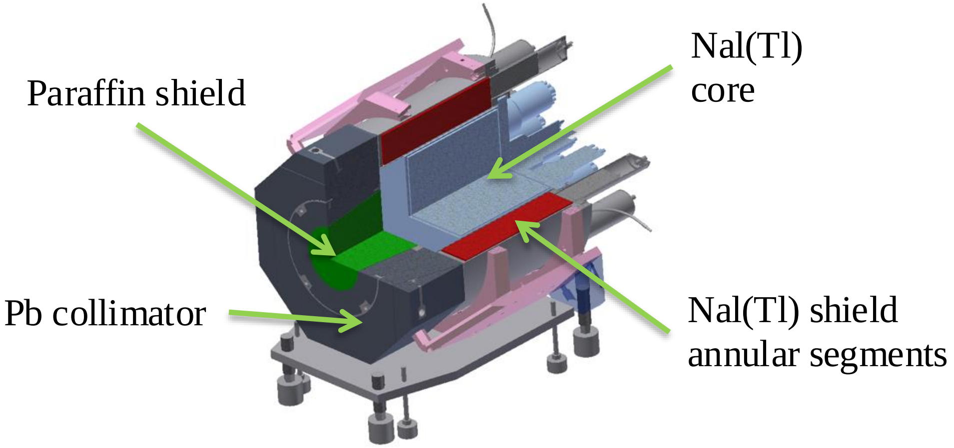


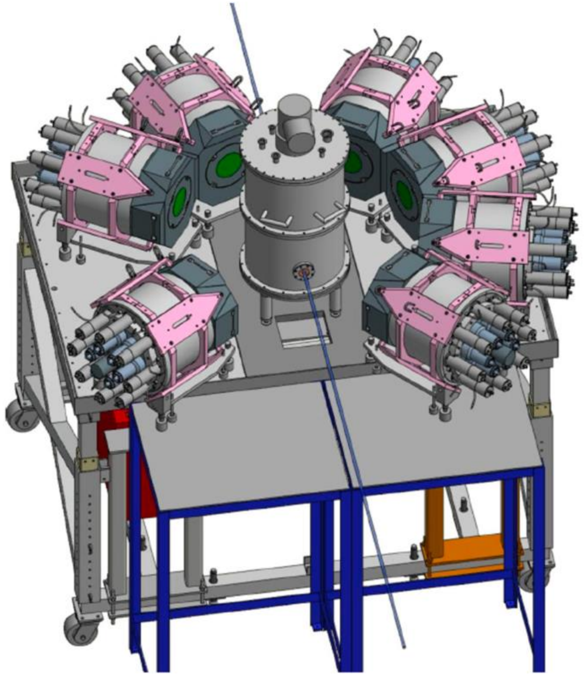
D. P. Kendellen *et al.*, Nucl. Instrum. and Meth. A 840, 174–180 (2016)

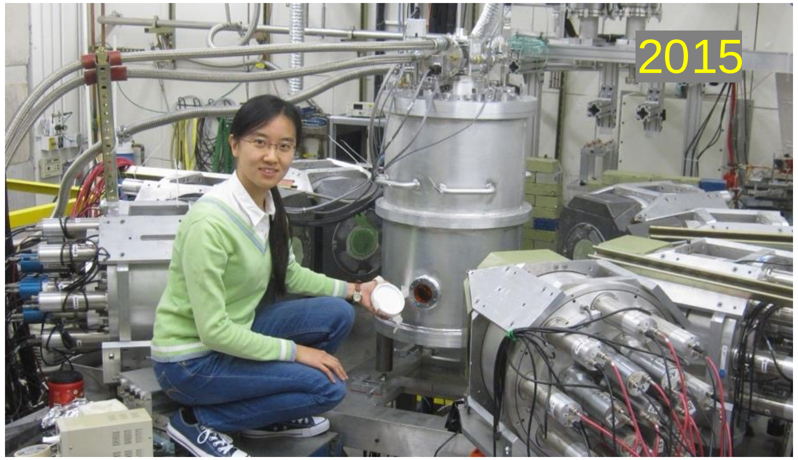
Photon Detectors for Compton Scattering

- Eight 10” x 12” NaI(Tl) detectors:

High Intensity NaI Detector Array (HINDA)



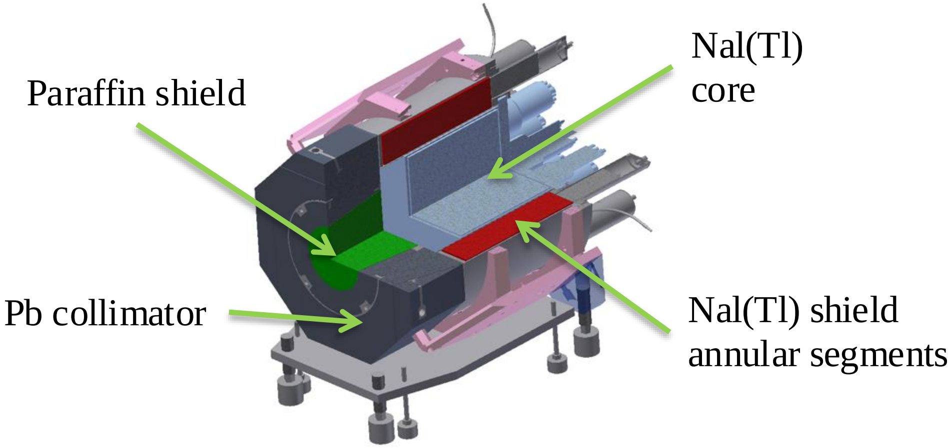


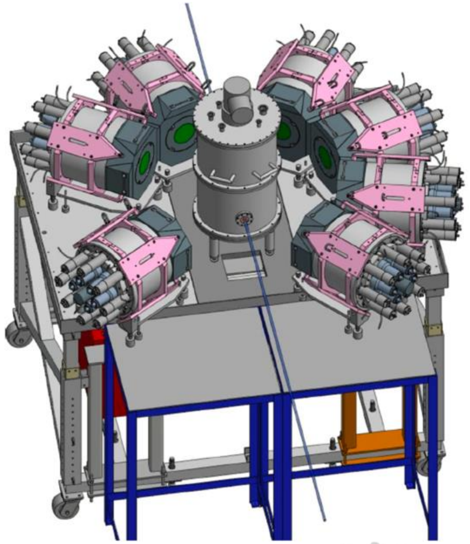


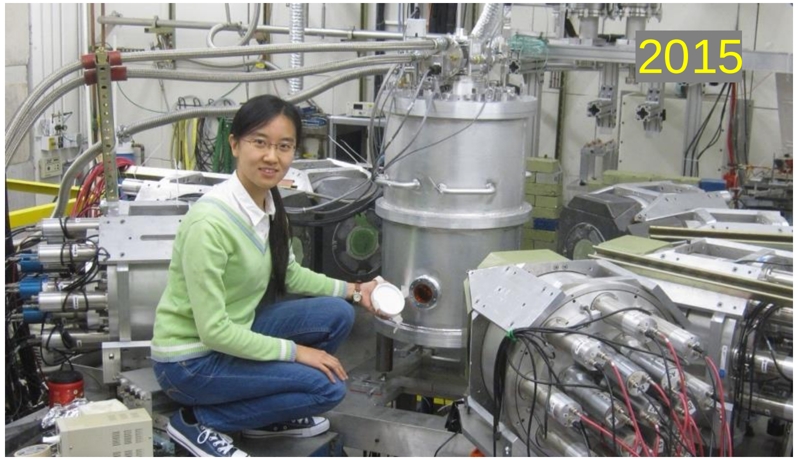
Photon Detectors for Compton Scattering

➢ Eight 10” x 12” NaI(Tl) detectors:

High Intensity NaI Detector Array (HINDA)

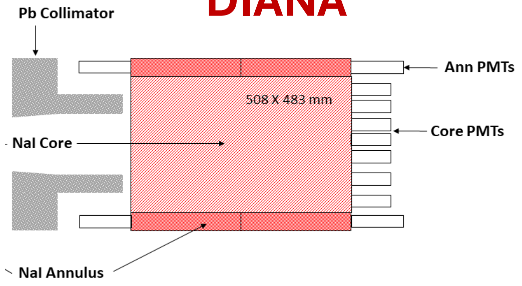




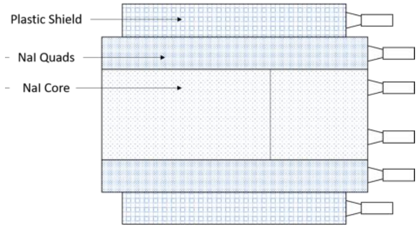


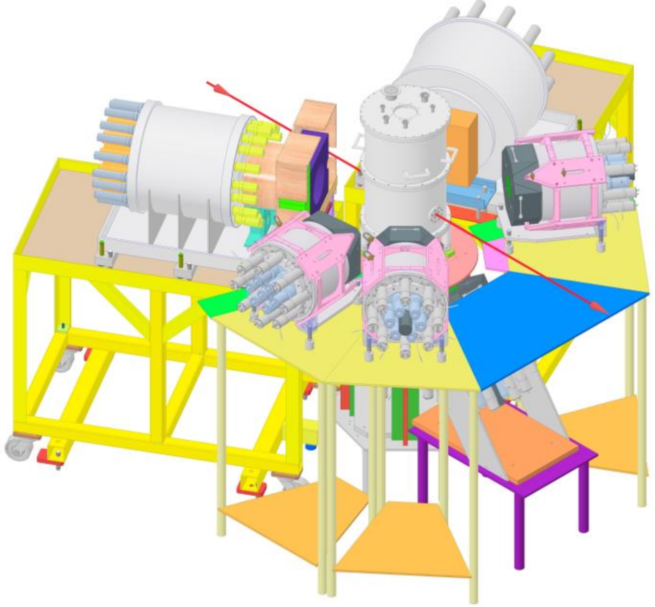
➢ Two larger NaI(Tl) detectors:

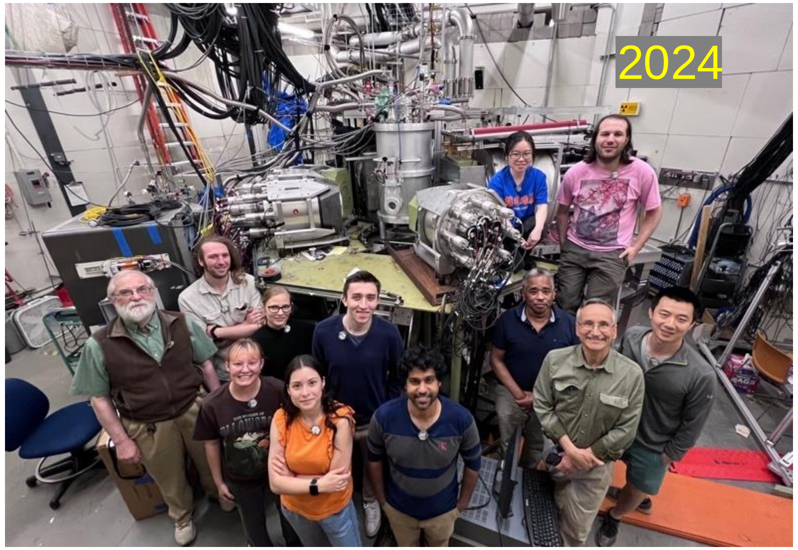
DIANA



BUNI







Compton Scattering Runs at HIGS

Year	Target	Beam Energy (MeV)	Beam Polarization	Run Hours
2015	Helium-4	61	Circular	54
2016	Deuteron	65	Circular	304
2016	Deuteron	85	Circular	268
2017	Helium-4	81	Circular	110
2017	Proton	81	Circular	107
2017	Proton	83	Linear	144
2021	Deuteron	61	Circular	227
2022	Deuteron	85	Circular	285
2024	Helium-3	60	Circular	210
2024	Helium-3	100	Circular	340

Compton Scattering from the Proton

PHYSICAL REVIEW LETTERS **128,** 132502 (2022)

Proton Compton Scattering from Linearly Polarized Gamma Rays

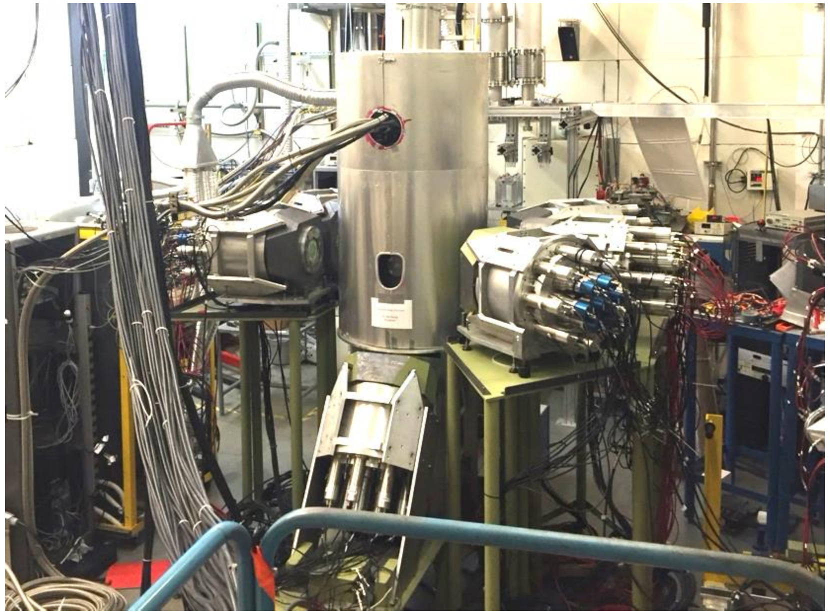
X. Li,[1,2,*] M. W. Ahmed,[2,3] A. Banu,[4] C. Bartram,[2,5] B. Crowe,[2,3] E. J. Downie,[6] M. Emamian,[2] G. Feldman,[6] H. Gao,[1,2] D. Godagama,[7] H. W. Grießhammer,[6,1] C. R. Howell,[1,2] H. J. Karwowski,[2,5] D. P. Kendellen,[1,2] M. A. Kovash,[7] K. K. H. Leung,[1,2,8] D. M. Markoff,[2,3] J. A. McGovern,[9] S. Mikhailov,[2] R. E. Pywell,[10] M. H. Sikora,[6,2] J. A. Silano,[2,5] R. S. Sosa,[3] M. C. Spraker,[11] G. Swift,[2] P. Wallace,[2] H. R. Weller,[1,2] C. S. Whisnant,[4] Y. K. Wu,[1,2] and Z. W. Zhao[1,2]

