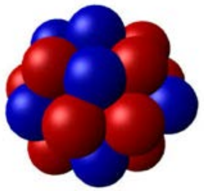
Experiments with Photon Beams at the HIγS Facility

TUNL

Calvin R. Howell

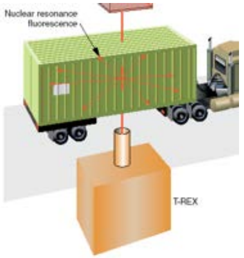
Duke University and Triangle Universities Nuclear Laboratory (TUNL)

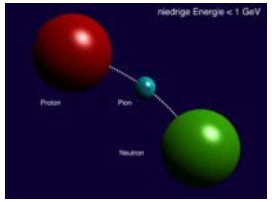
Program Components:



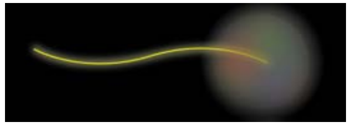
- Nuclear structure and Astrophysics: NRF, (γ, particle) and (γ, fission) at $E_\gamma < 20$ MeV; and Compton scattering at $E_\gamma < 60$ MeV

- Applications: $E_\gamma < 20$ MeV





- Investigation of the strong nuclear force in the context of few-nucleon systems: *photodisintegration of 3N systems*

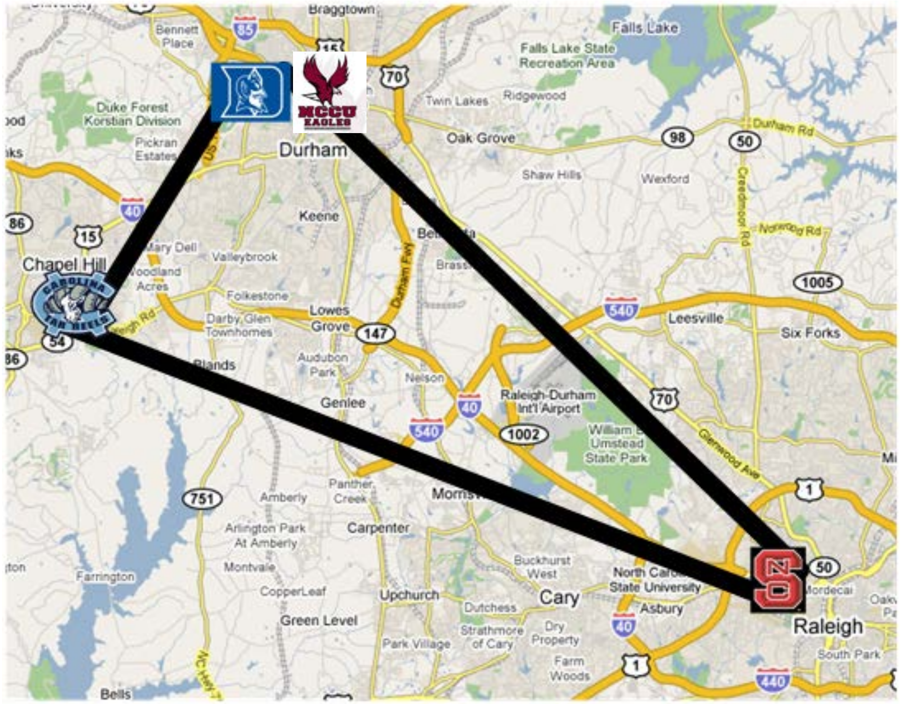
* 

- Nucleon structure in terms of low-energy effective degrees of freedom: Compton scattering at $E_\gamma > 60$ MeV

* Picture from: J. Arrington, arXiv:1208.4047v1[nucle-ex]

Triangle Universities Nuclear Laboratory (TUNL)

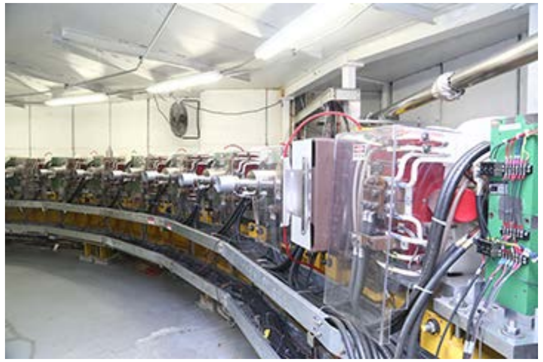
- High Intensity Gamma-ray Source (HIγS) is operated by the Triangle Universities Nuclear Laboratory (TUNL)
- Which is one of four U.S. Department of Energy (DOE) Centers of Excellence in Nuclear Physics
- TUNL consists of 4 universities in the Research Triangle Area in North Carolina: Duke University and NC Central University in Durham, NC State University in Raleigh, and The University of NC in Chapel Hill
- HIγS is located on the campus of Duke University

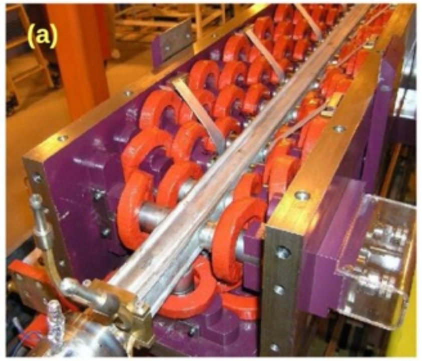


High Intensity Gamma-ray Source (HIγS)

Features that enable basic and applied research

- Wide beam energy range: 1 to 110 MeV
- Selectable beam energy spread (by collimation)
- High beam intensity on target ($>10^7$ γ/s @ $\Delta E/E = 5\%$)
- >95% beam polarization (linear and circular)

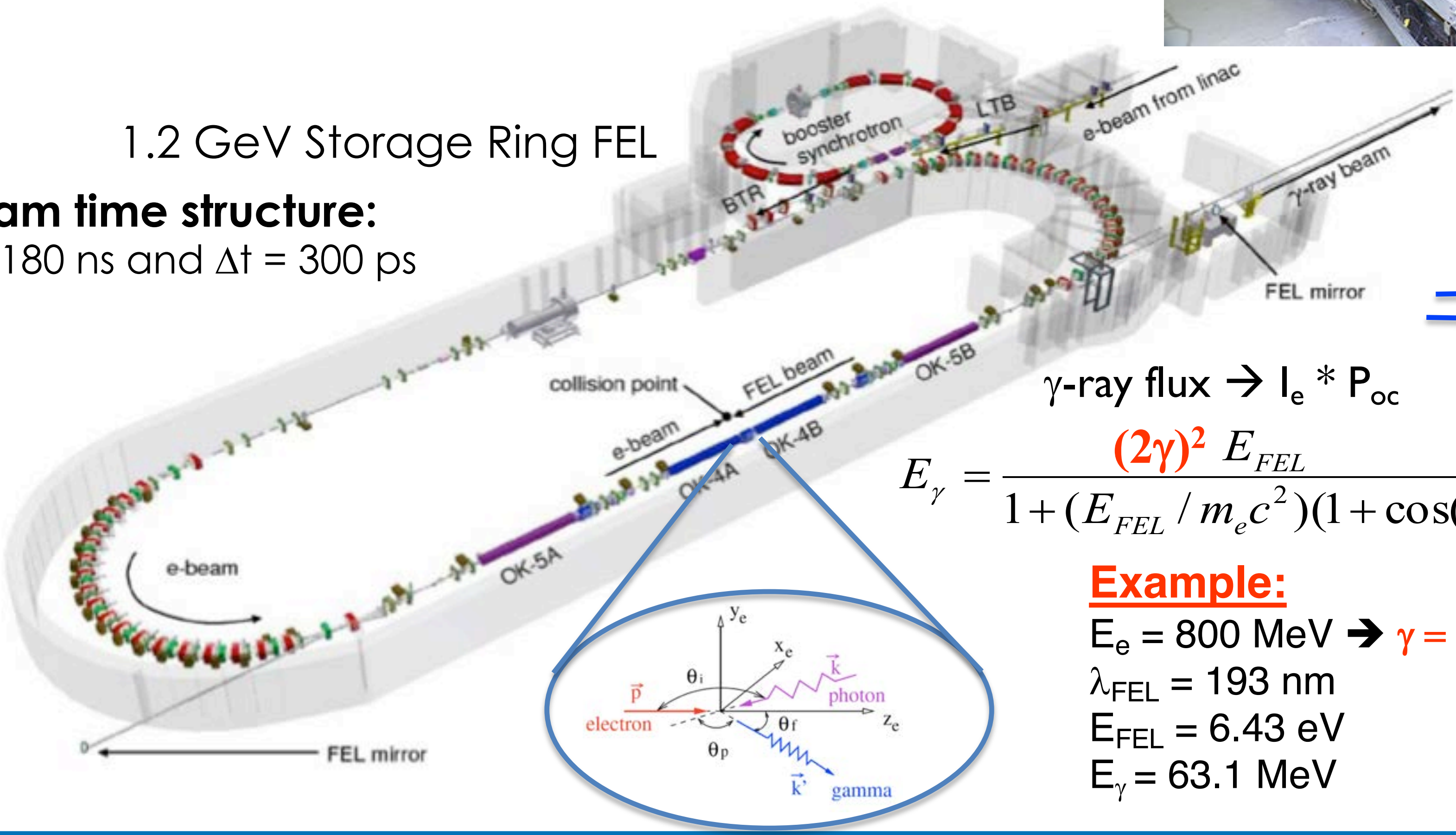




1.2 GeV Storage Ring FEL

Beam time structure:

T = 180 ns and Δt = 300 ps



γ-ray flux → $I_e * P_{oc}$

$$E_\gamma = \frac{(2\gamma)^2\ E_{FEL}}{1 + (E_{FEL}/m_e c^2)(1+\cos(\theta))}$$

Example:

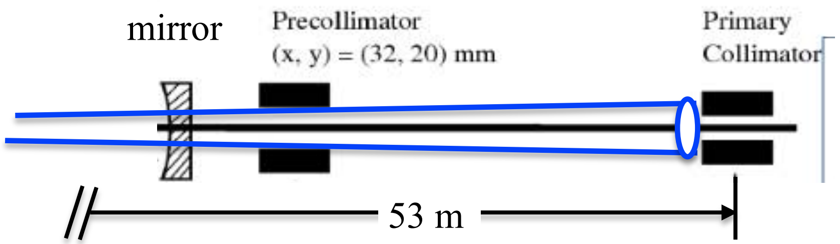
E_e = 800 MeV → $\gamma = 1566$

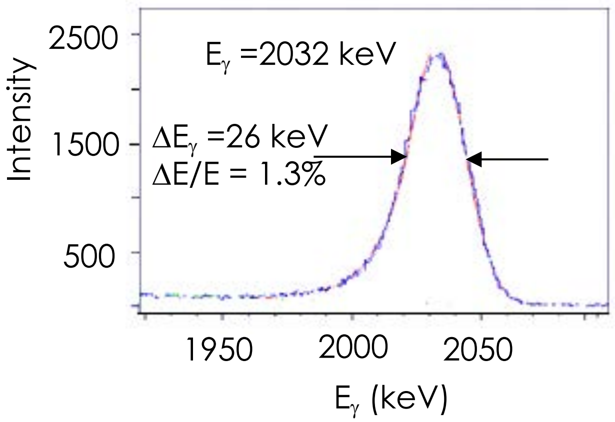
λ_{FEL} = 193 nm

E_{FEL} = 6.43 eV

E_γ = 63.1 MeV

Energy resolution by collimation





Zoomed Out View of Research at HIγS

HIγS operates about 1800 hours/year for nuclear physics research

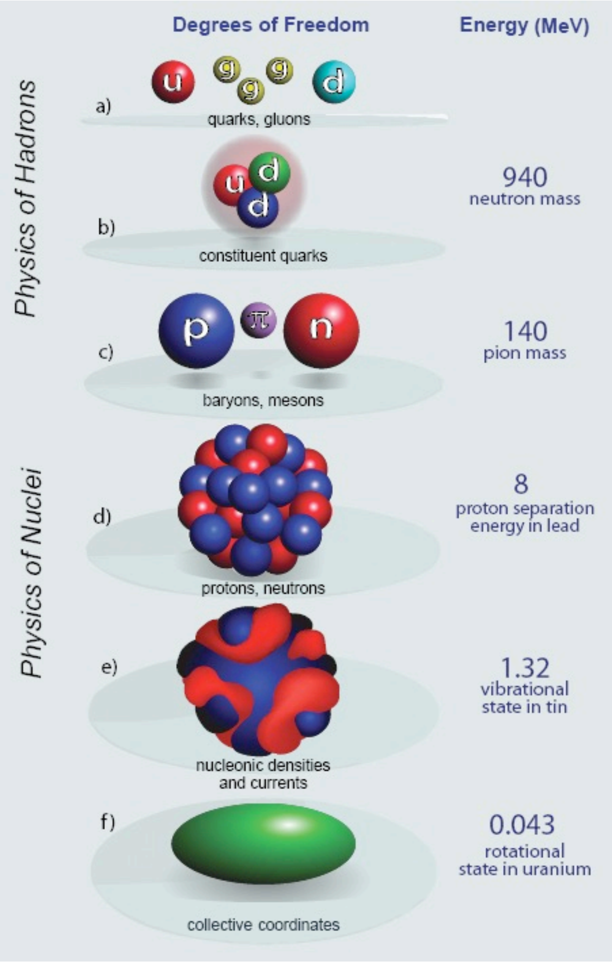


Figure from 2007 USA Nuclear Science LRP

Low-Energy QCD:

Compton Scattering

nucleon electric and magnetic polarizabilities

nucleon spin polarizabilities

Few-nucleon Systems

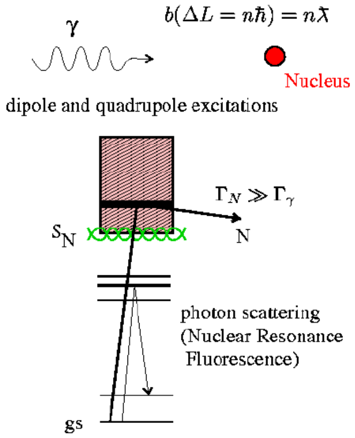
photodisintegration of ^{2}H, ^{3}He and ^{3}H (cross sections, target-beam helicity dependent cross sections, polarization transfer)

Many-body Strongly Interacting Systems:

Nuclear Structure and Nuclear Astrophysics

NRF, (γ,γ')

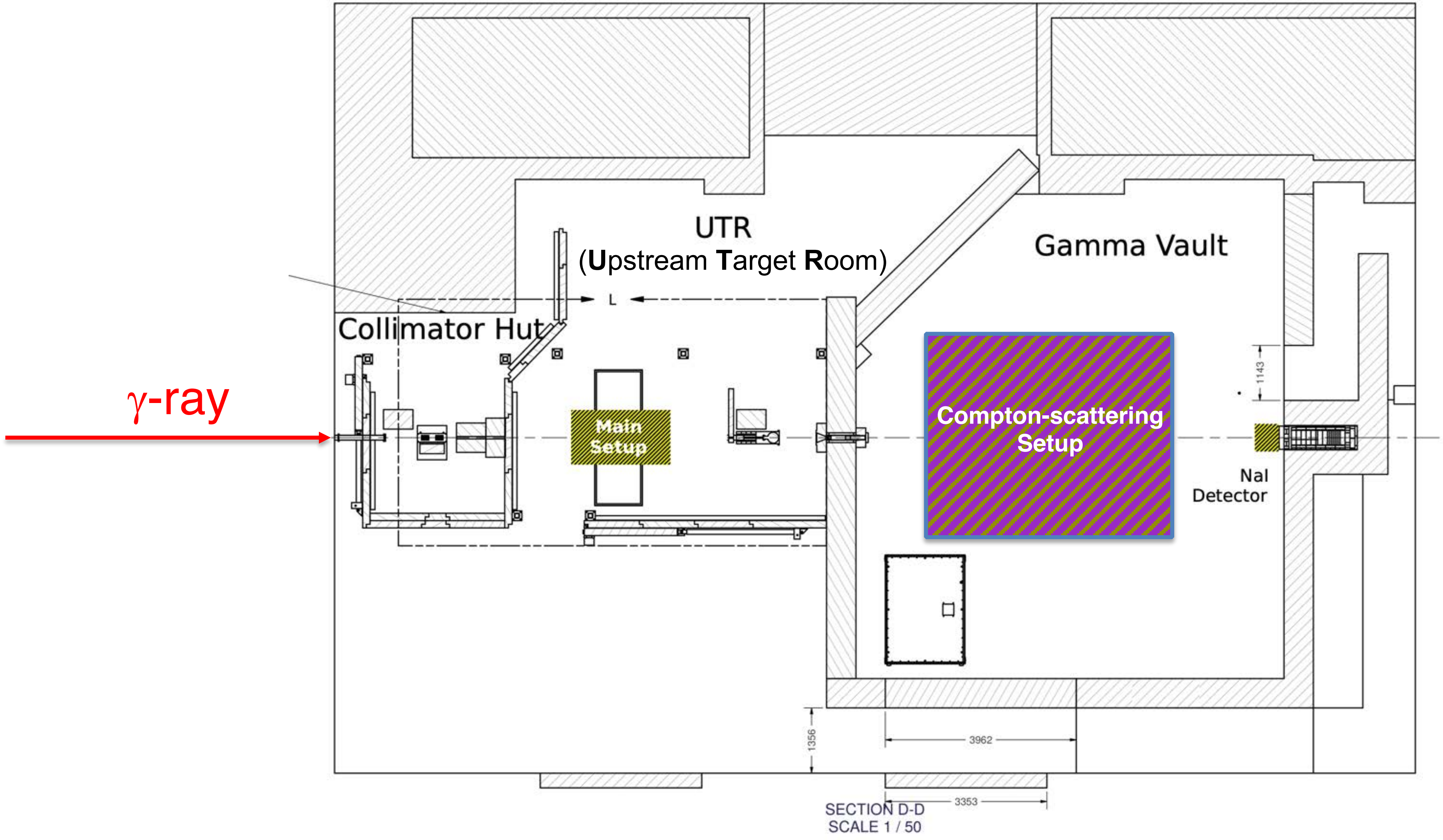
(γ,n), (γ,p), (γ,α) and (γ, fission) reactions



