HIGS2: Facility and Research Opportunities

Calvin R. Howell

Duke University, Durham, NC
and
Triangle Universities Nuclear Laboratory (TUNL)
Durham, NC   USA

Outline

1. Overview of the Triangle Universities Nuclear Laboratory (TUNL)
2. HIGS: the accelerator and research program
3. HIGS2 concept: accelerator and research

Triangle Universities Nuclear Laboratory (TUNL)

A Department of Energy Center of Excellence

Three-University Consortium in the Research Triangle Area

- Duke University, Durham
- North Carolina State University, Raleigh
- University of North Carolina, Chapel Hill

Mission

1) To contribute to advancing the frontiers of nuclear physics research and to the application of nuclear physics in response to national needs; and

2) To educate the next generation of nuclear physicists

Web: *http://www.tunl.duke.edu*

TUNL: Faculty, Researchers and Staff

Faculty (15 tenured/tenure-track)

Duke University	**NC State University**	**UNC – Chapel Hill**
M. W. Ahmed[1]	D.G. Haase	A.E. Champagne
H. Gao	P.R. Huffman	T.B. Clegg
C.R. Howell	R. Golub	R. Henning
W. Tornow (Emeritus)	C.R. Gould	C. Iliadis
H.R. Weller (Emeritus)	J.H. Kelley (Research)	H.J. Karwowski
Y.K. Wu	G.E. Mitchell (Research)	J.F. Wilkerson
	A.R. Young	

Researchers

- 42 graduate students (12+13+17)
- 18 postdocs (9+5+ 4)
- 5 research scientists

Staff

- 3 Administrative staff
- 5 R&D Engineers
- 5 technicians
- 2 accelerator operators/technicians