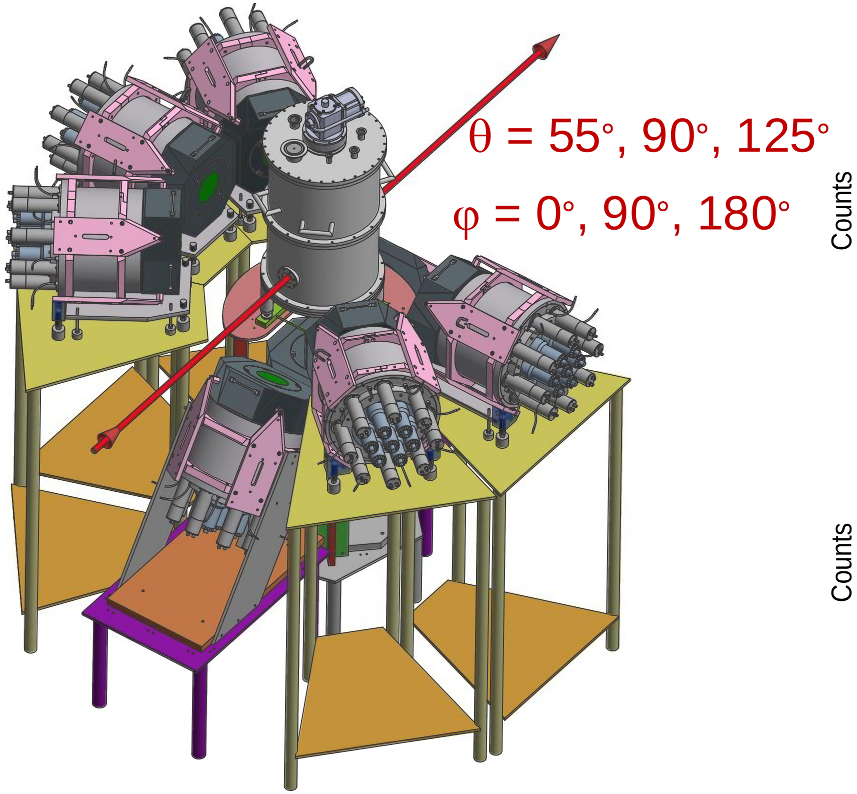
Circular pol.: E_γ = 81.3 MeV

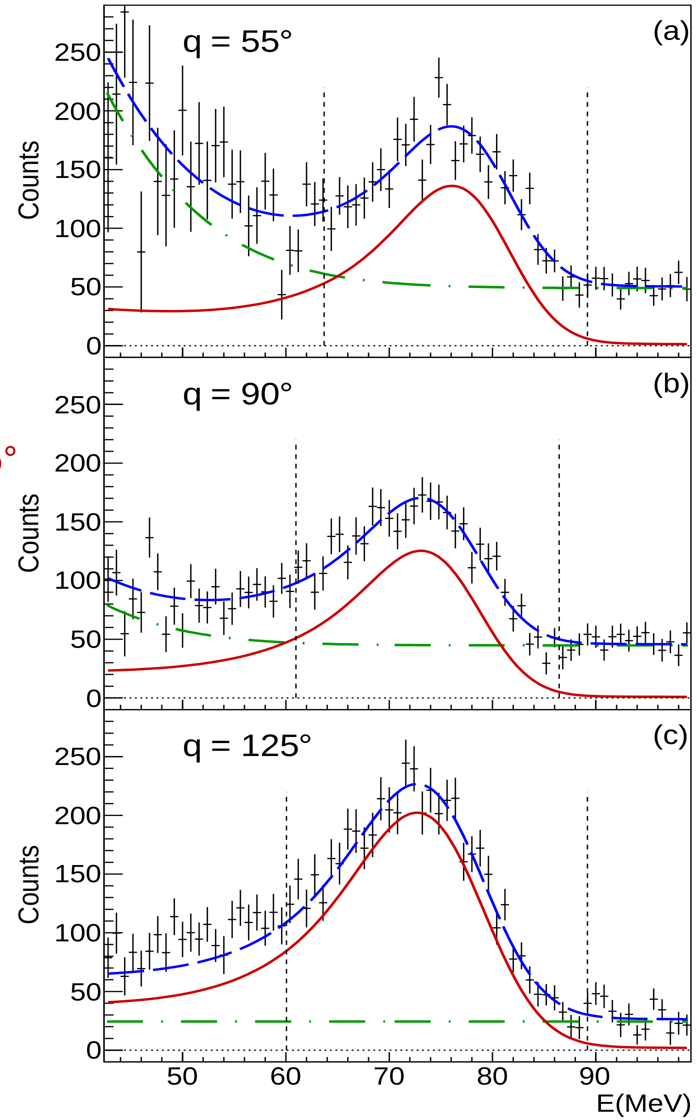
Linear pol.: E_γ = 83.4 MeV

$$\frac{d\sigma(\theta)}{d\Omega}$$

$$\Sigma_3(\theta)$$







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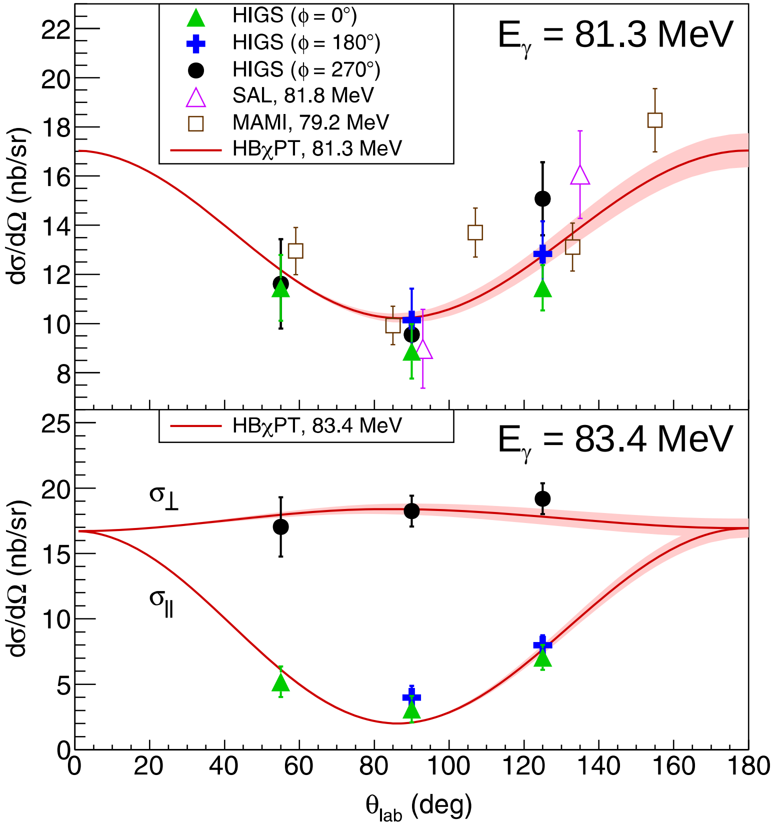