Applied Research:

- Nuclear Security
- Medical Isotope R&D
- Particle Detector R&D

Target Room Layout at HIγS



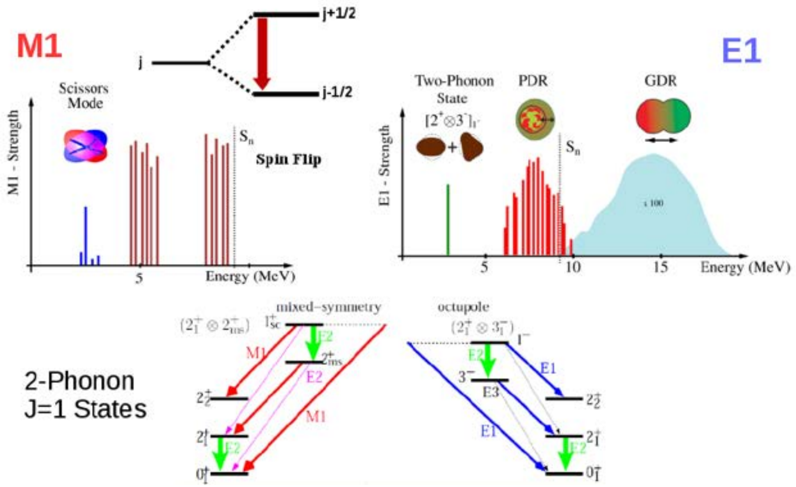
TUNL

A. Nuclear Structure and Many-Body Reactions

A.1. NRF (γ,γ’), (γ,n), (γ,α)
- Collective excitations, e.g., PDR, multiple phonon exchange
- Dipole strength (M1 and E1)
- Structure near the ground state (shapes, coexistence, effective int.)

A.2. Compton Scattering (linearly polarized beam) from Nuclei
- IVGQR → Asymmetry term in the nuclear EOS

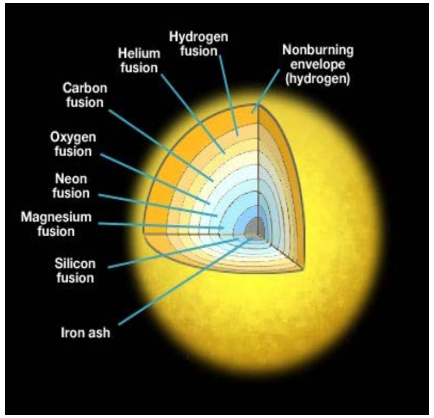
A.3. Photon-Induced Fission
- Fission Product Yields **(activation)**
- Cross sections **(fission chamber and prompt neutron detection)**



B. Nuclear Astrophysics

B.1. NRF (γ,γ’)
- Dipole strength function (M1 and E1)
- Identification & properties of states near/at the particle threshold

B.2. (γ,n), (γ,p) and (γ,α) reaction measurements
- Cross sections near reaction threshold
- Resonance studies



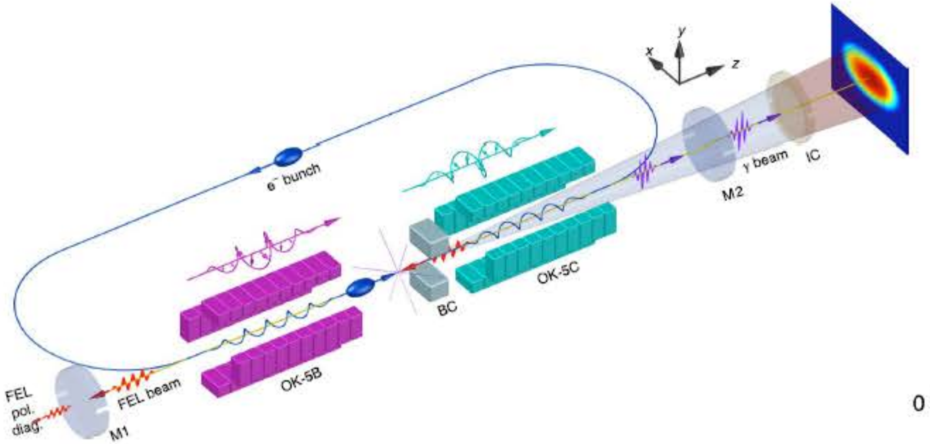
The mass and size of the final iron core is critically dependent on the $^{12}C(\alpha,\gamma)^{16}O$ reaction rate

$\alpha + \alpha + \alpha \rightarrow {}^{12}C + \gamma$; production of ^{12}C during helium burning

$^{12}C + \alpha \rightarrow {}^{16}O + \gamma$; converts ^{12}C to ^{16}O

➔ determines $^{12}C/^{16}O$

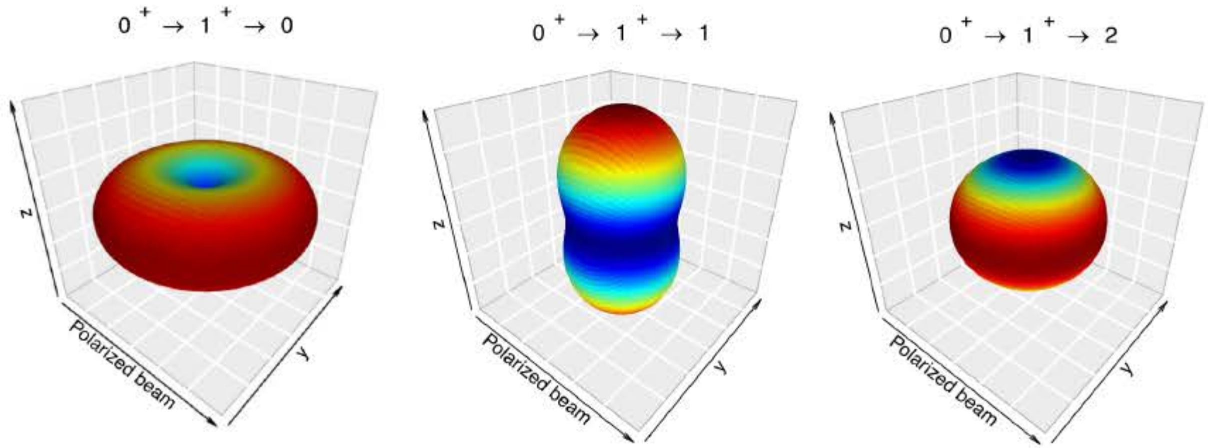
HIγS @ TUNL



- Highly intense ($\approx 10^8 \gamma s^{-1}$)
- Quasi-monochromatic ($\mathrm{FWHM} \approx 100 - 300\,\mathrm{keV}$)
- Polarized ($> 99\%$)
- Bunched ($5.58\,\mathrm{MHz}$)

H. R. Weller *et al.*, *Research opportunities at the upgraded HIγS facility*, Prog. Part. Nucl. Phys. **62**, 257 (2009)

- EM excitation from ground state like Coulomb Excitation plus polarization information.
- Decay of high-lying states like neutron capture, but variable energy.

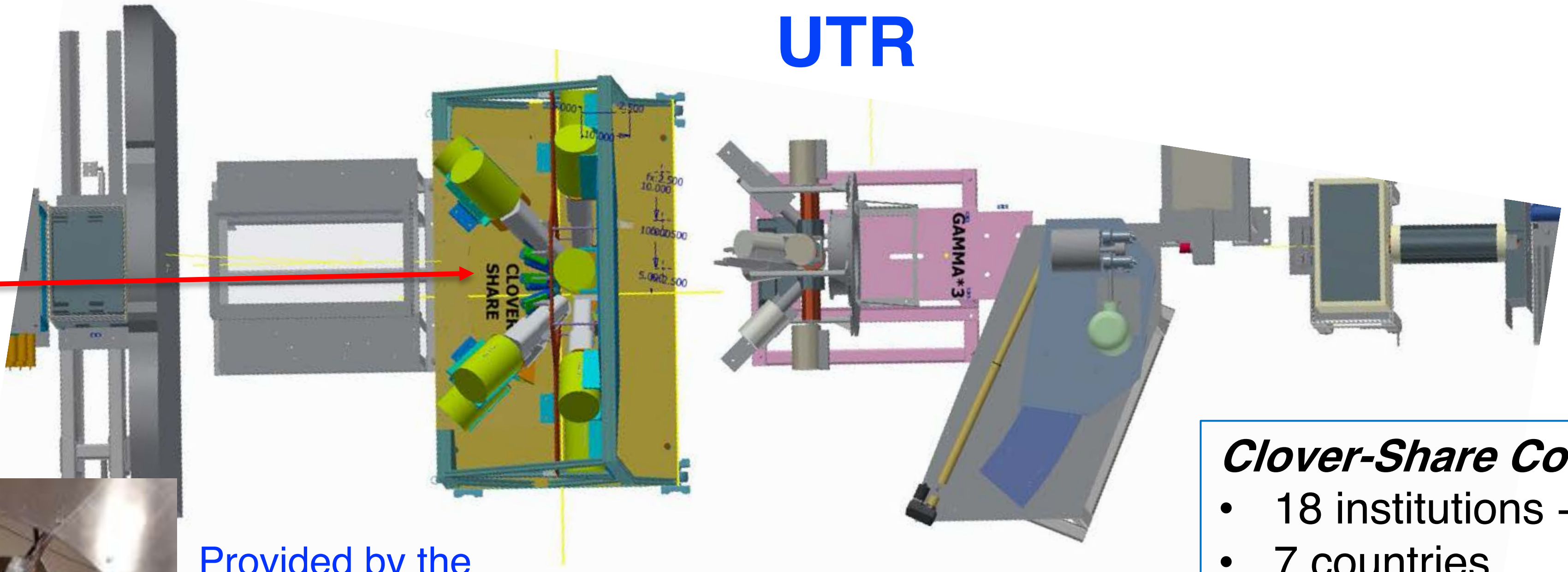


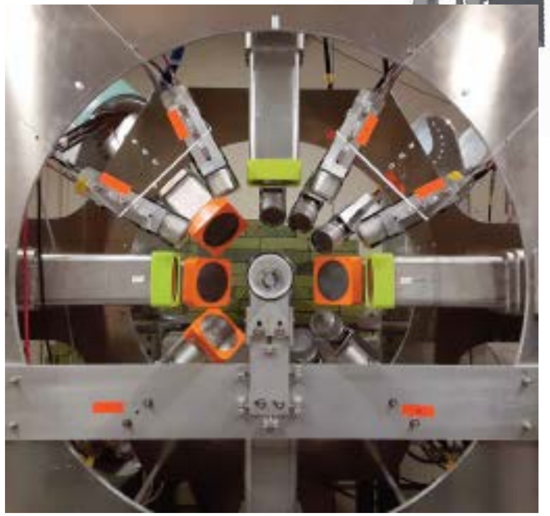
A. Zilges *et al.*, *Photonuclear reactions – From basic research to applications*, Prog. Part. Nucl. Phys. *in press*
C. Iliadis and U. Friman-Gayer, *Linear polarization-direction correlations in γ-ray scattering experiments*, Eur. Phys. J. A **57**, 190 (2021)

Nuclear Structure and Astrophysics: Clover-share Array

UTR

γ-ray beam





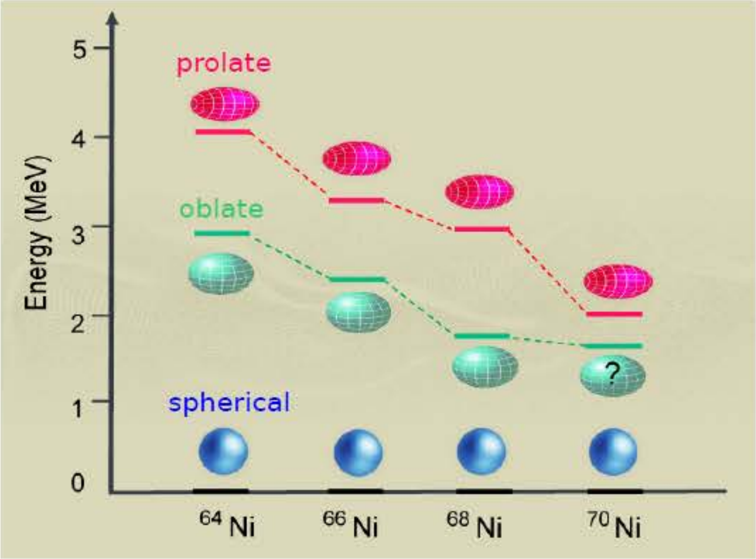
Provided by the Clover Share Consortium, the US Naval Academy, the US Army Research Lab, and TUNL

- 8 HPGe clover detectors
- Up to 12 CeBr scintillator detectors

Clover-Share Collaboration
- 18 institutions + TUNL
- 7 countries

Argonne National Lab (USA)	Technische Universität Darmstadt (Germany)
Diakonie-Klinikum Schw¨abisch Hall (Germany)	U.S. Naval Academy (USA)
GSI Helmholtz Centre (Germany)	Univ. of Kentucky (USA)
Helmholtz-Zentrum Dresden-Rossendorf (Germany)	Univ. of Köln (Germany)
Inst. for Nuclear Research (Hungary)	Univ. Libre de Bruxelles (Belgium)
James Madison Univ. (USA)	Univ. of Oslo (Norway)
Lawrence Livermore National Lab (USA)	Univ. of the West Scotland (Scotland)
Mississippi State Univ. (USA)	Univ. of Witwatersrand (South Africa)
NSCL/Michigan State Univ. (USA)	Univ. of Zululand (South Africa)

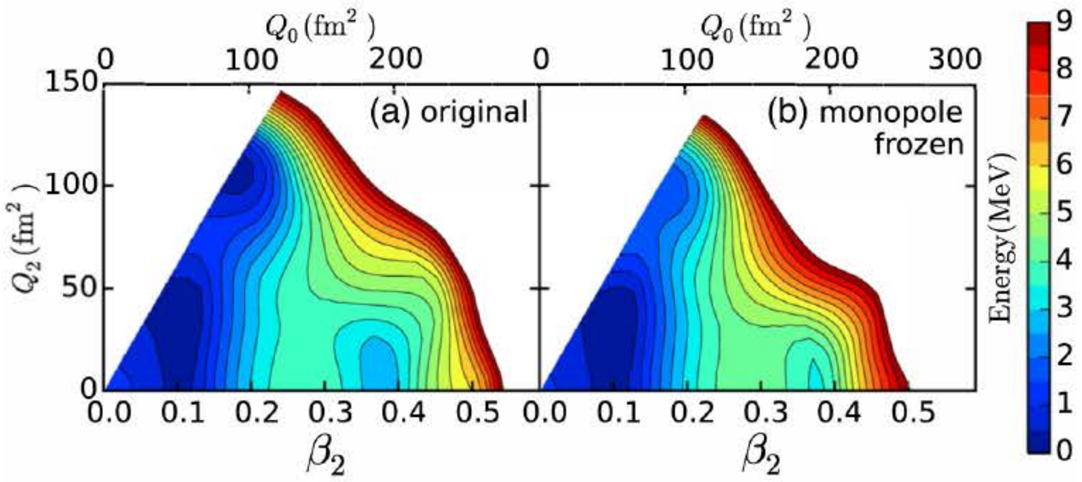
Shape Coexistence in Nickel Isotopes



- Triple shape coexistence
- Signatures
  - Spin sequences (0^+ states)
  - Transitions strengths ($E0$, $E2$)
  - Multipole mixing ratios