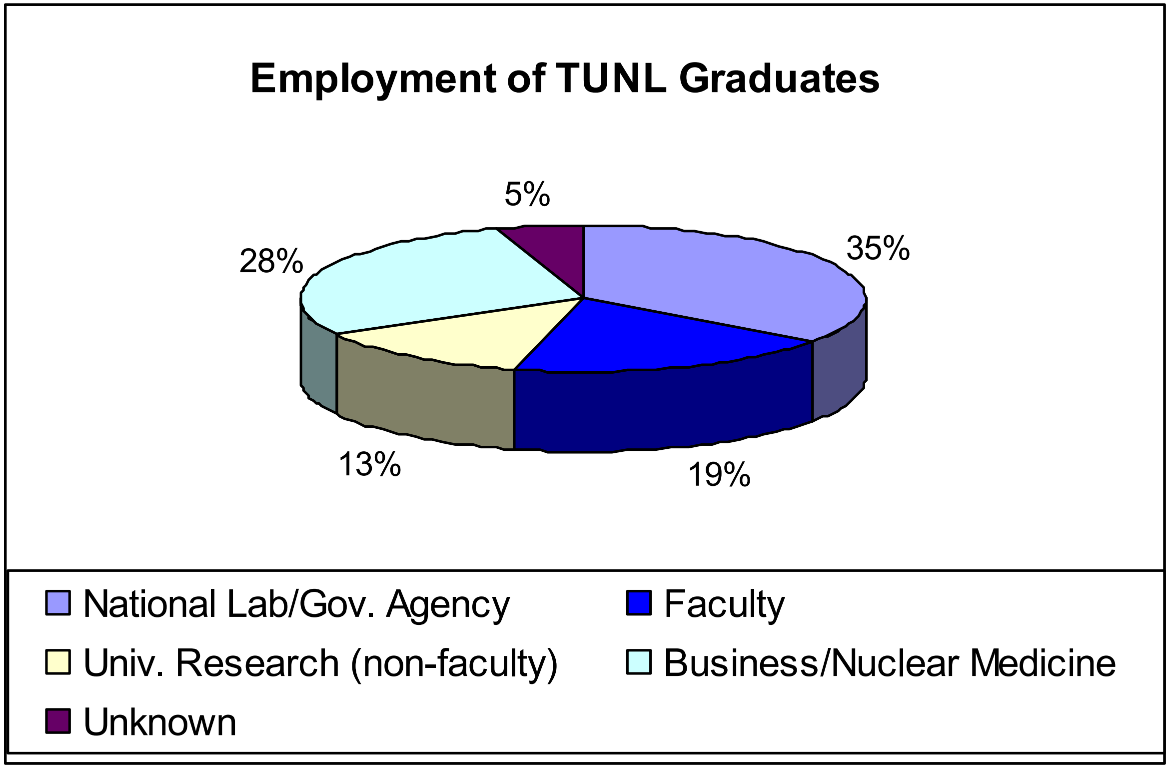
[1] Joint position at NCCU and TUNL

TUNL: Graduate Education

About **8%** (5.6 out of 70 annually) of the nation's PhDs in experimental nuclear physics are educated at TUNL

270 Ph.D. degrees awarded since inception of TUNL

Most recent 10 years: Total PhDs = **56**



Employment of TUNL Graduates

TUNL Research Community

TUNL Research Program

A. Strong Interactions and applications

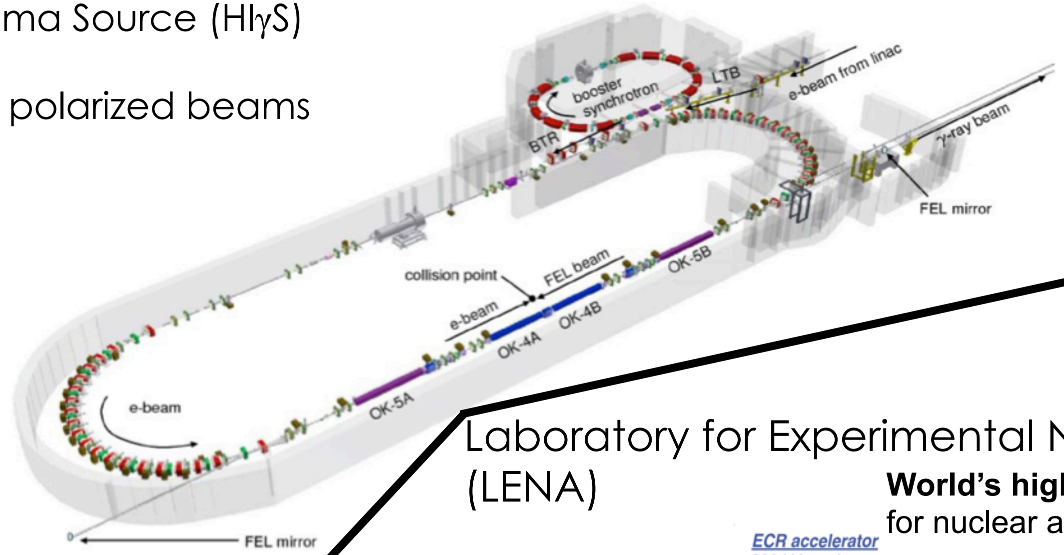
- Nuclear Structure and Few-Nucleon Systems
- Nuclear Astrophysics
- Hadron Structure and QCD
- Neutron scattering
- Applications (DHS/DNDO, DOE/NNSA, energy, plants-environment, medicine)

B. Weak-Interaction and Neutrino Physics

- neutron EDM at SNS – test of CP violation beyond the Standard Model
- MAJORANA Demonstrator – search for 0ν ββ decay ➔ Lepton Number violation
- KATRIN – neutrino mass measurement via triton beta decay
- UCNA at LANL – precision measurements of weak couplings
- KamLAND-Zen – search for neutrinoless ββ decay