Without BSR applied

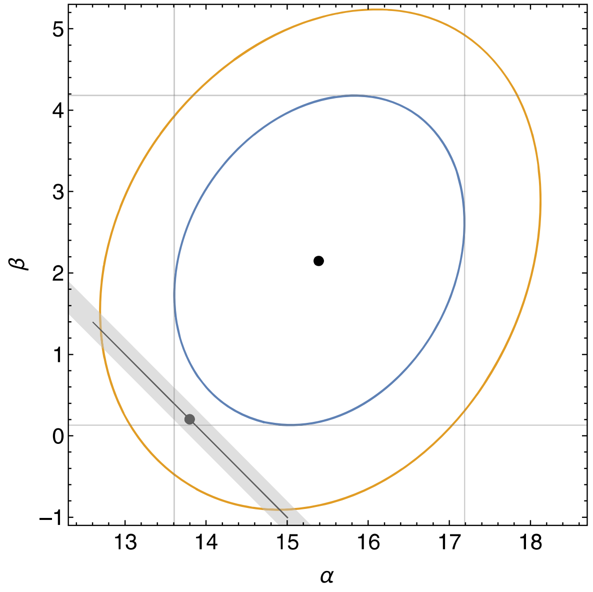
$$\alpha^p_{E1} = 15.4 \pm 1.8_{\rm stat},$$
$$\beta^p_{M1} = 2.1 \pm 2.0_{\rm stat},$$

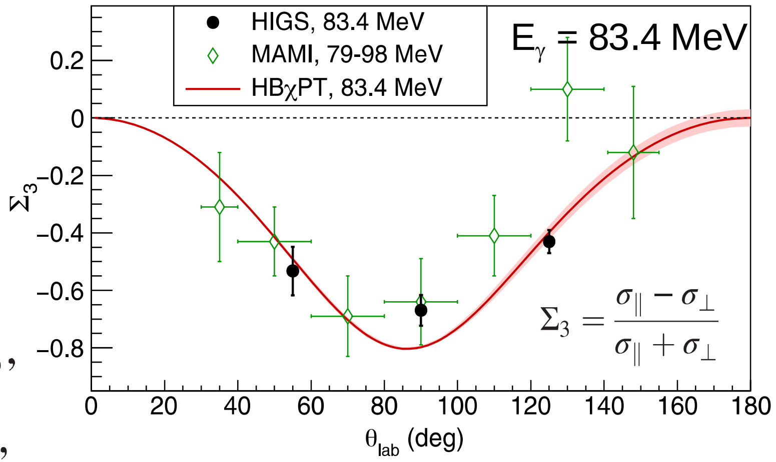
PDG2018 values

$$\alpha^{(p)}_{E1} = 11.2 \pm 0.4$$
$$\beta^{(p)}_{M1} = 2.5 \pm 0.4$$

With BSR applied

$$\alpha^p_{E1} = 13.8 \pm 1.2_{\rm stat} \pm 0.1_{\rm BSR} \pm 0.3_{\rm theo},$$
$$\beta^p_{M1} = 0.2 \mp 1.2_{\rm stat} \pm 0.1_{\rm BSR} \mp 0.3_{\rm theo},$$





Compton Scattering from ^{4}He

PHYSICAL REVIEW C **96**, 055209 (2017)

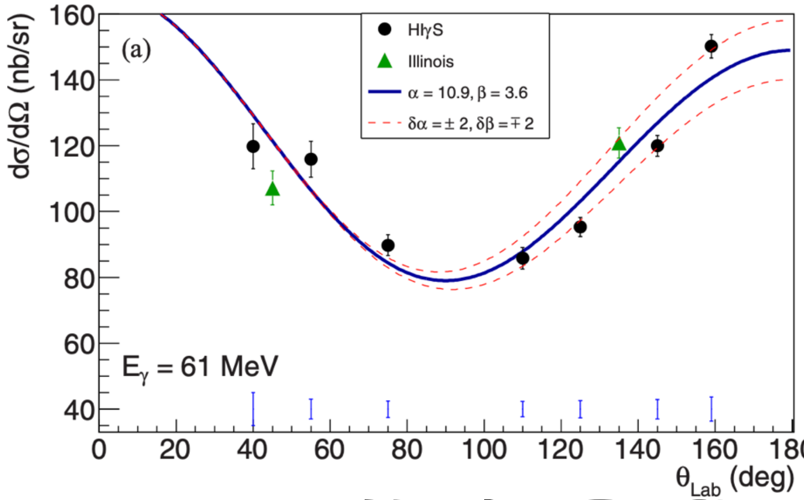
Compton scattering from ^{4}He at 61 MeV

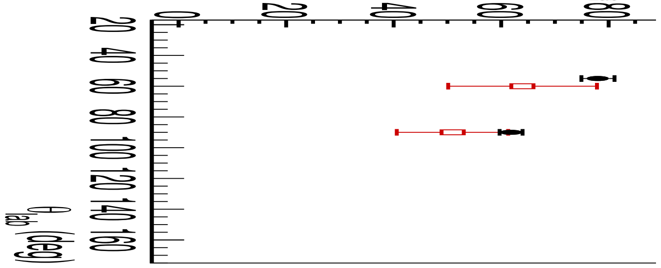
M. H. Sikora,[1,2,*] M. W. Ahmed,[1,2,3] A. Banu,[4] C. Bartram,[2,5] B. Crowe,[2,3] E. J. Downie,[6] G. Feldman,[6] H. Gao,[1,2] H. W. Grießhammer,[6] H. Hao,[2] C. R. Howell,[2] H. J. Karwowski,[2,5] D. P. Kendellen,[1,2] M. A. Kovash,[7] X. Li,[1,2] D. M. Markoff,[2,3] S. Mikhailov,[2] V. Popov,[2] R. E. Pywell,[8] J. A. Silano,[2,5] M. C. Spraker,[9] P. Wallace,[2] H. R. Weller,[1,2] C. S. Whisnant,[4] Y. K. Wu,[1,2] W. Xiong,[1,2] X. Yan,[1,2] and Z. W. Zhao[1,2]