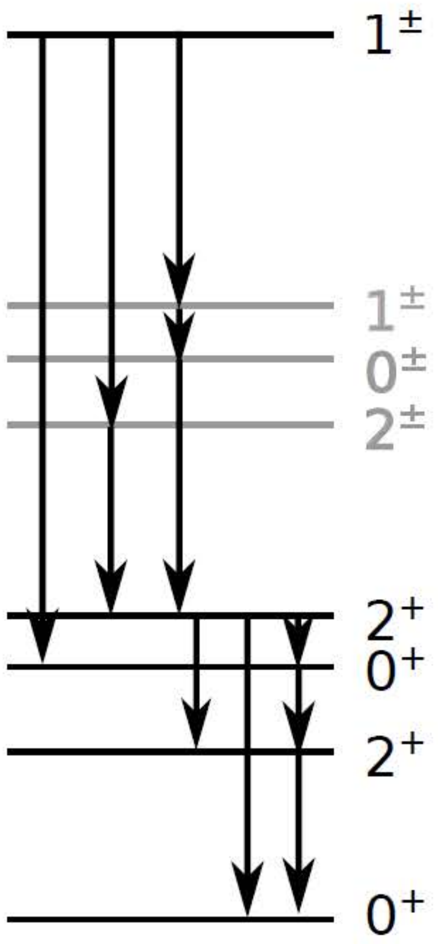
K. Heyde and J. L. Wood, *Shape coexistence in atomic nuclei*, Rev. Mod. Phys. **83** 1467 (2011)

- Theoretical description of exotic nickel isotopes
  - Large model space
  - Monopole tensor interaction
- Predictions for stable ^{64}Ni



N. Mărginean *et al.*, *Shape Coexistence at Zero Spin in ^{64}Ni Driven by the Monopole Tensor Interaction*, Phys. Rev. Lett. **125**, 102502 (2020)
T. Otsuka *et al.*, *Underlying Structure of Collective Bands and Self-Organization in Quantum Systems*, Phys. Rev. Lett. **123**, 222502 (2019)

Shape Coexistence in ^{64}Ni

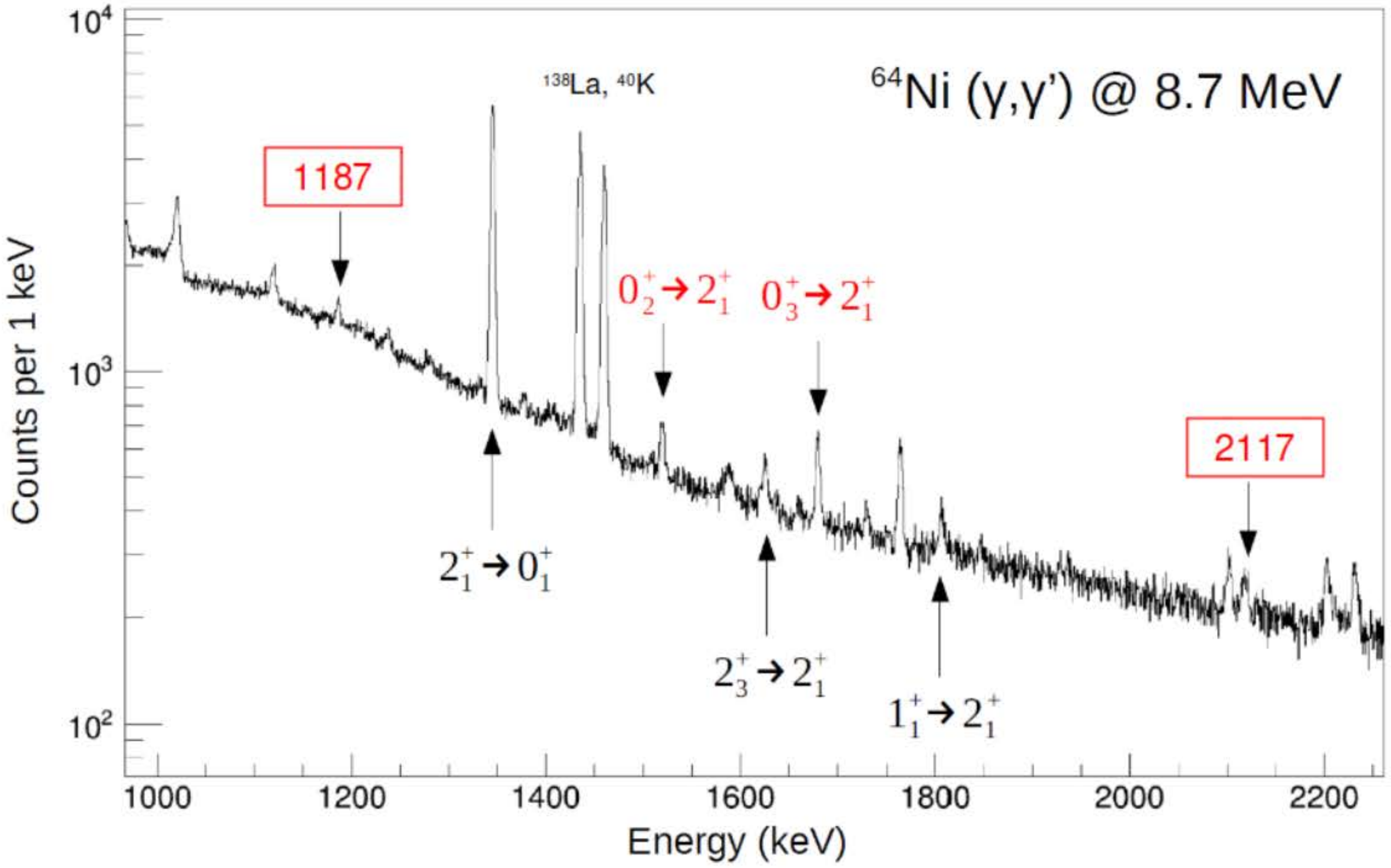


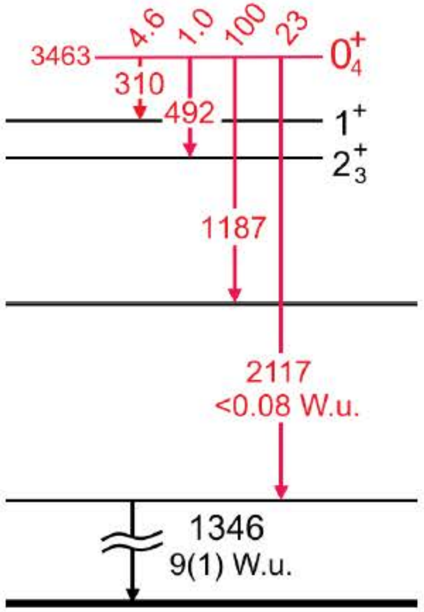
^{64}Ni

- 2*n* Transfer @ IFIN-HH
  - Decay of up to spin-7 states up to 4.6 MeV
  - Lifetimes
- Multi-step Coulomb Excitation @ ANL
  - Excitation from ground state, purely electromagnetic (EM)
  - Transition matrix elements
- Neutron Capture @ ILL
  - Decay of 0^-, 1^- capture states at 9657 keV
  - Branching ratios, multipole mixing ratios
- **Nuclear Resonance Fluorescence @ TUNL**
  - Decay of dipole-excited states at various energies, purely EM, polarized beam
  - Branching ratios, mixing ratios, lifetimes, matrix elements

N. Mărginean *et al.*, *Shape Coexistence at Zero Spin in ^{64}Ni Driven by the Monopole Tensor Interaction*, Phys. Rev. Lett. **125**, 102502 (2020)

HPGe Sum Spectrum





nature COMMUNICATIONS

ARTICLE

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https://doi.org/10.1038/s41467-021-26179-x

OPEN

Precision measurements on oxygen formation in stellar helium burning with gamma-ray beams and a Time Projection Chamber

R. Smith[1,2]✉, M. Gai[2], S. R. Stern[2], D. K. Schweitzer[2] & M. W. Ahmed[3,4]

The carbon/oxygen (C/O) ratio at the end of stellar helium burning is the single most important nuclear input to stellar evolution theory. However, it is not known with sufficient accuracy, due to large uncertainties in the cross-section for the fusion of helium with ^{12}C to form ^{16}O, denoted as $^{12}C(\alpha,\gamma)^{16}O$. Here we present results based on a method that is significantly different from the experimental efforts of the past four decades. With data measured inside one detector and with vanishingly small background, angular distributions of the $^{12}C(\alpha,\gamma)^{16}O$ reaction were obtained by measuring the inverse $^{16}O(\gamma,\alpha)^{12}C$ reaction with gamma-beams and a Time Projection Chamber (TPC) detector. We agree with current world data for the total reaction cross-section and further evidence the strength of our method with accurate angular distributions measured over the 1^- resonance at $E_{cm} \sim 2.4$ MeV. Our technique promises to yield results that will surpass the quality of the currently available data.

Optical Time Projection Chamber (O-TPC)

TUNL

JINST

PUBLISHED BY IOP PUBLISHING FOR SISSA

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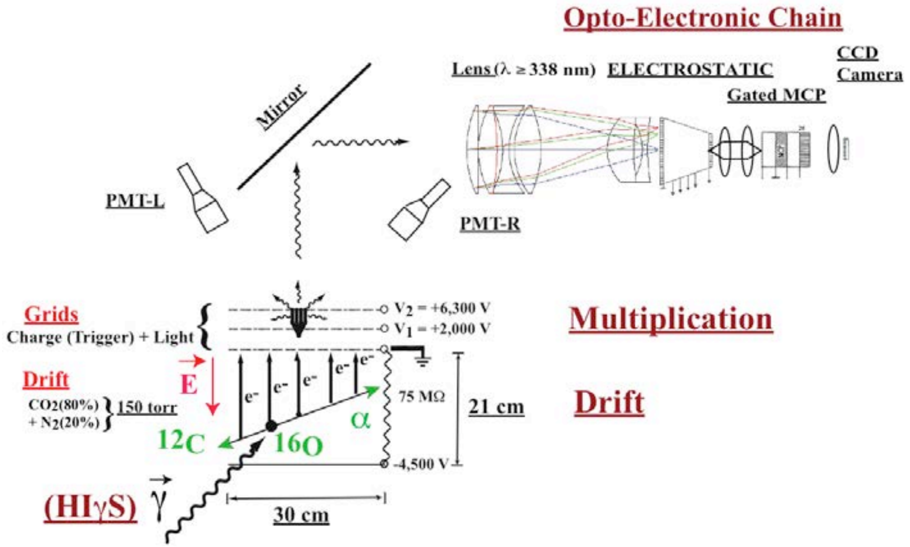
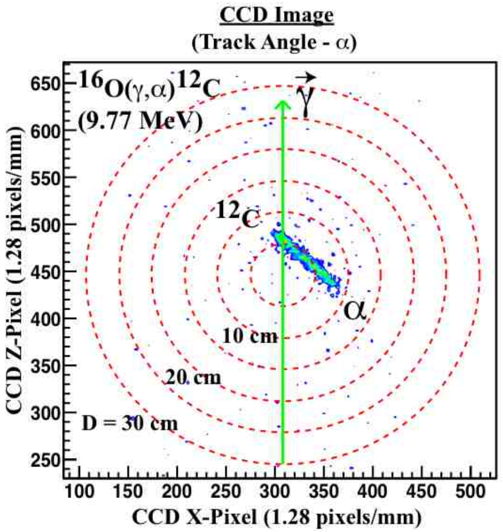
ACCEPTED: *November 22, 2010*
PUBLISHED: *December 15, 2010*

An optical readout TPC (O-TPC) for studies in nuclear astrophysics with gamma-ray beams at HIγS[1]

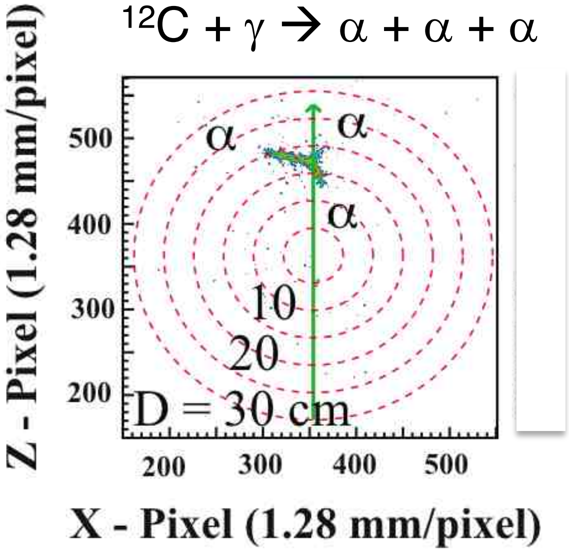
M. Gai,[a,b,2] M.W. Ahmed,[c] S.C. Stave,[c] W.R. Zimmerman,[a,b] A. Breskin,[d] B. Bromberger,[e] R. Chechik,[d] V. Dangendorf,[e] Th. Delbar,[f] R.H. France III,[g] S.S. Henshaw,[c] T.J. Kading,[a] P.P. Martel,[c,h] J.E.R. McDonald,[b,i] P.-N. Seo,[a,c] K. Tittelmeier,[e] H.R. Weller[c] and A.H. Young[a]

2. The O-TPC Detector System
2.1 The TPC



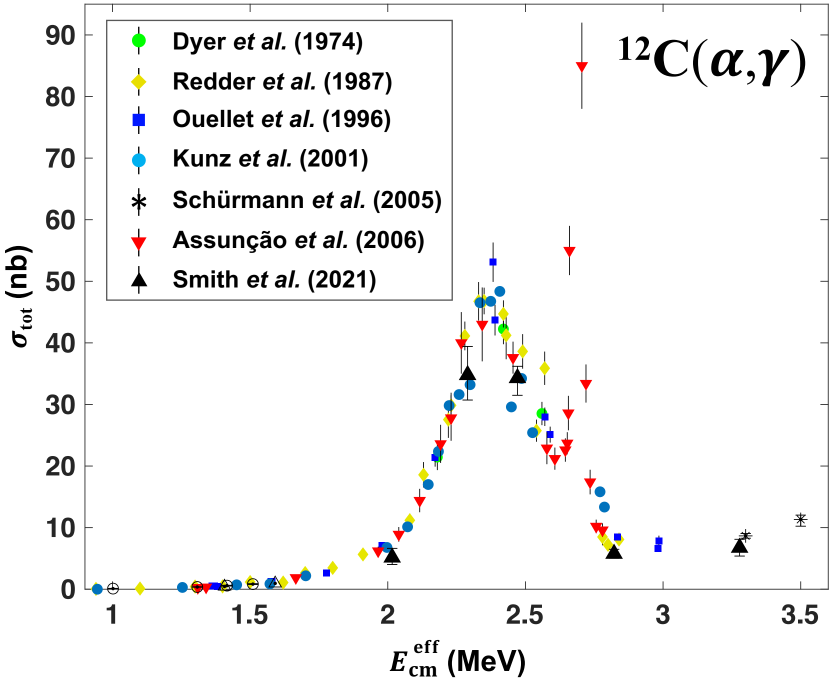


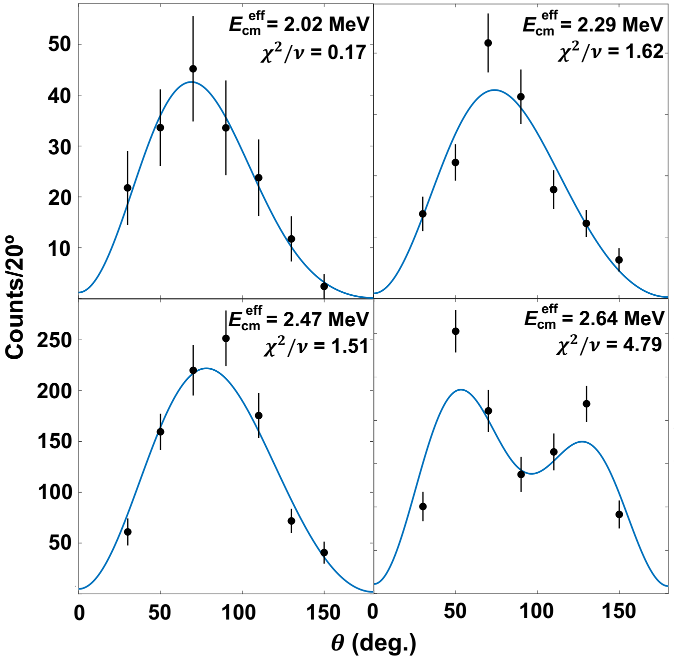
$^{12}C + \gamma \rightarrow \alpha + \alpha + \alpha$