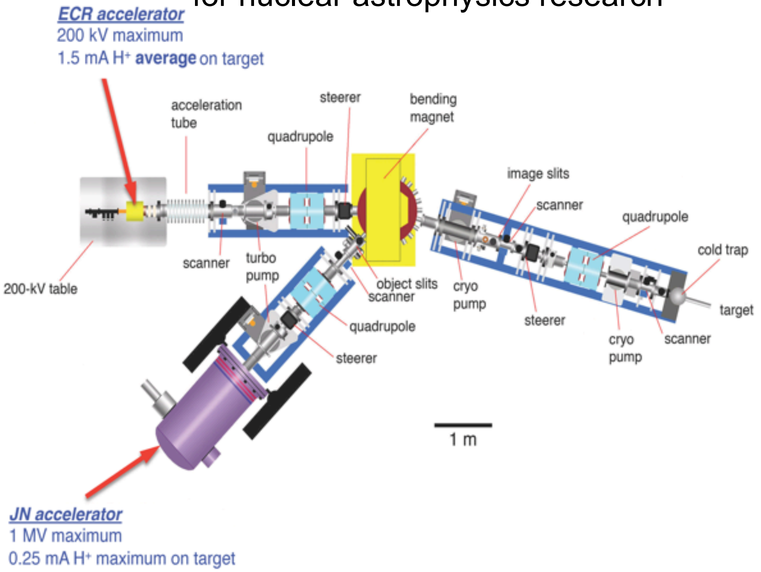
TUNL: Accelerator Facilities

High Intensity Gamma Source (HIγS)
E_γ = 1 – 100 MeV
Linear and circular polarized beams

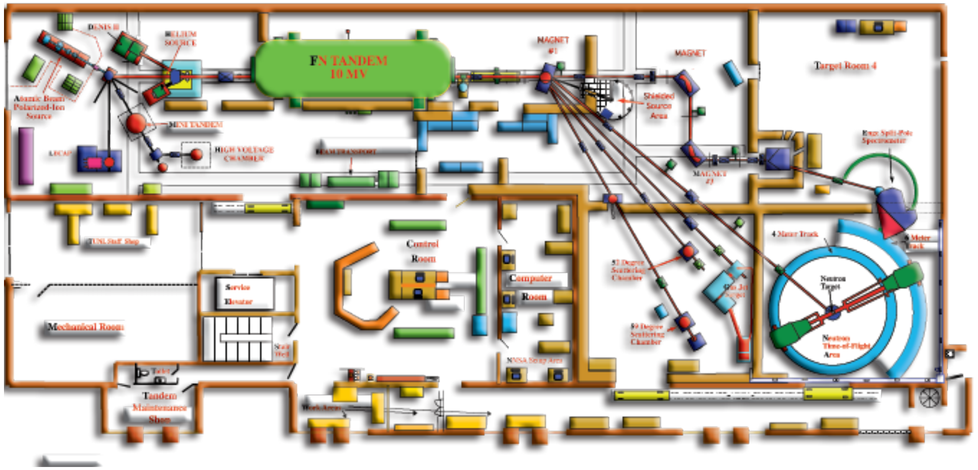


Laboratory for Experimental Nuclear Astrophysics (LENA)