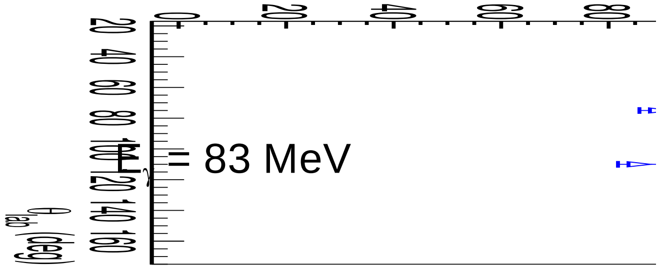
PHYSICAL REVIEW C **101**, 034618 (2020)

Compton scattering from ^{4}He at the TUNL HIγS facility

X. Li,[1,2,*] M. W. Ahmed,[1,2,3] A. Banu,[4] C. Bartram,[2,5] B. Crowe,[2,3] E. J. Downie,[6] M. Emamian,[2] G. Feldman,[6] H. Gao,[1,2] D. Godagama,[7] H. W. Grießhammer,[6,1] C. R. Howell,[1,2] H. J. Karwowski,[2,5] D. P. Kendellen,[1,2] M. A. Kovash,[7] K. K. H. Leung,[2,8] D. Markoff,[2,3] S. Mikhailov,[2] R. E. Pywell,[9] M. H. Sikora,[6,2] J. A. Silano,[2,5] R. S. Sosa,[3] M. C. Spraker,[10] G. Swift,[2] P. Wallace,[2] H. R. Weller,[1,2] C. S. Whisnant,[4] Y. K. Wu,[1,2] and Z. W. Zhao[1,2]







- **Fore-aft asymmetry at higher energies** indicates a strong sensitivity to subnuclear effects
- ***α* and *β* for the neutron** to be extracted from the high precision ^{4}He data with upcoming new χEFT calculation

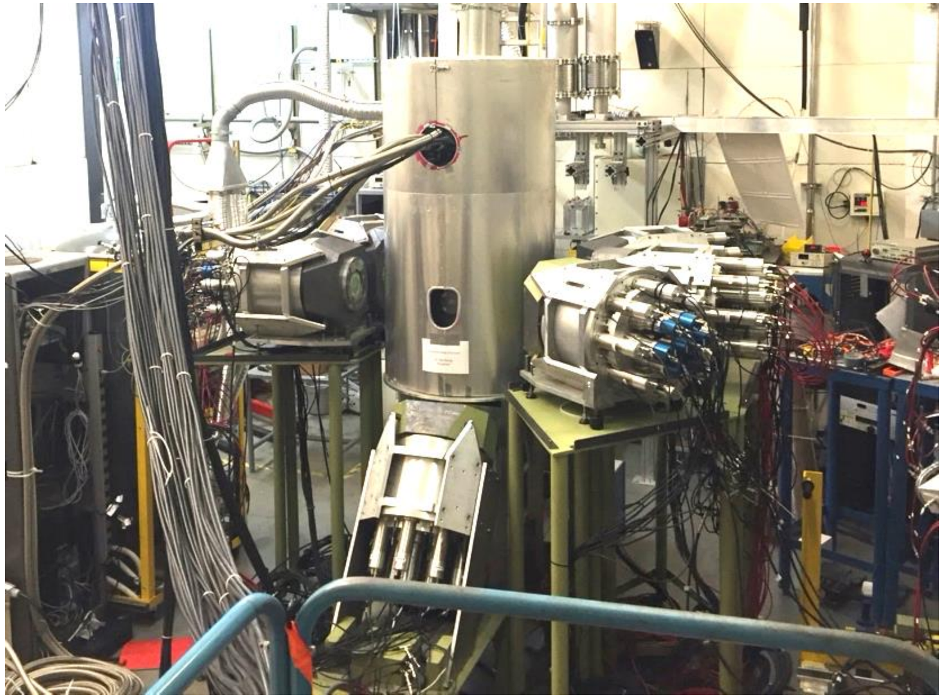
Compton Scattering from Deuteron

Elastic and Inelastic Compton Scattering from Deuterium at 65 and 85 MeV

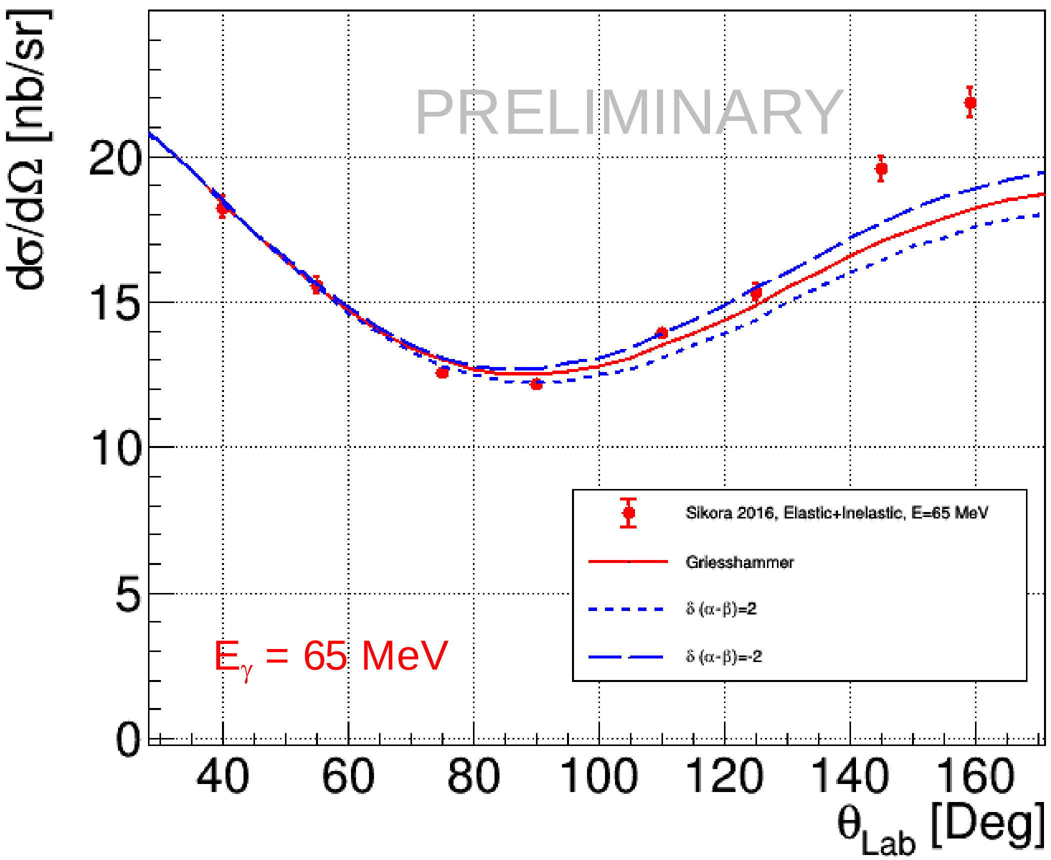
Mohammad Ahmed (Spokesperson)
Department of Mathematics and Physics, North Carolina Central University, Durham, NC 27707, 919-530-6100, ahmed2@nccu.edu