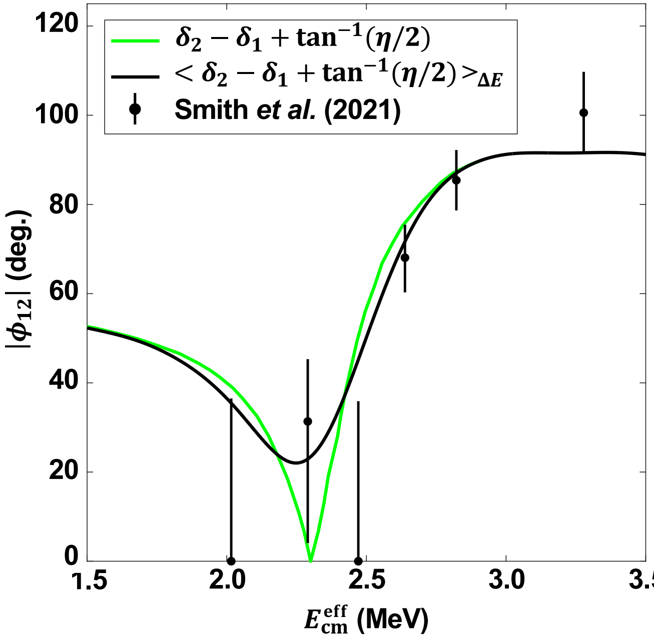


Nuclear Astrophysics: NATURE COMMUNICATIONS | https://doi.org/10.1038/s41467-021-26179-x

$$^{12}C + \alpha \leftrightarrow {}^{16}O + \gamma$$

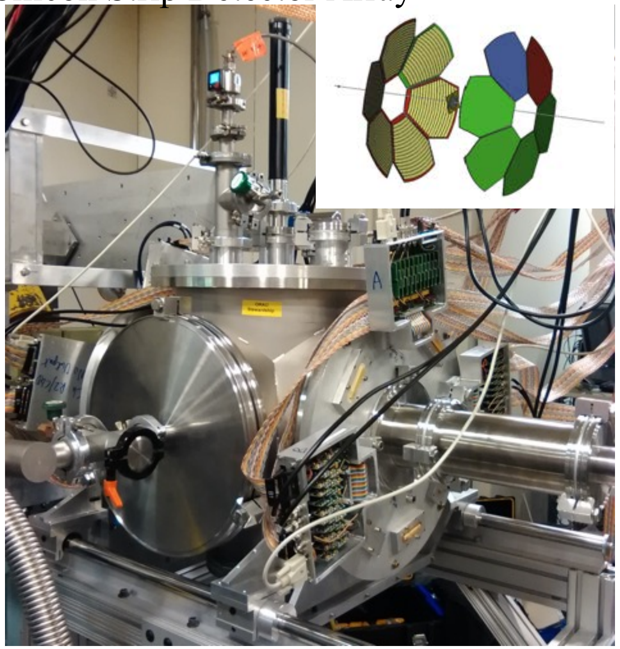




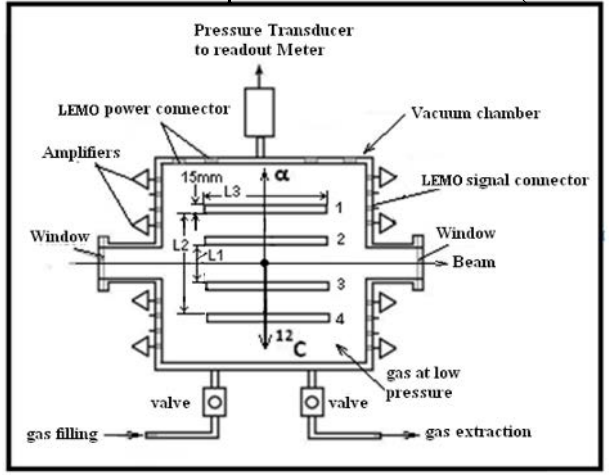


$$
\begin{aligned}
W(\theta) = {} & (3|A_{E1}|^2 + 5|A_{E2}|^2)P_0(\cos\,\theta) \\
& + \left(\frac{25}{7}|A_{E2}|^2 - 3|A_{E1}|^2\right)P_2(\cos\,\theta) \\
& - \frac{60}{7}|A_{E2}|^2 P_4(\cos\,\theta) \\
& + 6\sqrt{3}|A_{E1}||A_{E2}|\cos\,\phi_{12}\left[P_1(\cos\,\theta) - P_3(\cos\,\theta)\right],
\end{aligned}
$$

Silicon Strip Detector Array



Multi-Wire Proportional Chamber (MWPC)

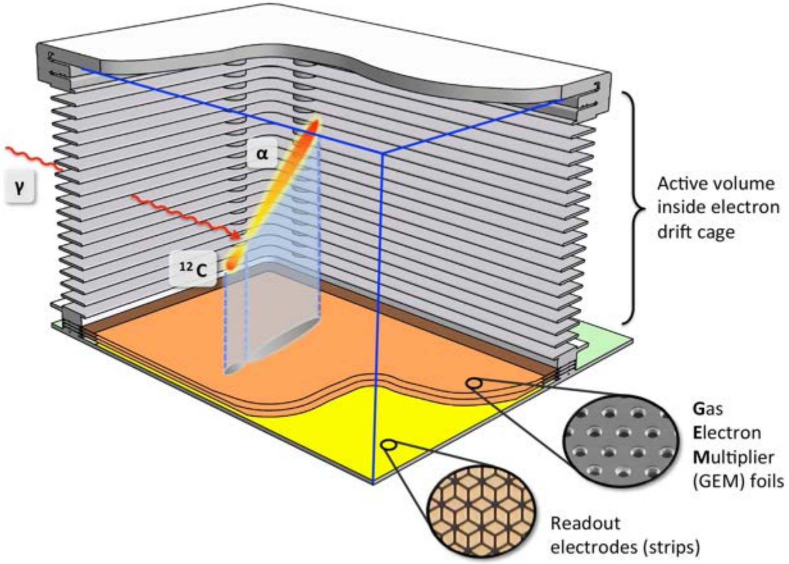


Photon-induced Nuclear Reactions with Emission of Charged Particles

Examples:

- ^{16}O(γ, α), ^{12}C(γ, 3α)
- ^{9}Be(γ, αα)n
- ^{2}H(γ, p)
- ^{7}Li(γ, t)

Time Projection Chamber (TPC)



Users

- 20 institutions + TUNL
- 10 countries

ANL (USA)	Sheffield Hallam Univ. (UK)
C.S.N.S.M, Orsay (France)	Sungkyunkwan (S. Korea)
ELI-NP and IFNN-HH (Romania)	Texas A&M Univ. (USA)
INFN, Catania (Italy)	TU Darmstadt (Germany)
Joint Res. Center, EC (Belgium)	Univ. Birmingham (UK)
LBNL (USA)	Univ. Connecticut (USA)
MTA Atomki (Hungary)	Univ. of Kentucky (USA)
NSCL/Michigan State Univ. (USA)	Univ. of Mainz (Germany)
ORNL (USA)	Univ. of Warsaw (Poland)
Ohio Univ. (USA)	Univ. of York (UK)

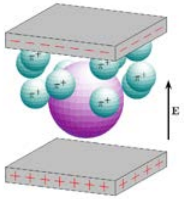
C. Low-Energy QCD

C.1. Compton Scattering from Unpolarized Nuclei:

Proton and Light Nuclei (A < 5)

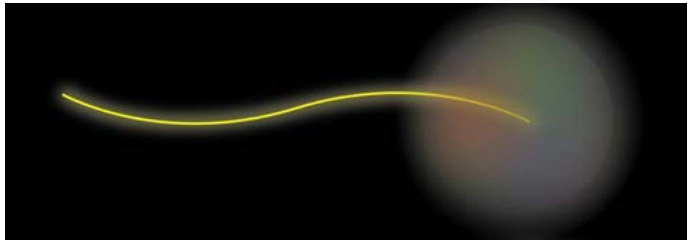
$d\sigma(\theta)/d\Omega$, Σ_{beam}, Σ_3 → [EFT analysis] → α^p, β^p, γ^p, α^N, β^N α^n, β^n

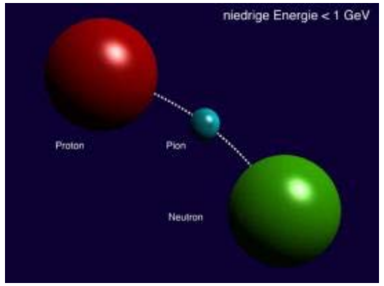
α



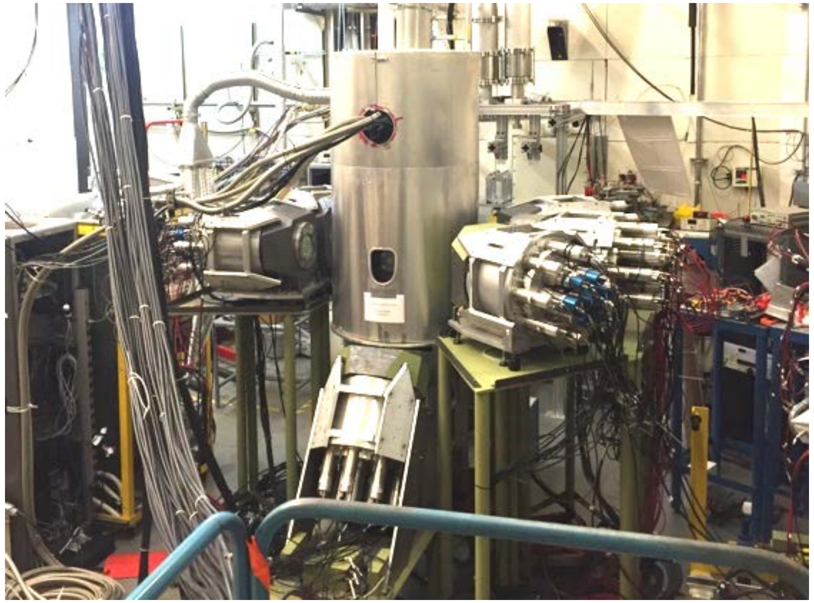
C.2. Polarization transfer in photodisintegration of ^2H

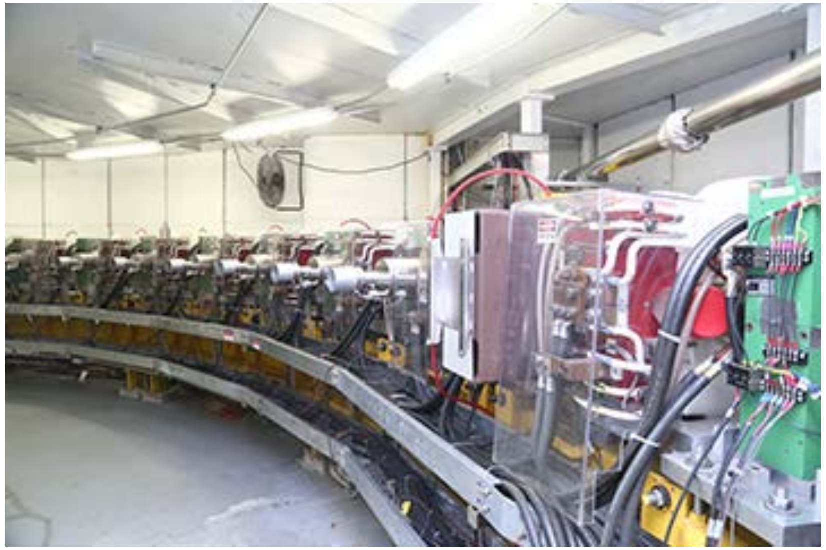
C.3. Photodisintegration of Few-Nucleon Systems, e.g., ^3He, ^3H





* Picture from: J. Arrington, arXiv:1208.4047v1 [nucle-ex]





Investigation of the ^{3}He GDH Sum Rule

S.B.Gerasimov in Sov. J. Nucl. Phys.; S.D. Drell *et al.*, in Phys. Rev. Lett. (1966)

$$I^{GDH} = \int_{\nu_{thr}}^{\infty} \frac{d\nu}{\nu}\left[\sigma_N^P(\nu) - \sigma_N^A(\nu)\right] = \frac{4\pi^2\alpha}{M_N^2}\kappa_N^2 I$$

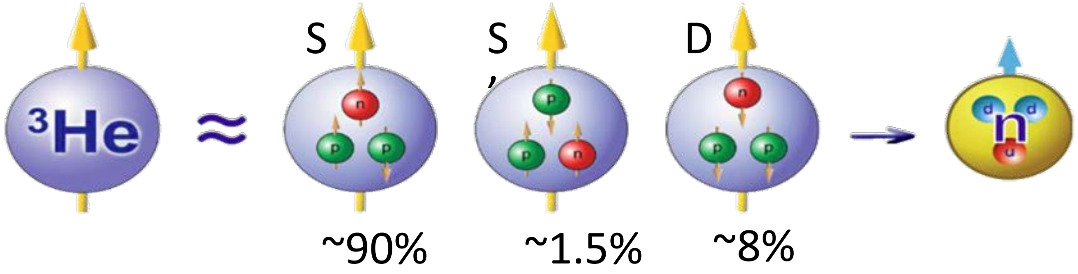
- σ_N^P σ_N^A spin dependent total photon-absorption cross section

  κ_N anomalous magnetic moment

  ν_{thr} pion production/photodisintegration threshold

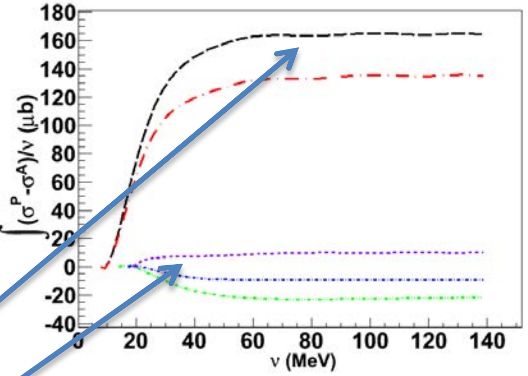
- HIγS provides unique contribution below the pion production threshold
- Connects to higher energy JLab program from inclusive e$^-$ scattering
- Provides stringent tests of few-body calculations
- Tests pol. ^{3}He as effective pol. neutron target

Based on general principles of physics: **Lorentz and gauge invariance, crossing symmetry, causality and unitarity**



Plateau value of the GDH integral of ^{3}He below pion threshold based on state-of-the-art calculations is ~140μb.

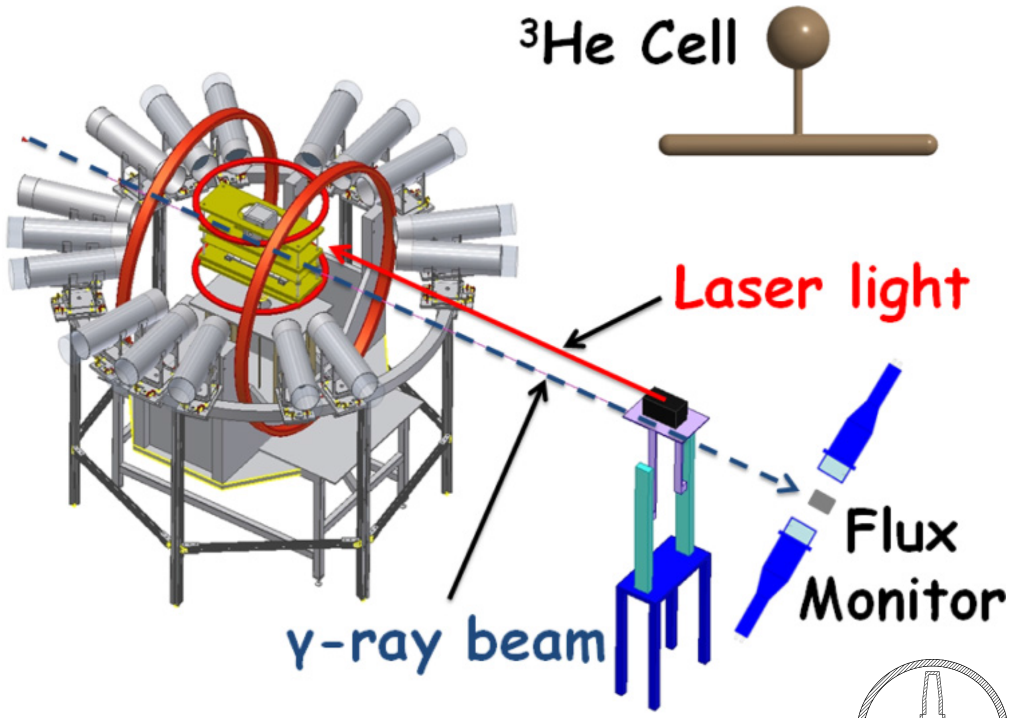
Total $I^{GDH,3He}$=496 μb

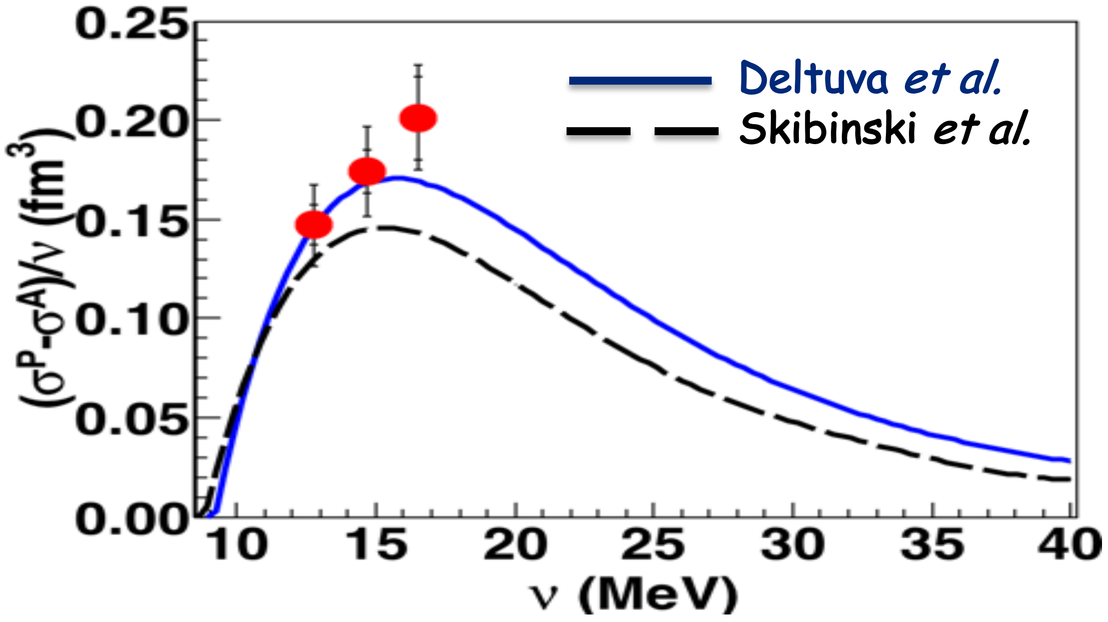


$$\gamma + {}^3He \rightarrow p + p + n$$

$$\gamma + {}^3He \rightarrow p + d$$

HIγS results on ^{3}He GDH integrand from three-body breakup with double polarizations