World's highest current proton beam
for nuclear astrophysics research



Tandem Laboratory: light-ion and pulsed neutron beams

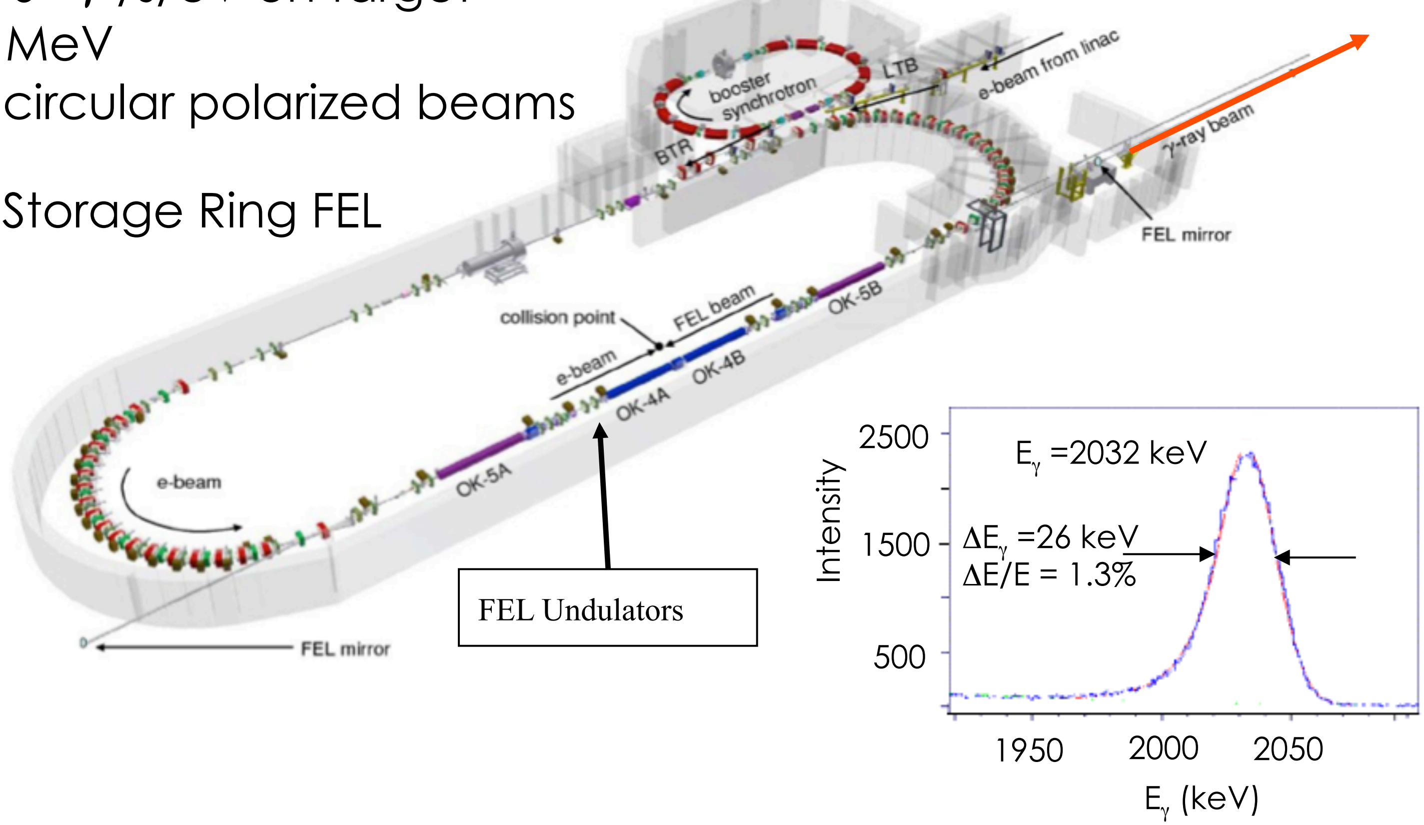


High Intensity Gamma-ray Source (HIγS)

HIγS is the most intense accelerator-driven γ-ray source in the world

Produces γ-rays by Compton backscattering
Intensity = 10^3 γ/s/eV on target
E_γ = 1 – 100 MeV
Linear and circular polarized beams