Michael A. Kovash (Spokesperson)
Department of Physics and Astronomy, University of Kentucky, Lexington, KY 40506-0055, 859-257-1150, kovash@pa.uky.edu

Compton@HIγS Collaboration



Deuteron measurement: need high-resolution detectors to separate elastic and inelastic scattering channels (2.2 MeV apart)



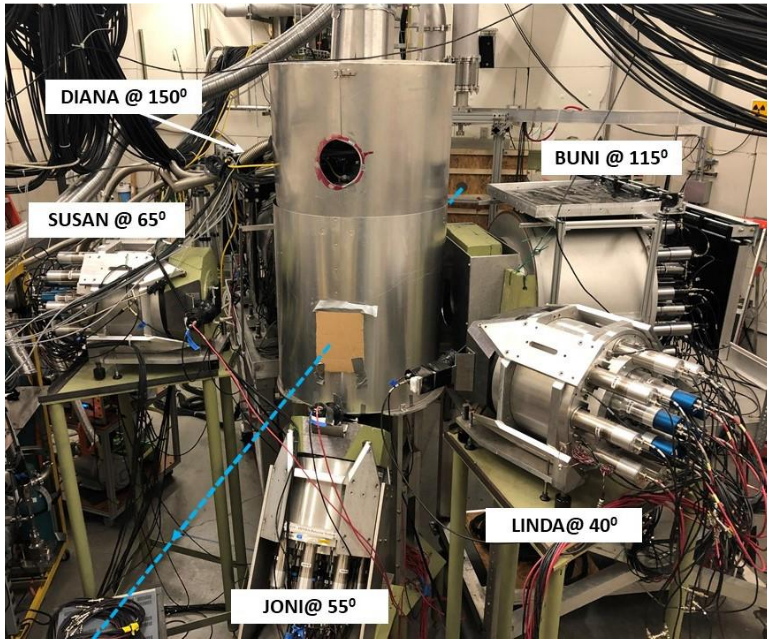
Compton Scattering from Deuteron

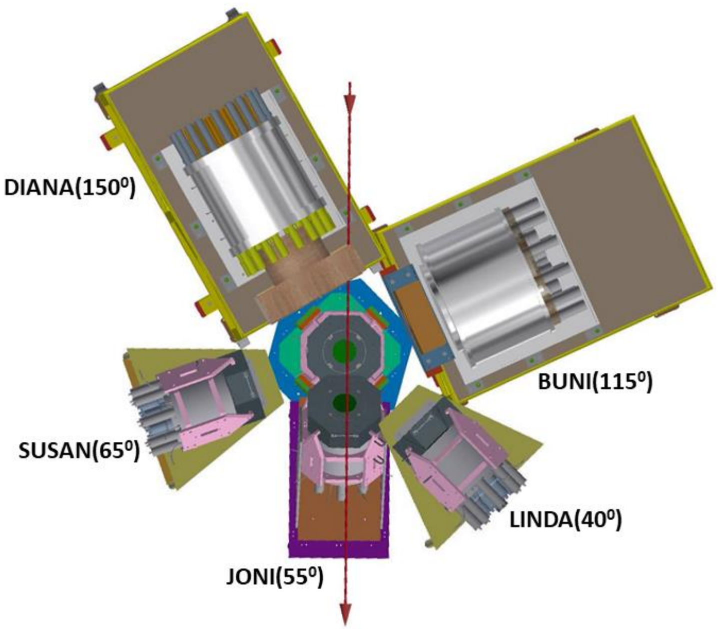
TUNL

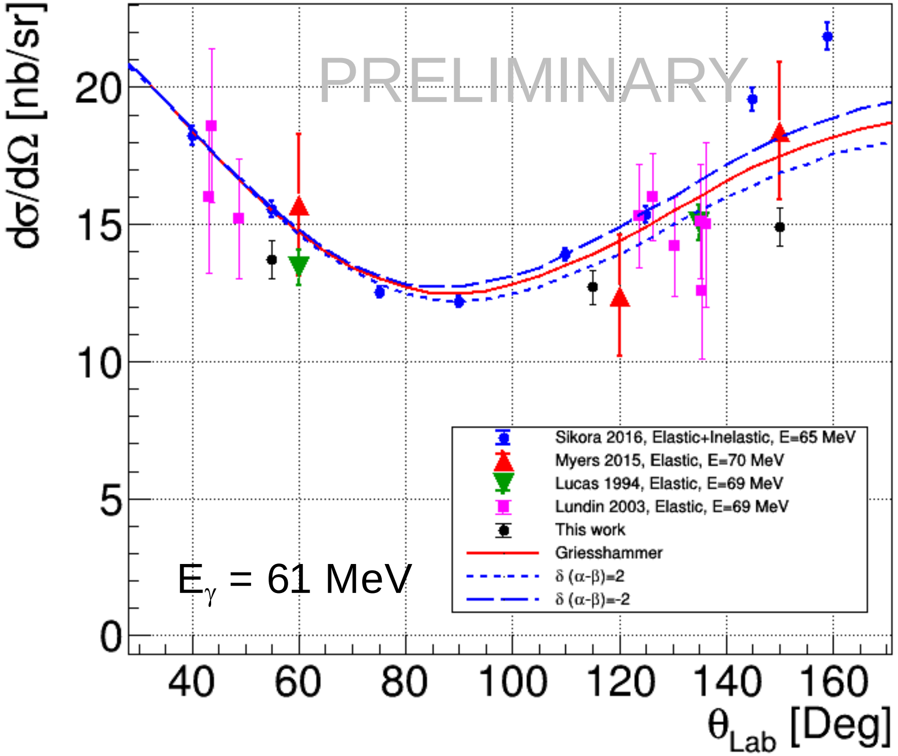
Elastic and Inelastic Compton Scattering from Deuterium at 61 MeV