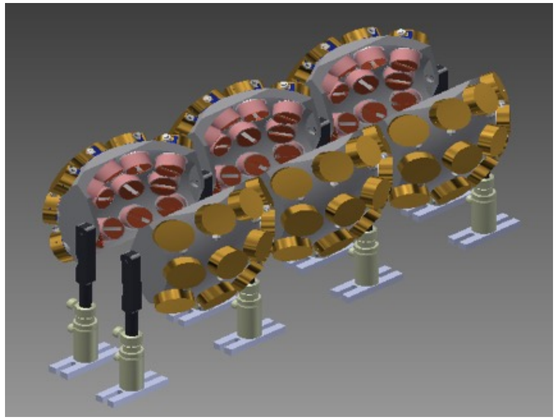


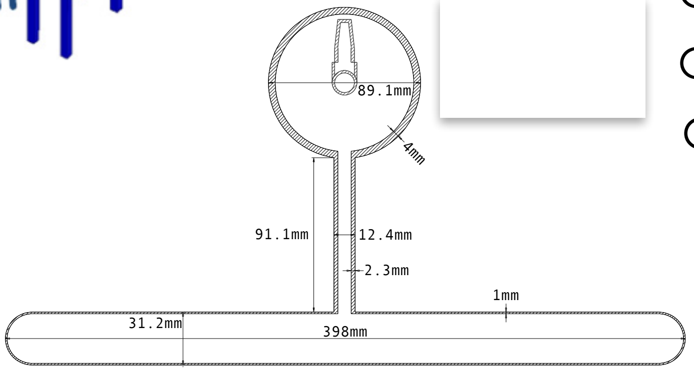


G. Laskaris *et al.*, Phys. Rev. Lett. **110**, 202501 (2013)

G. Laskaris *et al.*, Phys. Rev. C **89**, 024002 (2014)

G. Laskaris *et al.*, Phys. Lett. B **750**, 547 (2015)





Target setup for two-body photodisintegration measurement by detection of protons

GDH Sum Rule: 2-body photodisintegration

First measurement of the asymmetry and the Gerasimov-Drell-Hearn integrand from the $^3\vec{\mathrm{He}}(\vec{\gamma}, p)\,^2\mathrm{H}$ reaction at an incident photon energy of 29 MeV

G. Laskaris,[1,2,*] W. Ji,[3] X. Yan,[1,2] J. Zhou,[1,2] W. R. Zimmerman,[1,2] M. W. Ahmed,[1,4] T. Averett,[5] A. Deltuva,[6] A. C. Fonseca,[6] H. Gao,[1,2,†] J. Golak,[7] A. Kafkarkou,[1,2,‡] H. J. Karwowski,[1,8] B. Lalremruata,[9] J. Manfredi,[10] J. M. Mueller,[1,2] P. U. Sauer,[11] R. Skibiński,[7] A. P. Smith,[1,2] M. B. Tsang,[10] H. R. Weller,[1,2] H. Witała,[7] Y. K. Wu,[1,2] and Z. W. Zhao[1,2]

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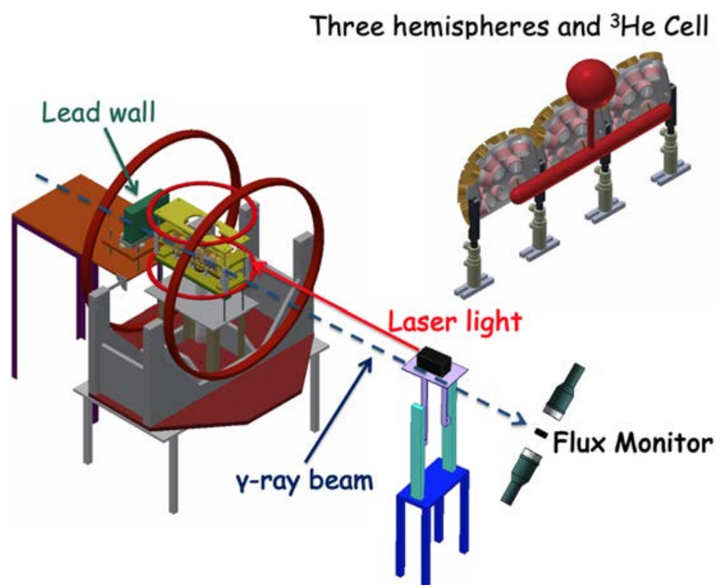
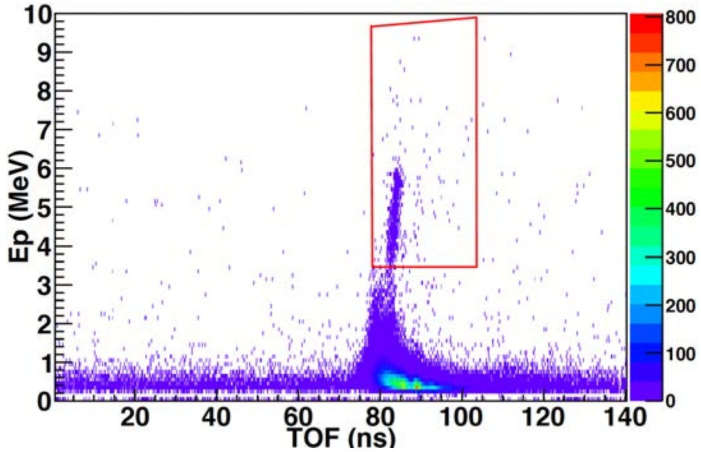
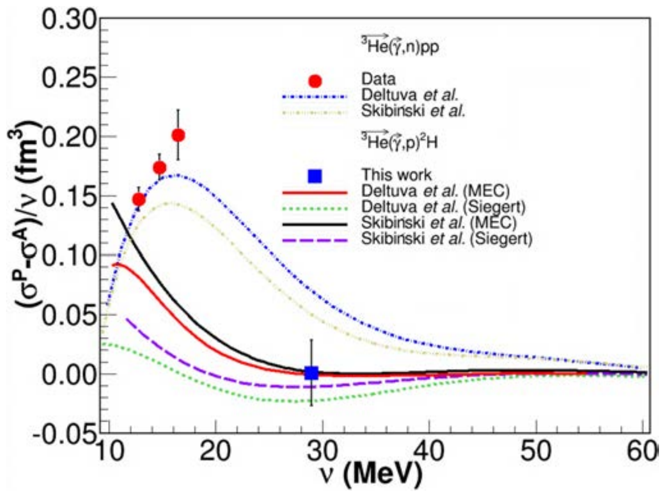
[8]*Department of Physics and Astronomy, University of North Carolina at Chapel Hill, Chapel Hill, North Carolina 27599, USA*
[9]*Mizoram University, Aizawl 796004, India*
[10]*NSCL, Michigan State University, East Lansing, Michigan 48824, USA*
[11]*Institut für Theoretische Physik, Leibniz Universität Hannover, D-30167 Hannover, Germany*







$$T_{fi} = \frac{4\pi W}{M}\sum_{i=1}^{6} \rho_i\, R_i(\omega, z)\,.$$

z = cos(θ)

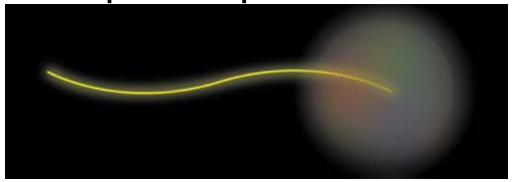
$$\rho_1 = \vec{\epsilon}^{\,\prime *}\cdot\vec{\epsilon}\,, \qquad \rho_2 = \vec{s}^{\,\prime *}\cdot\vec{s}\,,$$
$$\rho_3 = i\,\vec{\sigma}\cdot(\vec{\epsilon}^{\,\prime *}\times\vec{\epsilon})\,, \qquad \rho_4 = i\,\vec{\sigma}\cdot(\vec{s}^{\,\prime *}\times\vec{s})\,,$$
$$\rho_5 = i\left(\left(\vec{\sigma}\cdot\hat{\vec{k}}\right)(\vec{s}^{\,\prime *}\cdot\vec{\epsilon}) - \left(\vec{\sigma}\cdot\hat{\vec{k}}'\right)(\vec{\epsilon}^{\,\prime *}\cdot\vec{s})\right),$$
$$\rho_6 = i\left(\left(\vec{\sigma}\cdot\hat{\vec{k}}'\right)(\vec{s}^{\,\prime *}\cdot\vec{\epsilon}) - \left(\vec{\sigma}\cdot\hat{\vec{k}}\right)(\vec{\epsilon}^{\,\prime *}\cdot\vec{s})\right)$$

with $\vec{s} = \hat{\vec{k}}\times\vec{\epsilon}$, $\vec{s}^{\,\prime *} = \hat{\vec{k}}'\times\vec{\epsilon}^{\,\prime *}$ and $\vec{\sigma}$ the vector of the Pauli spin matrices. Furthermore, $\hat{\vec{k}} = \vec{k}/\omega$ ($\hat{\vec{k}}' = \vec{k}'/\omega$) is the unit vector in the direction of the momentum of the incoming (outgoing) photon with polarization $\vec{\epsilon}$ ($\vec{\epsilon}^{\,\prime *}$).

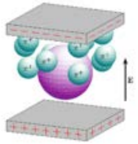
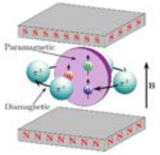
$$R_i(\omega,z) = R_i^{\mathrm{pole}}(\omega,z) + R_i(\omega,z)$$

Nucleon Dipole Polarizabilities

Stiff core + pliable pion cloud



Scalar polarizabilities:

α  β 

$$\alpha_{E1}(\omega) = \left[2\, f_{EE}^{1+}(\omega) + f_{EE}^{1-}(\omega)\right]/\omega^2\,,$$
$$\beta_{M1}(\omega) = \left[2\, f_{MM}^{1+}(\omega) + f_{MM}^{1-}(\omega)\right]/\omega^2\,,$$

Spin-dependent polarizabilities:

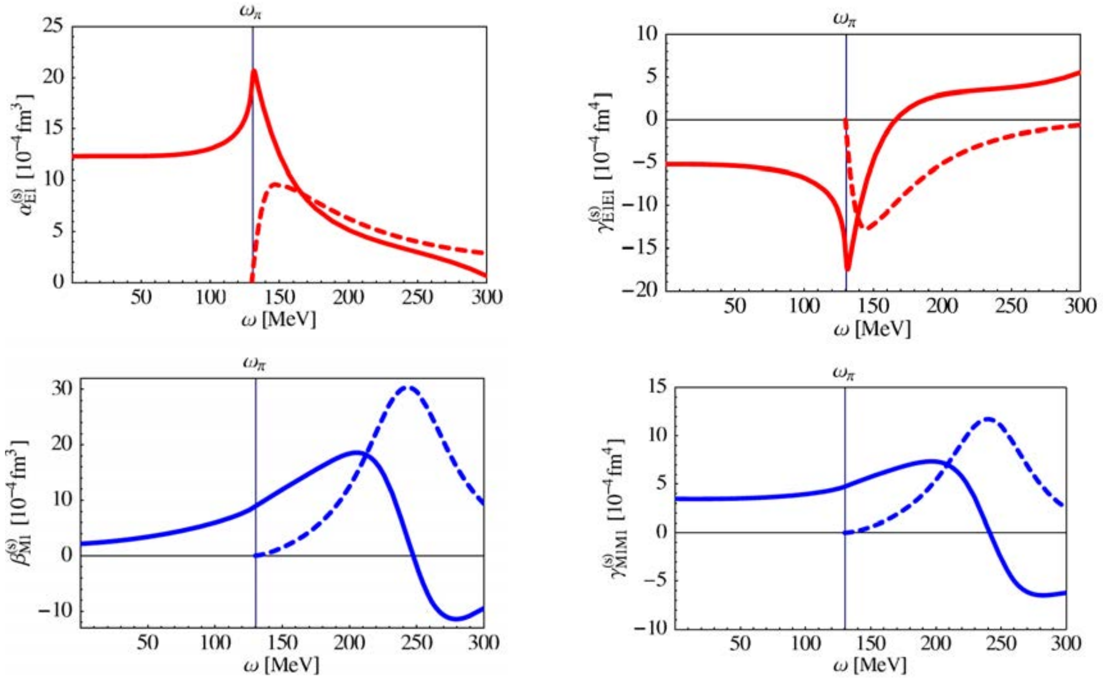
$$\gamma_{E1E1}(\omega) = \left[f_{EE}^{1+}(\omega) - f_{EE}^{1-}(\omega)\right]/\omega^3 \quad (E1\rightarrow E1)\,,$$
$$\gamma_{M1M1}(\omega) = \left[f_{MM}^{1+}(\omega) - f_{MM}^{1-}(\omega)\right]/\omega^3 \quad (M1\rightarrow M1)\,,$$
$$\gamma_{E1M2}(\omega) = 6\, f_{EM}^{1+}(\omega)/\omega^3 \quad (E1\rightarrow M2)\,,$$
$$\gamma_{M1E2}(\omega) = 6\, f_{ME}^{1+}(\omega)/\omega^3 \quad (M1\rightarrow E2)\,.$$

$$H_{\mathrm{eff}}^{(3),\mathrm{spin}} = -\frac{1}{2}4\pi\left(\gamma_{E1E1}\vec{\sigma}\cdot\vec{E}\times\dot{\vec{E}} + \gamma_{M1M1}\vec{\sigma}\cdot\vec{B}\times\dot{\vec{B}} - 2\gamma_{M1E2}E_{ij}\sigma_j H_j + 2\gamma_{E1M2}H_{ij}\sigma_j E_j\right)$$

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

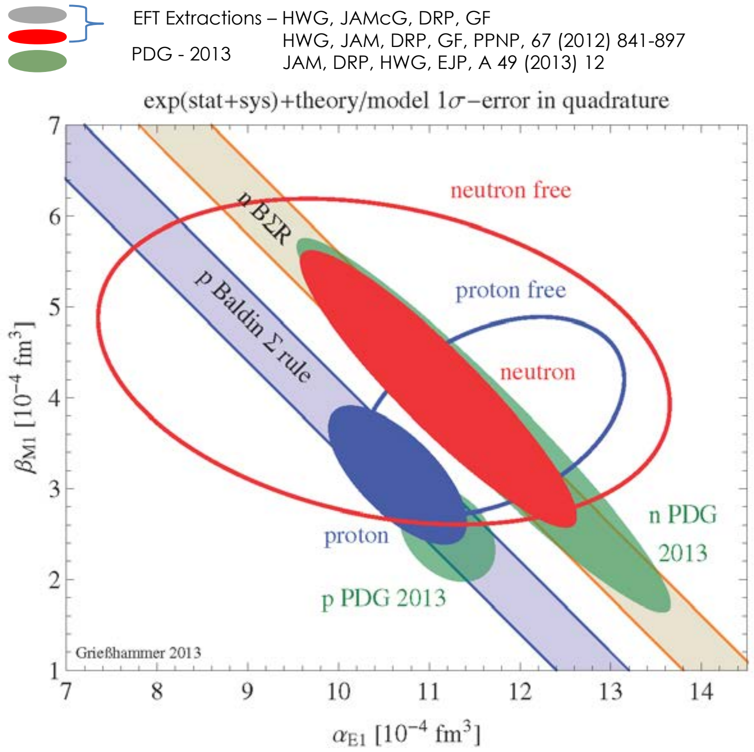
Energy Dependence of Nucleon Scalar Polarizabilities

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



Provides insights about:

- Freq. response of system
- Binding energy of charged constituents
- Confinement volume of charged constituents
- $\Delta\beta_n$ causes a significant uncertainty in calc. m_n-m_p
- β_p input to Lamb-shift corr. In μH atoms
- Collective response of internal spin dof to em pulse



Plots courtesy of Harald Grießhammer

Baldin sum rule:

$$\alpha_E + \beta_M = \frac{1}{2\pi^2}\int_0^\infty \frac{\sigma_P^N - \sigma_A^N}{\omega^2}\, d\omega$$

$\alpha^p = 10.65 \pm 0.35_{\text{stat}} \pm 0.2_\Sigma \pm 0.3_{\text{theory}}$ $\quad \beta^p = 3.15 \mp 0.35_{\text{stat}} \pm 0.2_\Sigma \mp 0.3_{\text{theory}}$

$\alpha^n = 11.1 \pm 1.8_{\text{stat}} \pm 0.4_\Sigma \pm 0.8_{\text{theory}}$ $\quad \beta^n = 4.1 \mp 1.8_{\text{stat}} \pm 0.4_\Sigma \mp 0.8_{\text{theory}}$

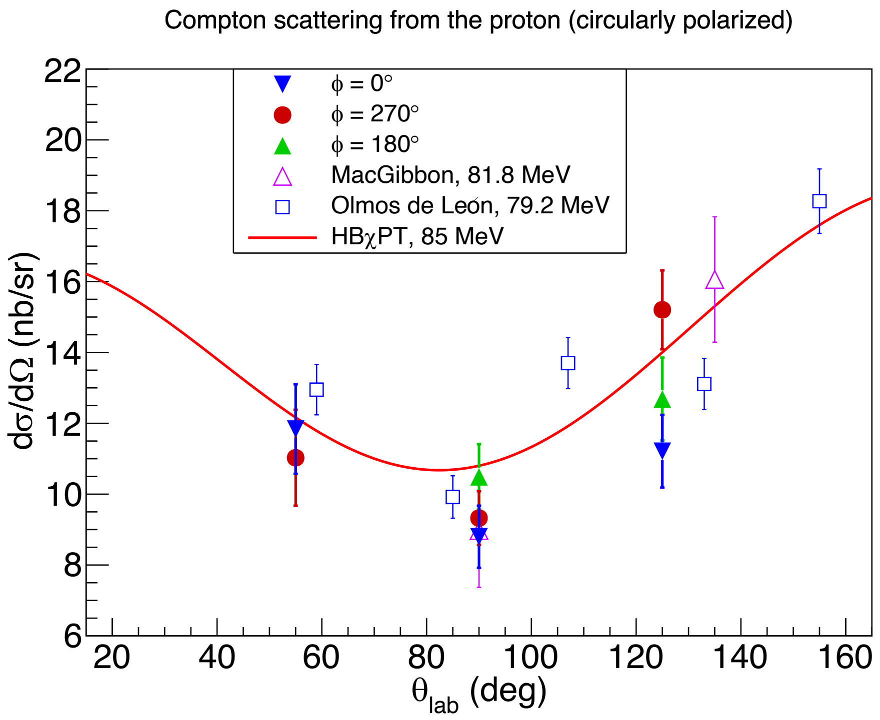
Goals of Compton-scattering Program at HIγS:

- determine of α_N and β_N using different light nuclei
- reduce $\Delta\beta_n$ by ~ factor of 2

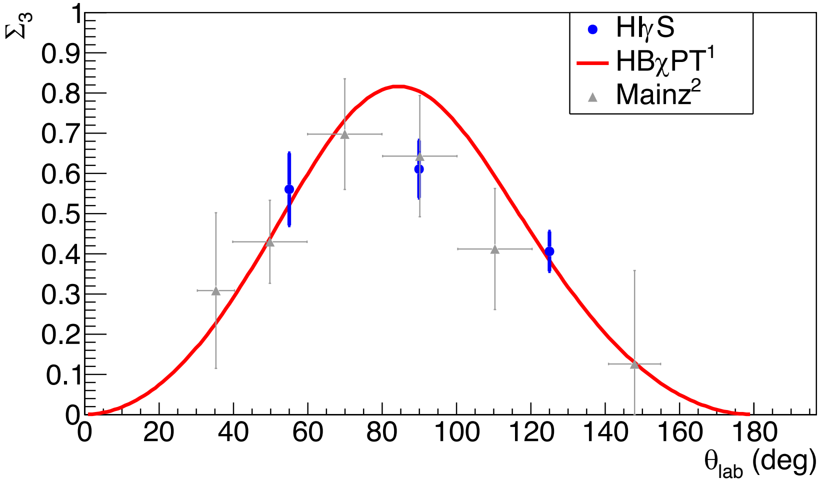
Proton Compton Scattering with Circular & Linear Polarization

E_γ = 85 MeV

Circular Polarization



Linear Polarization



$$\Sigma_3(\theta) = \frac{\frac{d\sigma_\perp(\theta)}{d\Omega} - \frac{d\sigma_\parallel(\theta)}{d\Omega}}{\frac{d\sigma_\perp(\theta)}{d\Omega} + \frac{d\sigma_\parallel(\theta)}{d\Omega}}$$

These data will allow for the extraction of the proton polarizabilities using LEX. Along with the Σ_3 measurement, a new extraction of the proton EM polarizabilities will be available soon.

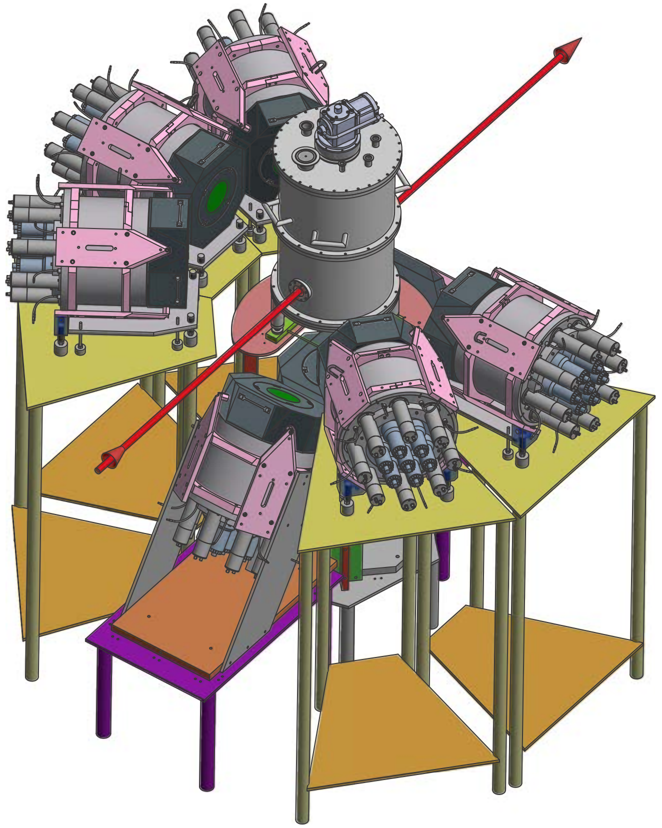
Theory by: J.A McGovern, D.R. Phillips, H.W. Grießhammer, Eur. Phys. J. A, 49, 12 (2013)

Recent Compton-scattering results from HIγS

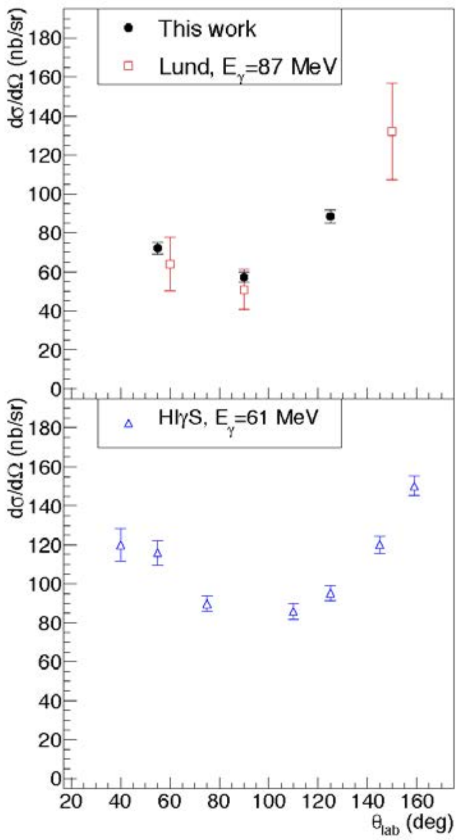
PHYSICAL REVIEW C 101, 034618 (2020)

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

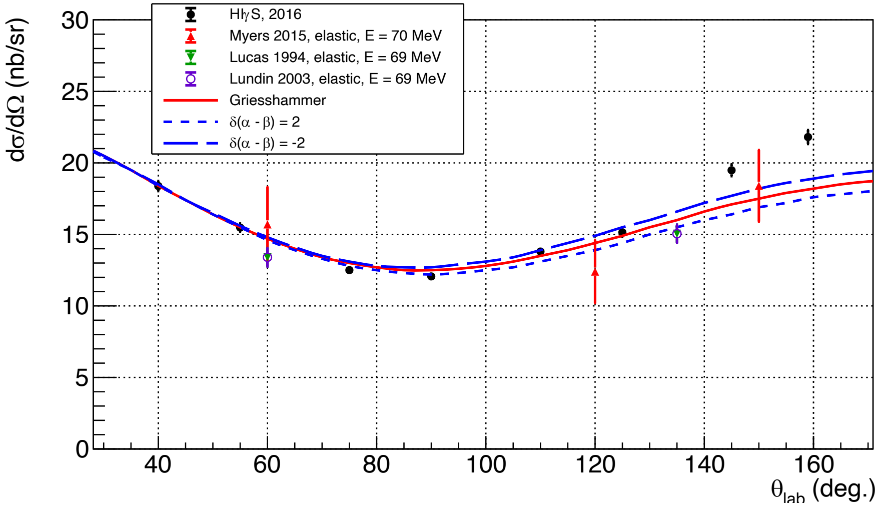
X. Li, M.W. Ahmed, A. Banu, C. Bartram, B. Crowe, E.J. Downie, M. Emamian, G. Feldman, H. Gao, D. Godagama, H.W. Grießhammer, C.R. Howell, H.J. K arwowski, D.P. Kendellen, M.A. Kovash, K.K.H. Leung, D. Markoff, S. Mikhailov, R.E. Pywell, M.H. Sikora, J.A. Silano, R.S. Sosa, M.C. Spraker, G. Swift, P. Wallace, H.R. Weller, C.S. Whisnant, Y.K. Wu, and Z.W. Zhao