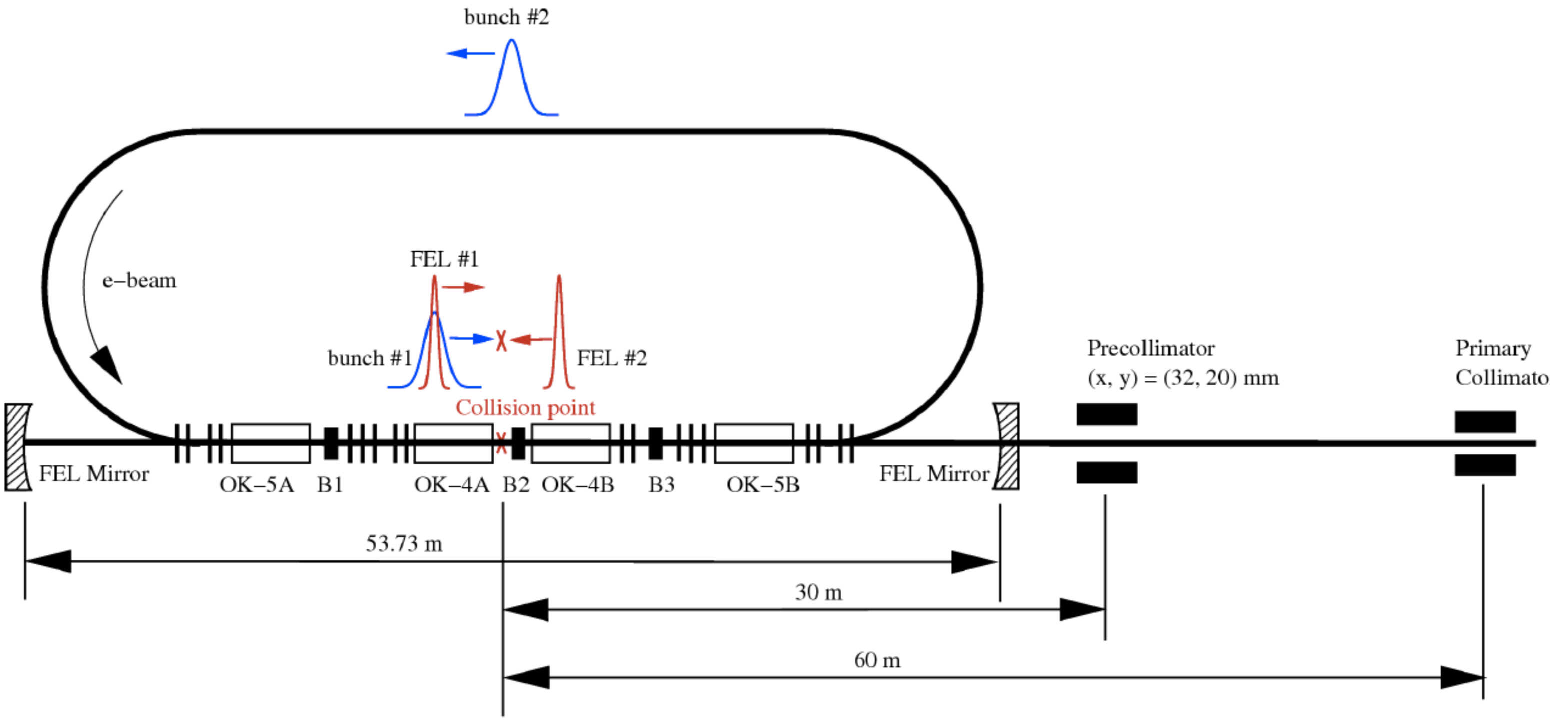
1.2 GeV Storage Ring FEL

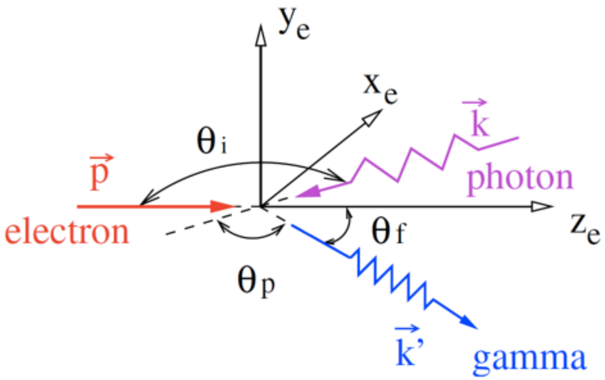


FEL Undulators

Beam time structure: Rep rate = 5.58 MHz and Δt = 100 ps

Intracavity Compton-back Scattering





$$E_\gamma \equiv \hbar\omega' = \frac{\hbar\omega(1-\beta\cos\theta_i)}{1-\beta\cos\theta_f+\frac{\hbar\omega}{\varepsilon_e}(1-\cos\theta_{ph})}$$