Ph.D Thesis

Danula Godagama, University of Kentucky

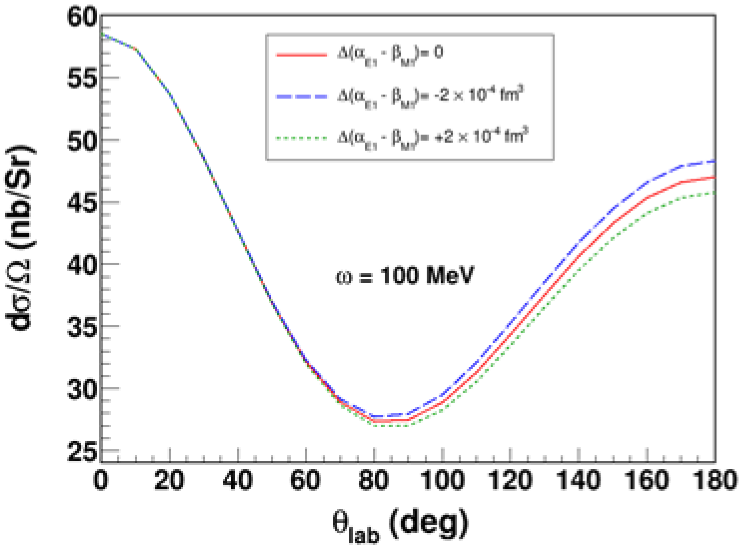


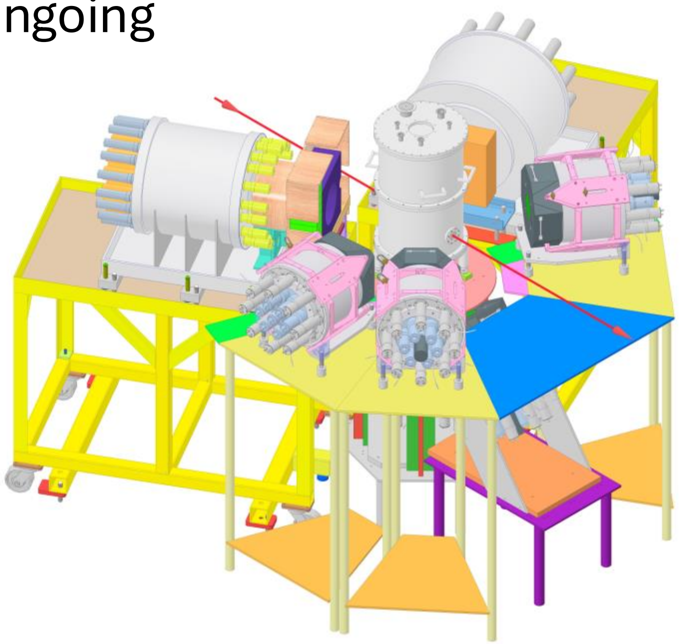


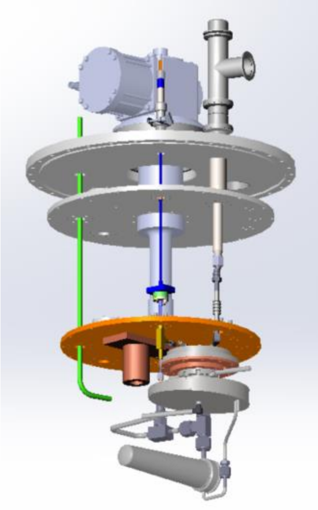


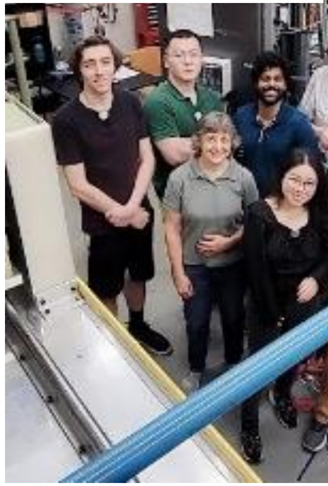
Compton Scattering from ^{3}He

- New gas handling system for 1.7 K liquid ^{3}He target
- Circularly polarized photon beam
  - 60 MeV data taking completed
  - 100 MeV data taking ongoing









- χEFT calculation availabel for ^{3}He Compton scattering
- Aim to extract neutron EM polarizabilities from the 100 MeV data with uncertainties $< 0.7 \times 10^{-4}$ fm^3

Spin Polarizabilities

$$\frac{d\sigma}{d\Omega} = \Phi^2 \, |T|^2$$

$$\begin{aligned} T(\omega,z) &= A_1(\omega,z)\,(\vec{\epsilon}'^* \cdot \vec{\epsilon}) \\ &+ A_2(\omega,z)\,(\vec{\epsilon}'^* \cdot \hat{k})\,(\vec{\epsilon} \cdot \hat{k}') \\ &+ iA_3(\omega,z)\,\vec{\sigma} \cdot (\vec{\epsilon}'^* \times \vec{\epsilon}) \\ &+ iA_4(\omega,z)\,\vec{\sigma} \cdot \left(\hat{k}' \times \hat{k}\right)(\vec{\epsilon}'^* \cdot \vec{\epsilon}) \\ &+ iA_5(\omega,z)\,\vec{\sigma} \cdot \left[\left(\vec{\epsilon}'^* \times \hat{k}\right)(\vec{\epsilon} \cdot \hat{k}') - \left(\vec{\epsilon} \times \hat{k}'\right)(\vec{\epsilon}'^* \cdot \hat{k})\right] \\ &+ iA_6(\omega,z)\,\vec{\sigma} \cdot \left[\left(\vec{\epsilon}'^* \times \hat{k}'\right)(\vec{\epsilon} \cdot \hat{k}') - \left(\vec{\epsilon} \times \hat{k}\right)(\vec{\epsilon}'^* \cdot \hat{k})\right] \end{aligned}$$

Spin polarizabilities

$$\begin{aligned} \gamma_{E1E1} &= -\gamma_1 - \gamma_3, \\ \gamma_{M1M1} &= \gamma_4, \\ \gamma_{M1E2} &= \gamma_2 + \gamma_4, \\ \gamma_{E1M2} &= \gamma_3. \end{aligned}$$

$$A_1(\omega,z) = -\frac{Z^2e^2}{M} + \frac{e^2\,\omega^2}{4M^3}\left((Z+\kappa)^2(1+z) - Z^2\right)(1-z) + 4\pi\omega^2(\alpha_{E1} + z\,\beta_{M1}) + \mathcal{O}(\omega^4),$$

$$A_2(\omega,z) = \frac{e^2\,\omega^2}{4M^3}\kappa(2Z+\kappa)z - 4\pi\omega^2\beta_{M1} + \mathcal{O}(\omega^4),$$

Spin-dependent scattering amplitude

$$A_3(\omega,z) = \frac{e^2\,\omega}{2M^2}\left(Z(Z+2\kappa) - (Z+\kappa)^2 z\right) + A_3^{\pi^0} + 4\pi\omega^3\left(\gamma_1 - (\gamma_2 + 2\gamma_4)z\right) + \mathcal{O}(\omega^5),$$

$$A_4(\omega,z) = -\frac{e^2\,\omega}{2M^2}(Z+\kappa)^2 + 4\pi\omega^3\gamma_2 + \mathcal{O}(\omega^5),$$

$$A_5(\omega,z) = \frac{e^2\,\omega}{2M^2}(Z+\kappa)^2 + A_5^{\pi^0} + 4\pi\omega^3\gamma_4 + \mathcal{O}(\omega^5),$$

$$A_6(\omega,z) = -\frac{e^2\,\omega}{2M^2}Z(Z+\kappa) + A_6^{\pi^0} + 4\pi\omega^3\gamma_3 + \mathcal{O}(\omega^5),$$