^{4}He CS



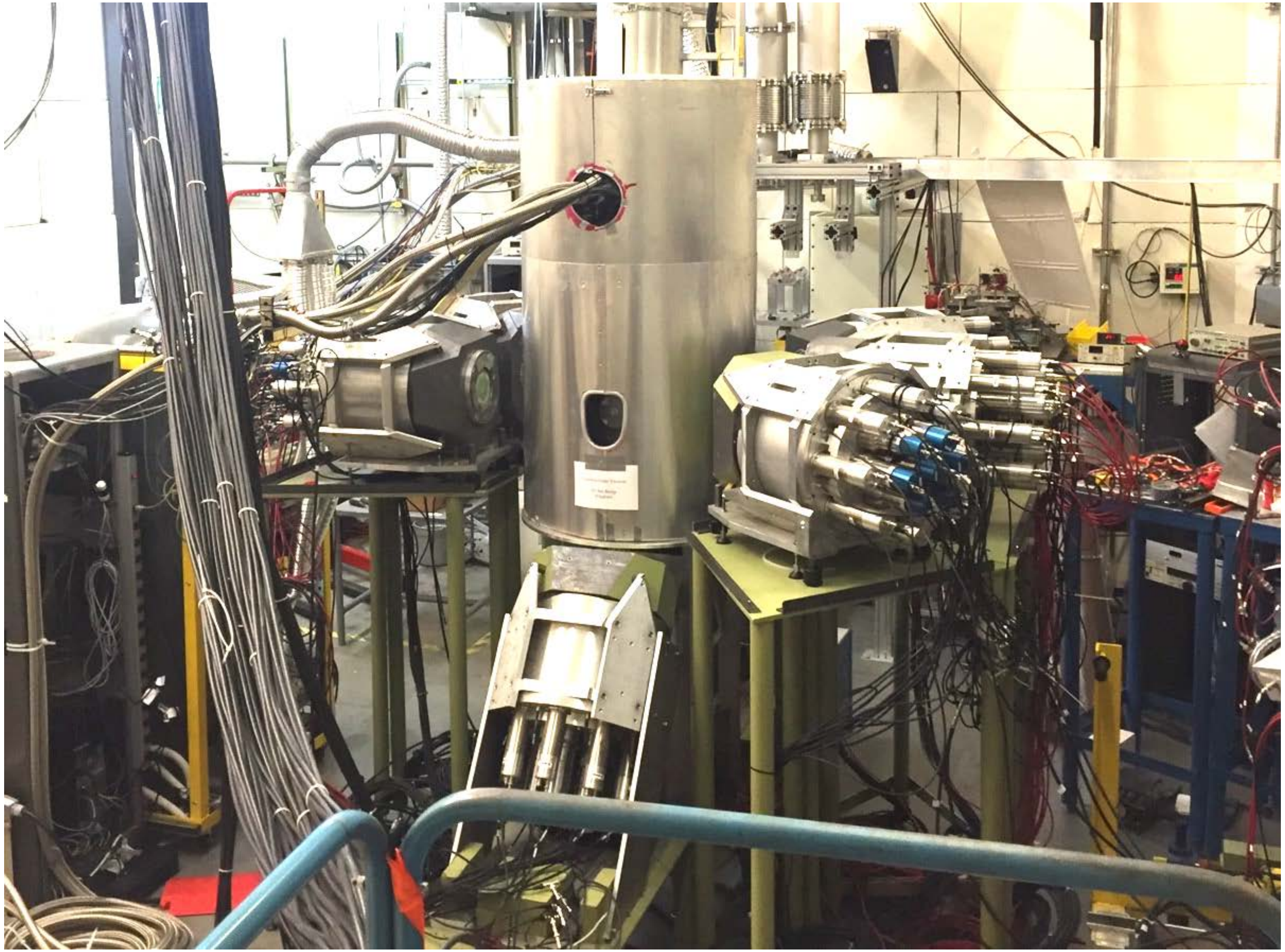
deuteron CS at E_γ = 65 MeV



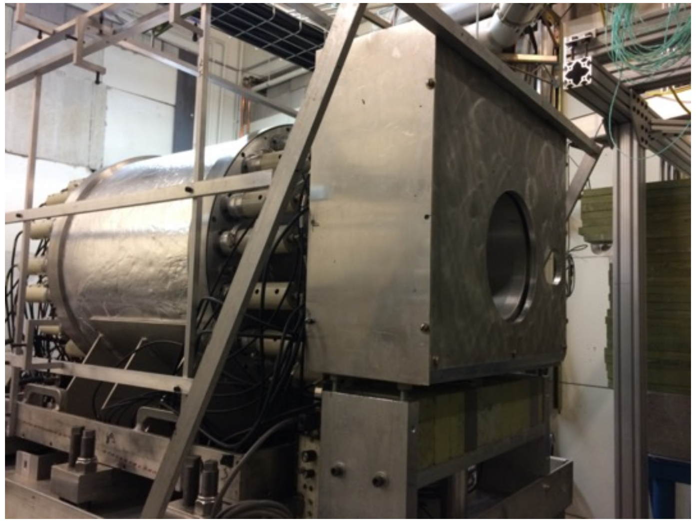
DIANA

BUNI

Next: Compton Scattering from ^{3}He



BUNI / DIANA at HIGS



Workshop sponsors

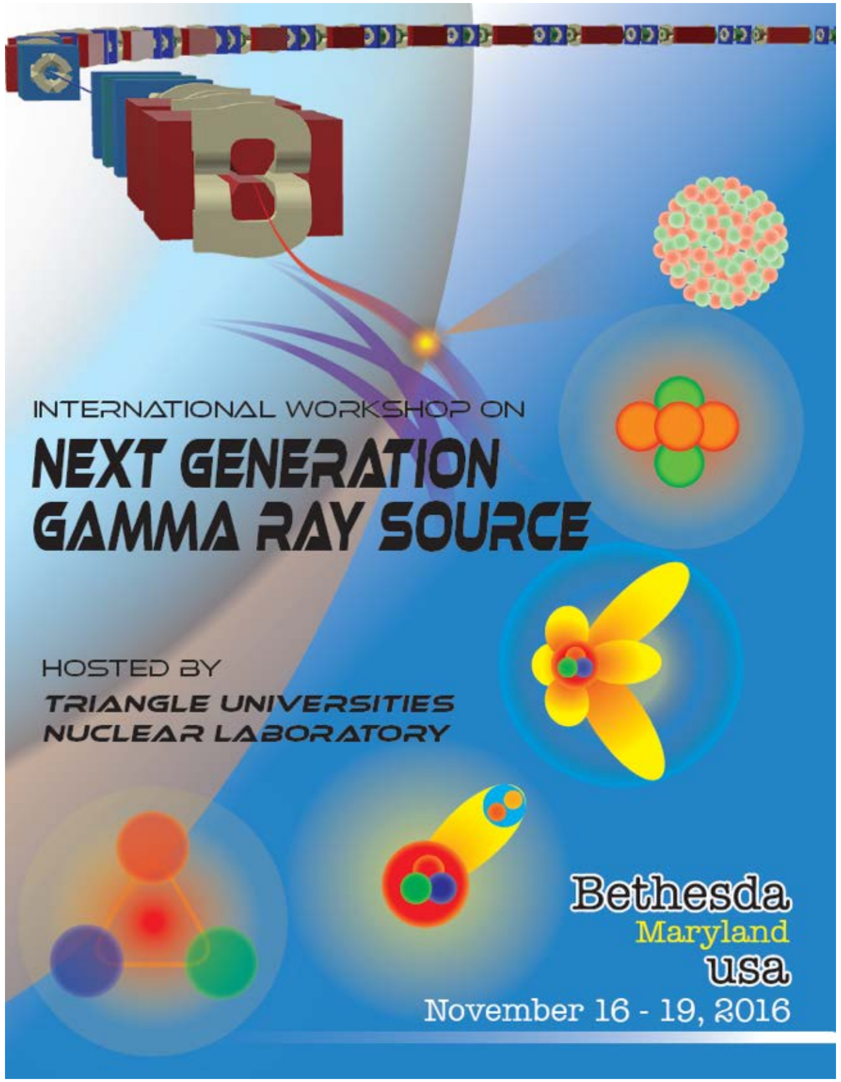
U.S. DEPARTMENT OF ENERGY

Office of Nuclear Physics
under grant # DE-SC0014616

TUNL

https://arxiv.org/abs/2012.10843

Will soon be published in **Journal of Phys G**



Contents

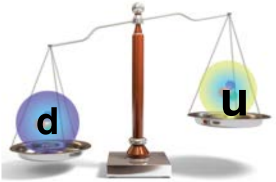
LE QCD:
The emergence of hadron structure and the nuclear force from QCD is a key scientific problem. These phenomena are a consequence of quarks and gluons interacting at confinement-scale distances where color forces are strong. The beams at a next generation Compton γ-ray source will enable measurements that uniquely probe hadron structure and hadronic interactions in this non-perturbative regime of QCD, achieving unprecedented precision in the photon energy range from about 60 MeV to the Nucleon-to-Delta(1232) transition. Key elements of the program include high-precision nucleon polarizability (scalar and spin) measurements by Compton scattering and near-threshold photo-pion production measurements; both rely on polarized beams and targets. Such measurements, together with advances in calculations using Lattice QCD and QCD-based effective field theories, will explore the QCD origin of nucleon structure and charge-symmetry breaking in novel contexts and with unprecedented sensitivity.

Physics Contributions:

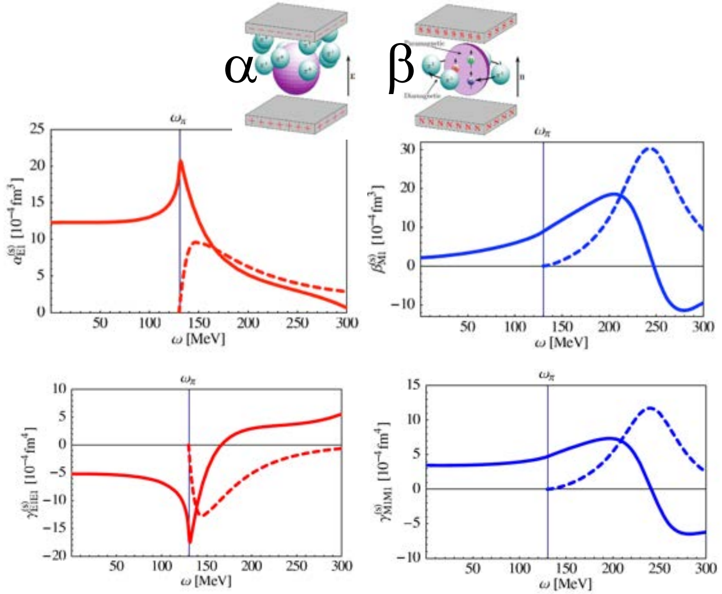
- Highest precision determinations of nucleon polarizabilities
  - Nucleon EM polarizabilities (E_γ = 65 – 250 MeV): α^p, β^p, α^n, β^n
  - Nucleon spin polarizabilities (E_γ = 120 – 250 MeV): γ_{E1E1}, γ_{M1M1}, γ_{E1M2}, γ_{M1E2}
- High-energy resolution measurement of π^0 production cross section near threshold ($\Delta E_\gamma/E_\gamma < 0.015$): QCD origin of CSB

Gamma-ray Source Capabilities:

- E_γ = 60 – 350 MeV
- Flux > 3 x 10^8 γ/s on target
- $\Delta E_\gamma/E_\gamma < 0.02$
- Circular and Linear Polarization > 90%
- Fast switching of beam polarization direction



$\gamma N \rightarrow \pi^0 N$
scattering length (a)



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

Nuclear Structure:

The beams at an advanced γ-ray source will enable systematic studies of weak collective dipole and quadrupole nuclear excitations with unprecedented precision. Such studies will provide nuclear structure details and information about the symmetry energy of the nuclear equation of state that are difficult to obtainable by other means. The increased γ-ray beam intensities at the next generation γ-ray source will enable mapping of M1 states in nuclei with a level of detail and breadth that will contribute to modeling of coherent neutrino-nucleus scattering and to calculating nuclear matrix elements for neutrinoless double-beta decay. Also, a next-generation γ-ray beam facility will enable new exclusive measurements of photodisintegration of few-nucleon systems with precision that provides the highest sensitivity to long-range three-nucleon interactions in such reactions.

Physics Contributions:

- High sensitivity NRF measurements for detailed mapping of M1 and E1 strengths
- Systematic studies of dipole strength along isotope to provide new insight at PDR and other weak modes of collective motion
- High-energy resolution measurements of photodisintegration cross sections of few-nucleon systems to determine NN scattering lengths with accuracies comparable to two-nucleon scattering methods

Gamma-ray Source Capabilities:

- E_γ = 1 – 20 MeV
- Flux > 1 x 10^9 γ/s on target
- $\Delta E_\gamma / E_\gamma < 0.02$
- Circular and Linear Polarization > 90%

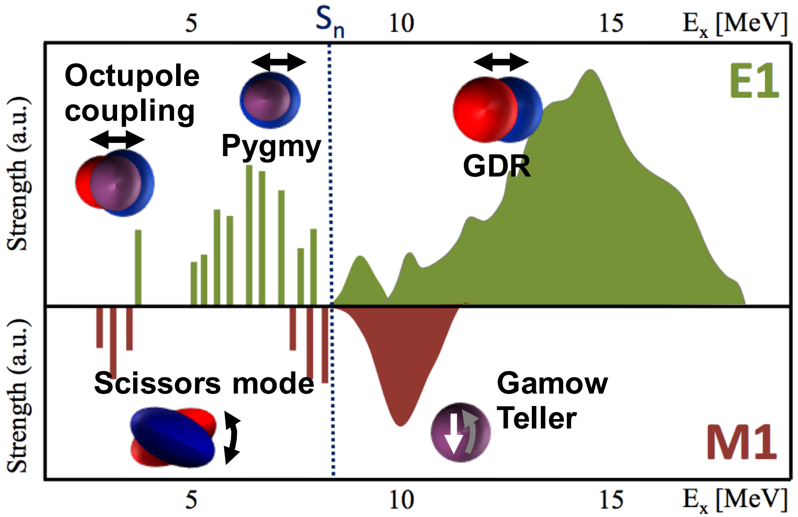
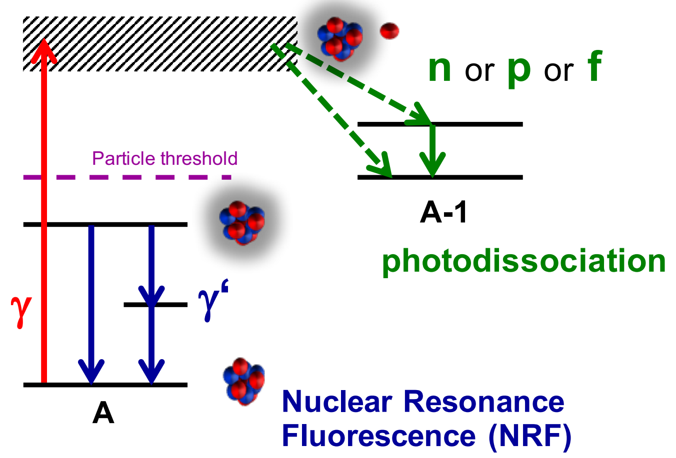


Figure by A. Zilges



TUNL

Nuclear Astrophysics:

Gamma-ray beams will enable measurements that contribute broadly to open questions in nuclear astrophysics, e.g., big-bang nucleosynthesis, helium burning in massive stars and synthesis of heavy nuclei. The $^{12}C(\alpha, \gamma)^{16}O$ reaction is one of the most important reactions in stellar modeling. The rate of this reaction relative to the carbon forming reaction, $^{8}Be(\alpha, \gamma)^{12}C$, determines the fate of massive stars. The grand challenge at an advanced γ-ray beam facility will be measurement of the reaction rate the $^{16}O(\gamma,\alpha)^{12}C$ reaction at energies approaching the temperatures at the core of stars.

Physics Contributions:

- High accuracy cross-section measurement of the $^{12}C(\alpha, \gamma)^{16}O$ reaction at $E_\gamma < 8$ MeV
- High sensitivity NRF measurements for detailed mapping of γ-ray strength functions

Gamma-ray Source Capabilities:

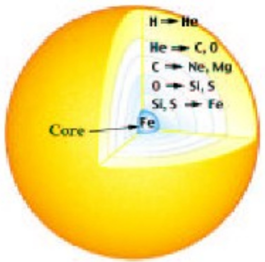
- $E_\gamma = 1 – 20$ MeV
- Flux > 1×10^{11} γ/s on target
- $\Delta E_\gamma/E_\gamma < 0.02$
- Linear Polarization > 90% and unpolarized

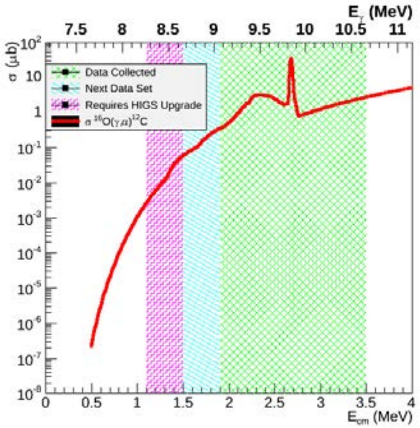
$\alpha + \alpha + \alpha \rightarrow {}^{12}C + \gamma$; production of ^{12}C during helium burning

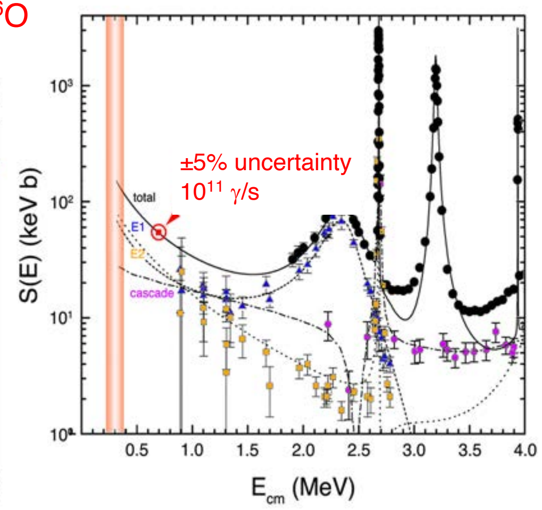
$^{12}C + \alpha \rightarrow {}^{16}O + \gamma$; converts ^{12}C to ^{16}O

➔ determines $^{12}C/^{16}O$

The mass and size of the final iron core is critically dependent on the $^{12}C(\alpha,\gamma)^{16}O$ reaction rate







Need to determine the $^{12}C(\alpha,\gamma)^{16}O$ cross section $\Delta\sigma/\sigma < 10\%$ at $E_{cm} = 300$ keV (0.2×10^9 K)

TUNL

Hadronic Parity Violation:
The beams at an advanced γ-ray beam facility will enable measurements of parity violating (PV) photodisintegration of few-nucleon systems. In particular, a measurement of parity violation in deuteron photodisintegration near threshold is sensitive to a nucleon-nucleon (NN) PV amplitude that is not accessible using other systems. Such measurements sample the short-range part of the NN interaction, providing unique quantities for comparison with Lattice QCD calculations.

Physics Contributions:

- First measurements of parity violating asymmetry for photodisintegration of deuterium

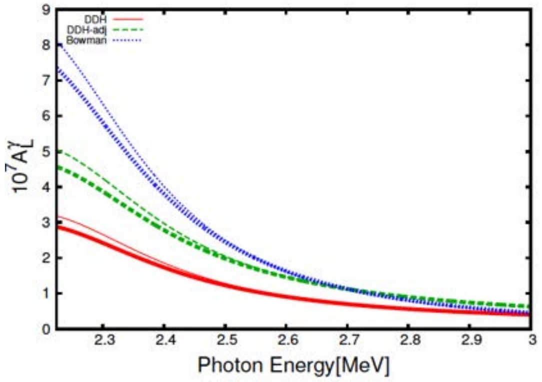
Gamma-ray Source Capabilities:

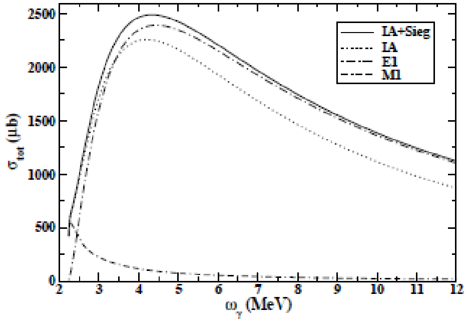
- E_γ = 1 – 5 MeV
- Flux > 1 x 10^{11} γ/s on target
- $\Delta E_\gamma/E_\gamma < 0.02$
- Circular Polarization > 90% and unpolarized

PV Asymmetry in $\gamma d \rightarrow np$

Vanasse/Schindler, PRC 90, 044001 (2014)

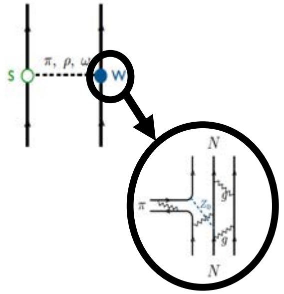
A_γ (threshold)= $-8.44\, h_\rho^0 + 3.63\, h_\omega^0 - 17.6\, h_\rho^2$





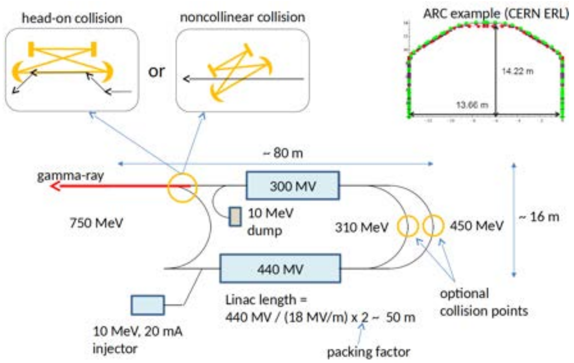
B. Despalnques, J.G. Donahue and B.R. Holstein, Ann. of Phys. 124, 449 (1980).