Head-on collision: $E_\gamma \approx 4\gamma^2\hbar\omega$

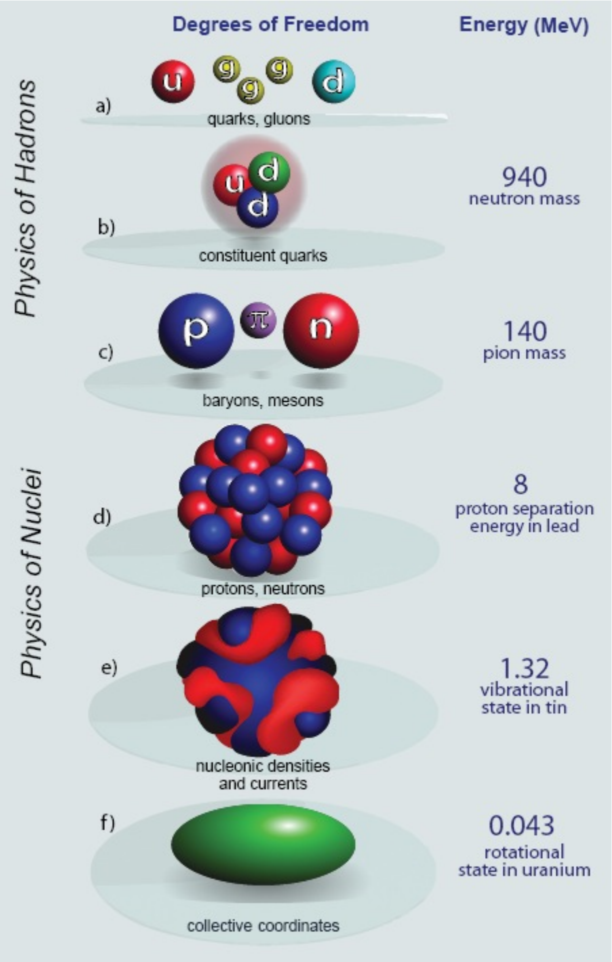
Example: E_e = 500 MeV ➔ $\gamma = 978$

λ_{FEL} = 400 nm

$\hbar\omega$ = 3.11 eV

E_γ = 11.9 MeV

Studies of Strongly Interacting Matter at HIγS



Compton Scattering
nucleon electric and magnetic polarizabilities
nucleon spin polarizabilities