Future Plan on Compton Scattering at HIGS

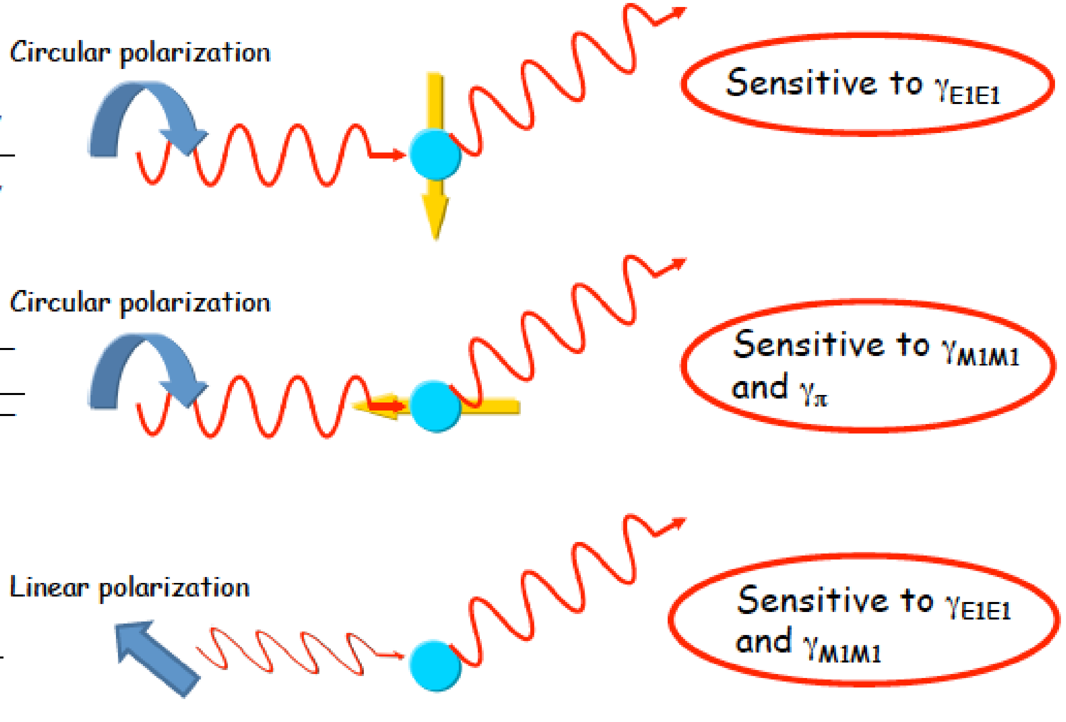
HIGS Scientific Program: Determination of the spin-dependent polarizabilities

Polarized photon beam and polarized target required

$$\Sigma_{2x} = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

$$\Sigma_{2z} = \frac{\sigma^{\rightarrow} - \sigma^{\leftarrow}}{\sigma^{\rightarrow} + \sigma^{\leftarrow}}$$

$$\Sigma_{3} = \frac{\sigma^{\parallel} - \sigma^{\perp}}{\sigma^{\parallel} + \sigma^{\perp}}$$



$$\gamma_0 = -\gamma_{E1E1} - \gamma_{E1M2} - \gamma_{M1M1} - \gamma_{M1E2}$$

$$\gamma_\pi = -\gamma_{E1E1} - \gamma_{E1M2} + \gamma_{M1M1} + \gamma_{M1E2}$$

$\gamma_0 = (-1.00 \pm 0.13) \times 10^{-4}$ fm^4

J. Ahrens *et al*. (GDH/A2), PRL **87**, 022003 (2001);
H. Dutz et al. (GDH), PRL **91**, 192001 (2003).

$\gamma_\pi = (-38.7 \pm 1.8) \times 10^{-4}$ fm^4

Recent result from MAMI
M. Camen *et al*., PRC **65**, 032202(R) (2022).

Beam Polarization

i = 1: unpolarized
i = 2: circular polarization
i = 3: linear polarization

Recent and Future Measurements:

Observable	Proton	Neutron: ^{2}H	Neutron: ^{3}He	Neutron: ^{4}He
$d\sigma/d\Omega$	MAMI/ **HIGS**	**HIGS**	**HIGS**	**HIGS**
Σ_3	MAMI/ **HIGS**			
Σ_{2x}	MAMI **HIGS**	**HIGS**		
Σ_{2z}	MAMI **HIGS**	**HIGS**		

HIGS unpolarized targets
HIGS liquid ^{3}He target
HIGS with polarized target capability

Outlook

Courtecy of Calvin R. Howell

- **Reduce uncertainty in the neutron scalar polarizabilities**
  - The goal is to reduce the uncertainties to be on par with the proton
  - Perform high-precision cross-section and Σ_3 Compton-scattering measurements on ^2H, ^3He and ^4He at E_γ = 100 to 130 MeV (e.g., map out $\alpha^n(\omega)$ over the π production threshold cusp)
- **Map out proton scalar polarizabilities over the unitary cusp**
  - Perform cross-section and Σ_3 Compton-scattering cross-section measurements on the proton at E_γ = 100 to 150 MeV
- **Determine proton spin polarizabilities up to pion-production threshold**
  - Measure asymmetry data (Σ_3, Σ_{2z} and Σ_{2x}) at energies E_γ = 100 to 130 MeV; complement data from Mainz
  - Use several χEFT calculations for reliable assessment of model dependence
- **Determine the neutron spin polarizabilities**
  - Measure asymmetry data (Σ_{2z} and Σ_{2x}) at energies E_γ = 100 to 300 MeV for Compton-scattering on polarized ^2H and ^3He targets; E_γ = 100 – 150 MeV at HIGS and E_γ = 250 – 300 MeV at Mainz

Outlook

Courtecy of Calvin R. Howell

- **Reduce uncertainty in the neutron scalar polarizabilities**
  - The goal is to reduce the uncertainties to be on par with the proton
  - Perform high-precision cross-section and Σ_3 Compton-scattering measurements on ^{2}H, ^{3}He and ^{4}He at E_γ = 100 to 130 MeV (e.g., map out $\alpha^n(\omega)$ over the π production threshold cusp)
- **Map out proton scalar polarizabilities over the unitary cusp**
  - Perform cross-section and Σ_3 Compton-scattering cross-section measurements on the proton at E_γ = 100 to 150 MeV
- **Establish a Cryogenic Polarized Proton Program**
  - Obtain funding for a TUNL staff position in low-temperature physics to lead polarized target R&D program
  - Obtain funding to build polarized target technical infrastructure
- **Improve determination of proton spin polarizabilities**
  - Measure asymmetry data (Σ_{2z} and Σ_{2x}) at energies E_γ = 100 to 130 MeV; complement data from Mainz at E_γ = 260 - 310 MeV
  - Use several χEFT calculations for reliable assessment of model dependence
- **Determine the neutron spin polarizabilities**
  - Measure asymmetry data (S_{2z} and S_{2x}) at energies E_γ = 100 to 130 MeV for Compton-scattering on polarized ^{2}H at E_γ = 100 – 130 MeV

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HIGS Compton Collaboration

Groups from 13 institutions: 10 USA + 3 international

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4) **Montclair State University:** K. Leung
5) **Mount Alison Univ.**, David Hornidge
6) **NC Central Univ.:** M.W. Ahmed, B. Crowe, D. Markoff
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13) **Univ. Saskatchewan:** R. Pywell

Blue font = TUNL consortium institution
Red font = Theorist

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Thanks for your attention!