$$
\begin{aligned}
V_{DDH}^{\mathrm{PNC}}(\vec{r}) = {} & i\frac{h_\pi^1 g_{\pi NN}}{\sqrt{2}}\left(\frac{\vec{\tau}_1\times\vec{\tau}_2}{2}\right)_z (\vec{\sigma}_1+\vec{\sigma}_2)\cdot\left[\frac{\vec{p}_1-\vec{p}_2}{2m_N}, w_\pi(r)\right] \\
& -g_\rho\left(h_\rho^0\vec{\tau}_1\cdot\vec{\tau}_2 + h_\rho^1\left(\frac{\vec{\tau}_1+\vec{\tau}_2}{2}\right)_z + h_\rho^2\frac{(3\tau_1^z\tau_2^z-\vec{\tau}_1\cdot\vec{\tau}_2)}{2\sqrt{6}}\right) \\
& \times\left((\vec{\sigma}_1-\vec{\sigma}_2)\cdot\left\{\frac{\vec{p}_1-\vec{p}_2}{2m_N}, w_\rho(r)\right\}\right. \\
+ & \left. i(1+\chi_V)\vec{\sigma}_1\times\vec{\sigma}_2\cdot\left[\frac{\vec{p}_1-\vec{p}_2}{2m_N}, w_\rho(r)\right]\right) \\
& -g_\omega\left(h_\omega^0 + h_\omega^1\left(\frac{\vec{\tau}_1+\vec{\tau}_2}{2}\right)_z\right) \\
& \times\left((\vec{\sigma}_1-\vec{\sigma}_2)\cdot\left\{\frac{\vec{p}_1-\vec{p}_2}{2m_N}, w_\omega(r)\right\}\right. \\
+ & \left. i(1+\chi_S)\vec{\sigma}_1\times\vec{\sigma}_2\cdot\left[\frac{\vec{p}_1-\vec{p}_2}{2m_N}, w_\omega(r)\right]\right) \\
& +\left(\frac{\vec{\tau}_1-\vec{\tau}_2}{2}\right)_z (\vec{\sigma}_1+\vec{\sigma}_2)\cdot\left(g_\rho h_\rho^1\left\{\frac{\vec{p}_1-\vec{p}_2}{2m_N}, w_\rho(r)\right\} - g_\omega h_\omega^1\left\{\frac{\vec{p}_1-\vec{p}_2}{2m_N}, w_\omega(r)\right\}\right) \\
& -g_\rho h_\rho^{1\prime} i\left(\frac{\vec{\tau}_1\times\vec{\tau}_2}{2}\right)_z (\vec{\sigma}_1+\vec{\sigma}_2)\cdot\left[\frac{\vec{p}_1-\vec{p}_2}{2m_N}, w_\rho(r)\right],
\end{aligned}
$$

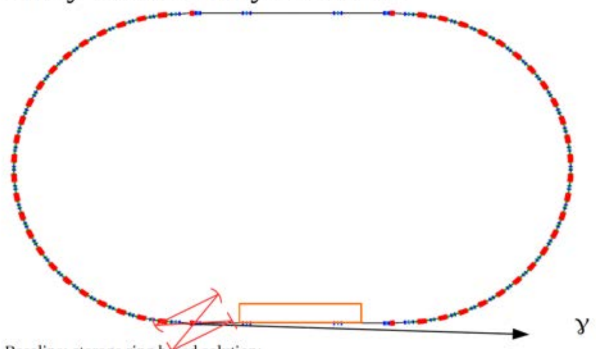


Observations:

- It is unlikely that a single γ-ray beam source can meet the requirements of the low-energy and medium-energy parts of the field.
- γ-rays are produced by Compton scattering of electrons from photons inside an optical cavity that is pumped with an external laser.
- **Low-energy facility ($E\gamma < 20$ MeV):** Options included an energy-recovery linac (with superconducting RF cavities) and a storage ring.
- **Medium-energy facility ($E\gamma = 60 – 350$ MeV):** A storage ring was the primary option for the higher energy γ-ray source. There is confidence that a high electron beam quality (low emittance and low energy spread) can be maintained in modern storage-ring lattices, thereby enabling production of γ-ray beams with low energy spread.
- **New facility cost:** The new facility construction cost of the storage-ring option for either a low-energy or medium-energy next-generation Compton γ-ray source will be over about **$150M**. This is extremely coarse and is intended only to set the cost scale within about a factor of two. Less expensive options for the low-energy sources, e.g., upgrades to existing facilities, were also presented.



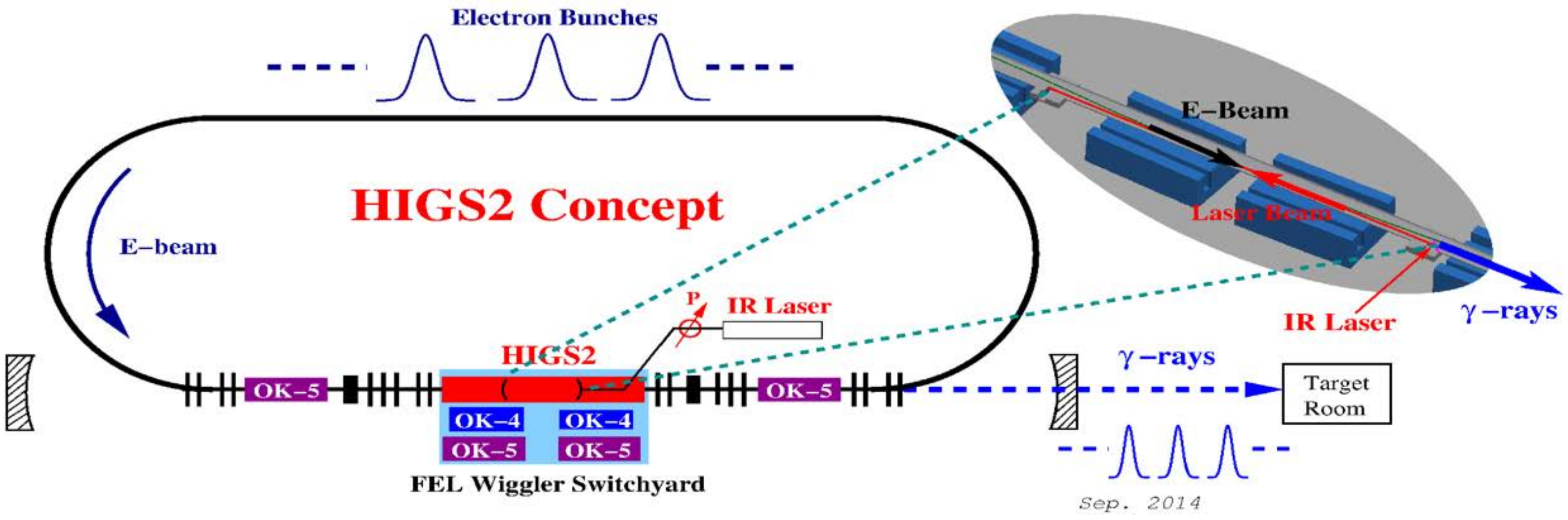
Fabry-Perot Cavity Beamline

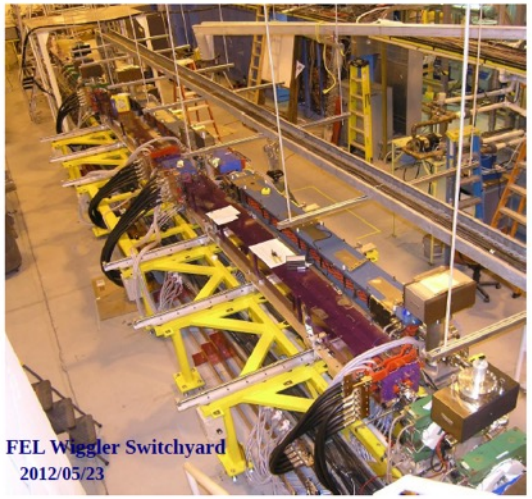


Baseline: storage ring based solution:
up to 3.5 GeV, 95 MHz, 64 bunches, ~5 nC, 3kW, total flux: 5e10 g/s

Workshop Recommendations

- R&D recommended to reduce risk on γ-ray source design, e.g., optical cavity development ⇨ **HIγS2**
- Investments in polarized targets needed to prepare for experiments at next generation Compton γ-ray beam facilities
- Investments in active targets are needed to carryout the highest impact nuclear astrophysics measurements at a γ-ray beam facility
- Investments in nuclear theory are needed to support LE QCD experiments at the next generation γ-ray beam facilities



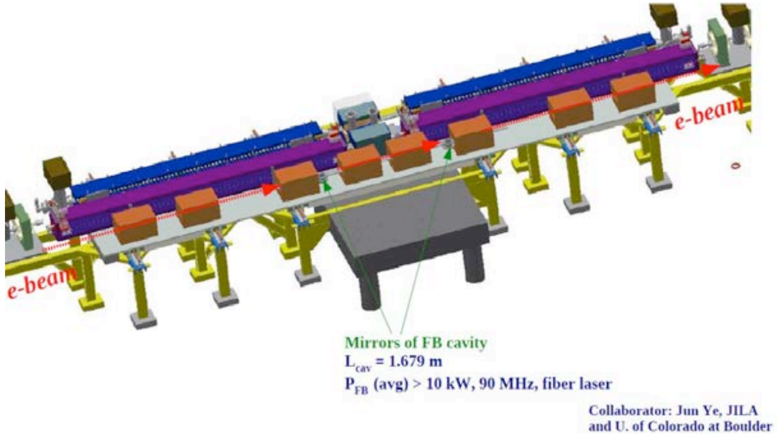


Projected Performance

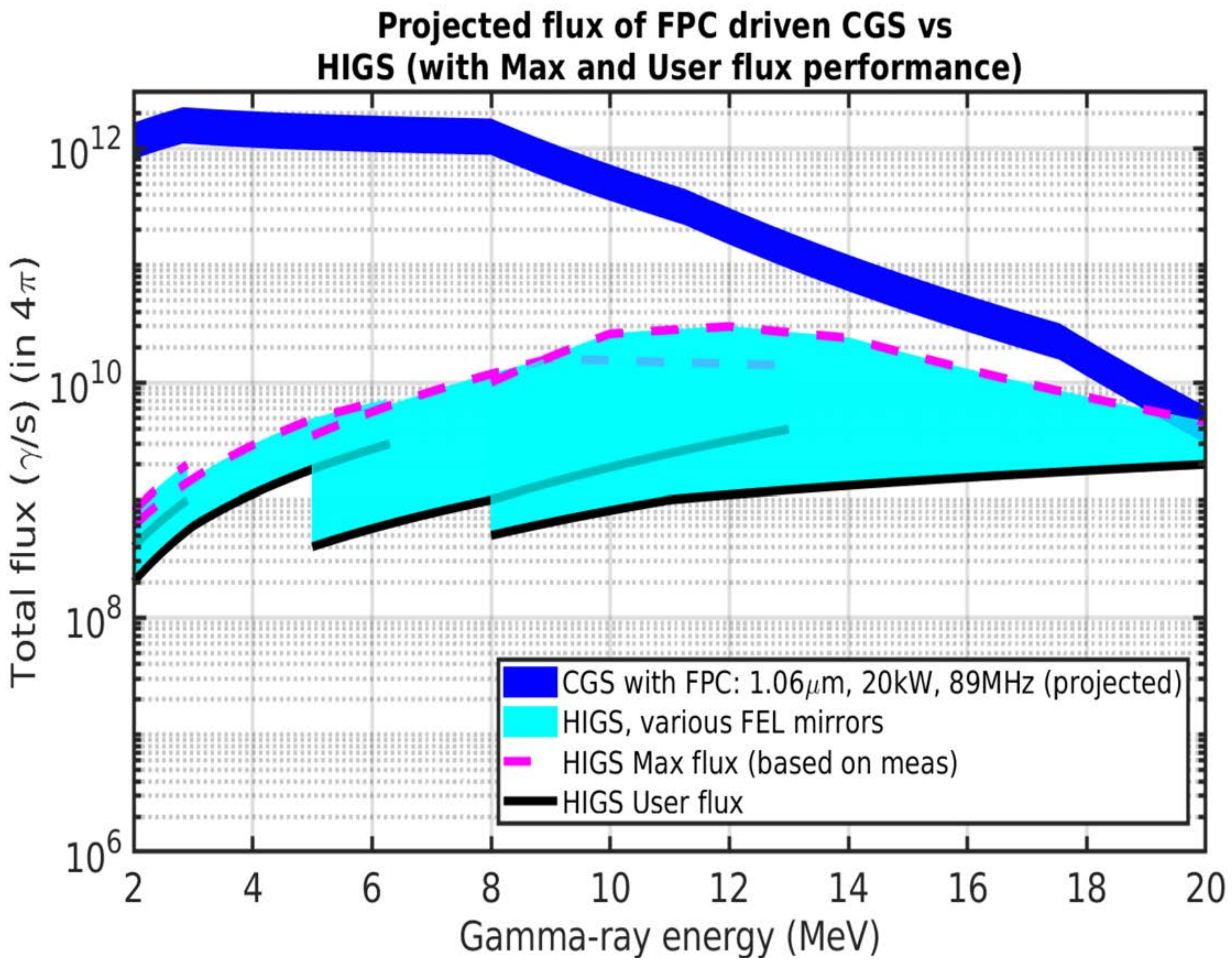
- 2–3 orders of higher flux than HIGS (2–8 MeV)
- 1064 nm FP Cavity: 2 – 12 MeV
- Total Flux: 10^{10} – 2 x 10^{12} γ/s
- Pol: Linear, or Circular (rapid switch)
- High-res capability: 0.6% (FWHM)

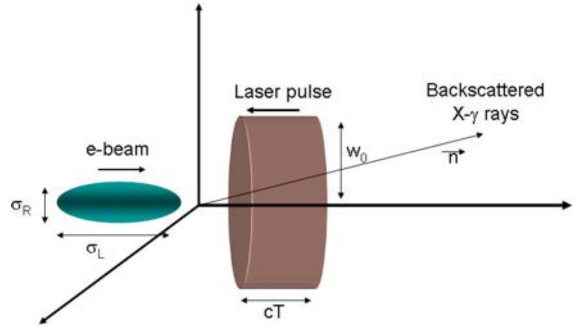
Research Programs

- Nuclear Structure
- Nuclear Astrophysics
- Hadronic Parity Violation



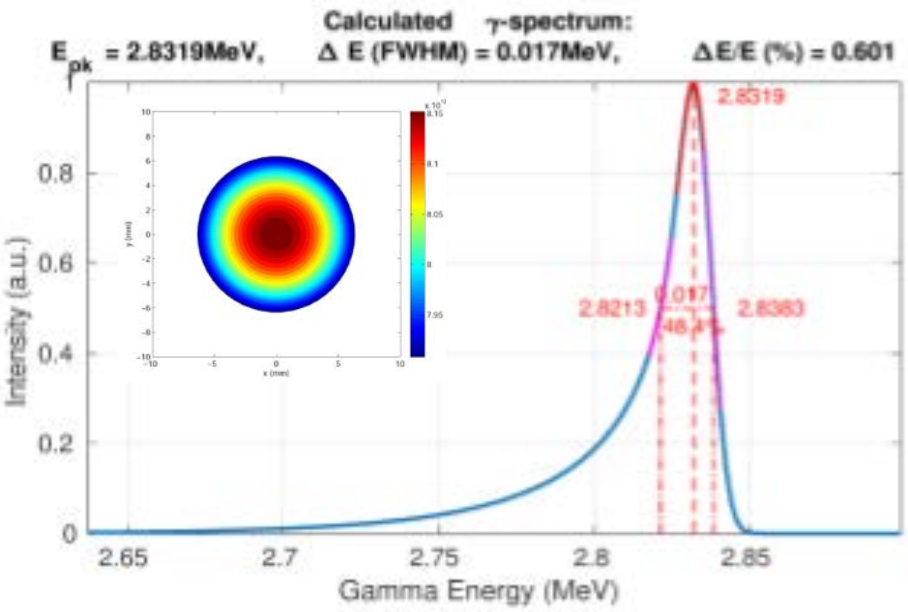
HIγS2: γ-ray Beam Flux Projection





2.5 MeV Beam Distribution

- **Collimator: D = 13 mm at 52.8 m**



HIγS2: Comparison to HIγS and NGLCGS

	HIGS Facility	HIGS2 Upgrade	Next-generation CGS (Low-energy Example)
Accelerator	Existing Storage Ring	Existing Storage Ring	Advanced Storage Ring
Energy (GeV)	0.24 – 1.2	0.38 – 1.1	0.30 – 0.75
Beam current (mA)	50 – 120	300 – 400	1,000
Beam pattern	two-bunch	32-bunch	multi-bunch
Laser System	Free-Electron Laser	Fabry-Perot Laser	Fabry-Perot Laser
Wavelength (nm)	1060 – 190	1064	1064, 1550, 517
Intracavity power (kW)	0.03 – 2	20 – 50	50 – 100
Repetition rate (MHz)	5.58	89.3	$\sim$ 120
Gamma-ray Beam			
Energy range (MeV)	1 – 100	2 – 20	1 – 20
Total flux (γ/s, in 4π solid angle)	$10^8 - 3\times10^{10}$	$5\times10^{10} - 5\times10^{12}$	few $10^{11} - 3\times10^{13}$
Gamma beam pulse rate (MHz)	5.58	89.3	$\sim$ 120
Polarization	Linear and Circular	Linear and Circular	Linear and Circular
Helicty switch	0.01 – few Hz	Tens of Hz	Tens of Hz
Example: 2.56 MeV γ-beam			
Total flux (γ/s, in 4π solid angle)	$\sim 1\times10^9$	$2-4\times10^{12}$	$1-3\times10^{13}$
Flux on target ($\frac{\Delta E}{E}=1\%$, FWHM)	(low flux)	$2-5\times10^{10}$	$1-3\times10^{11}$
Flux on target ($\frac{\Delta E}{E}=5\%$, FWHM)	$\sim 6\times10^7$	$1-3\times10^{11}$	$0.6-2\times10^{12}$

Table 2: Comparison of HIGS2 with the HIGS facility and a storage ring based future next-generation, low-energy Compton Gamma-ray source (an example).

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Grant #: 20CWDARI00035-01-00