Photo-pion Production

GDH Sum Rule
^{2}H
^{3}He

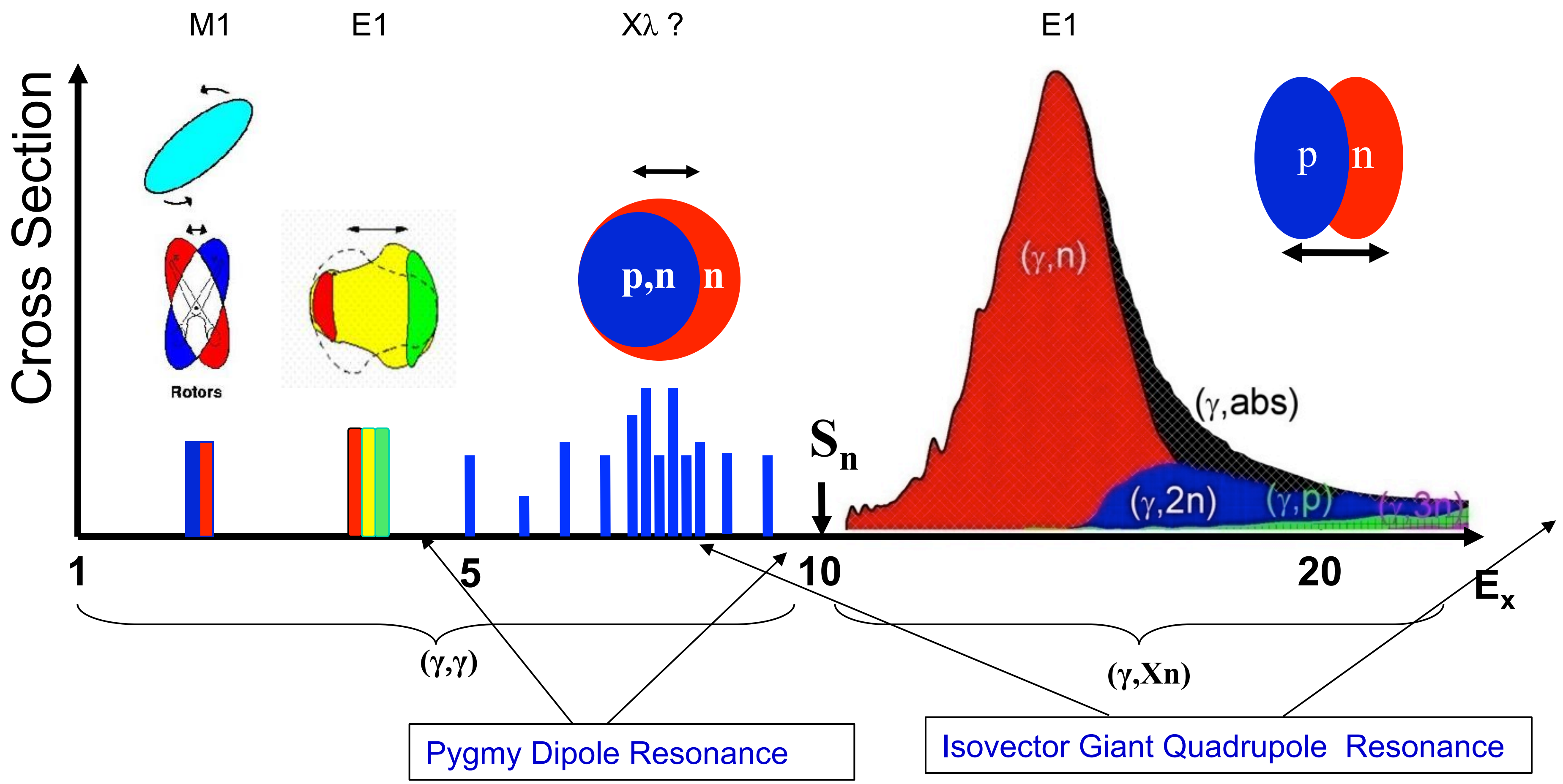
Few-nucleon Systems
photodisintegration

Nuclear Structure
NRF, (γ,γ’), Compton Scattering
(γ,n) reactions, photofission

Nuclear Astrophysics
(γ,α), (γ,n) reactions

From 2007 Nuclear Science LRP

Collective Excitations of Nuclei



Pygmy Dipole Resonance

Isovector Giant Quadrupole Resonance

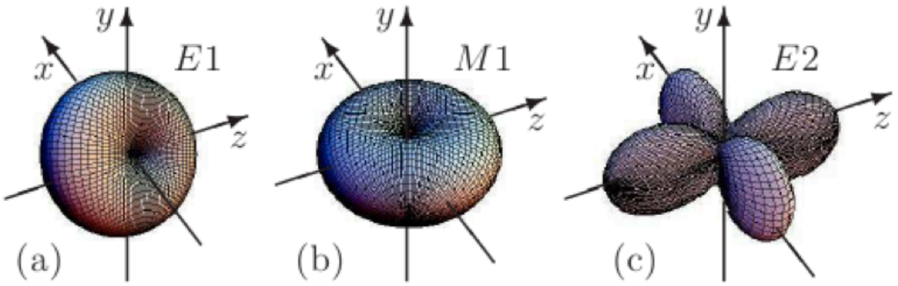
NRF

Compton scattering

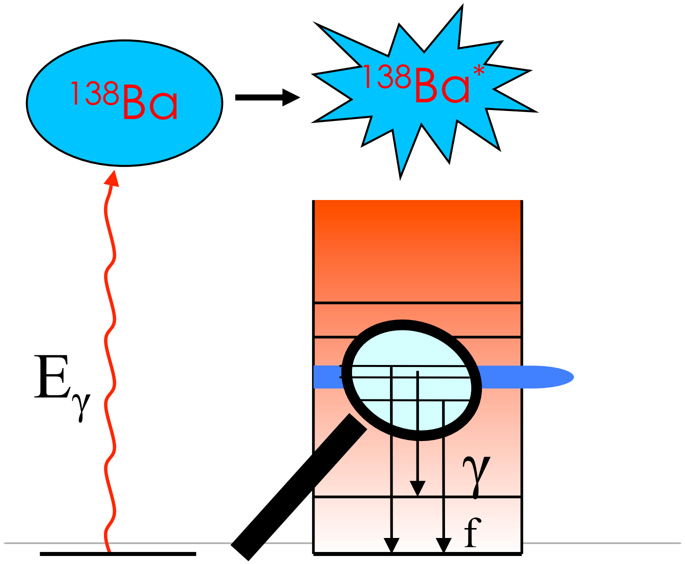
Spin and Parity Determination in Even-Mass Nuclei

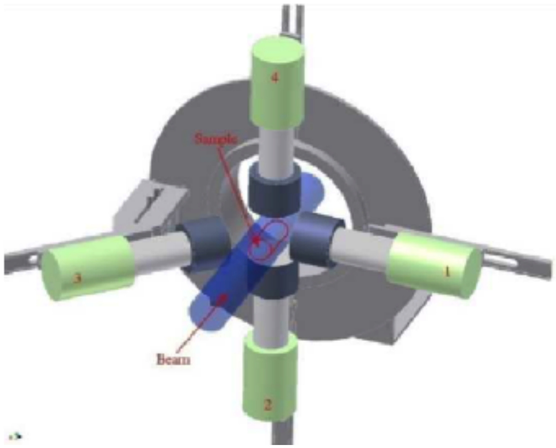
$0^+ \rightarrow 1^{(+,-)} \rightarrow 0^+$

$0^+ \rightarrow 2^+ \rightarrow 0^+$

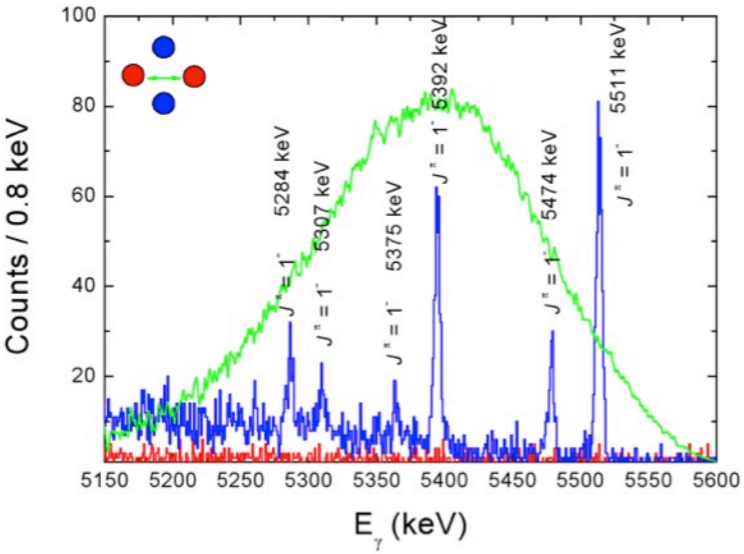


z axis: beam direction; x axis: vector of polarization





^{138}Ba(γ ,γ') E_γ = 5.40 MeV



Pygmy Dipole Resonance: viewed as an oscillation of the neutron skin against a T=0 isospin symmetric core.

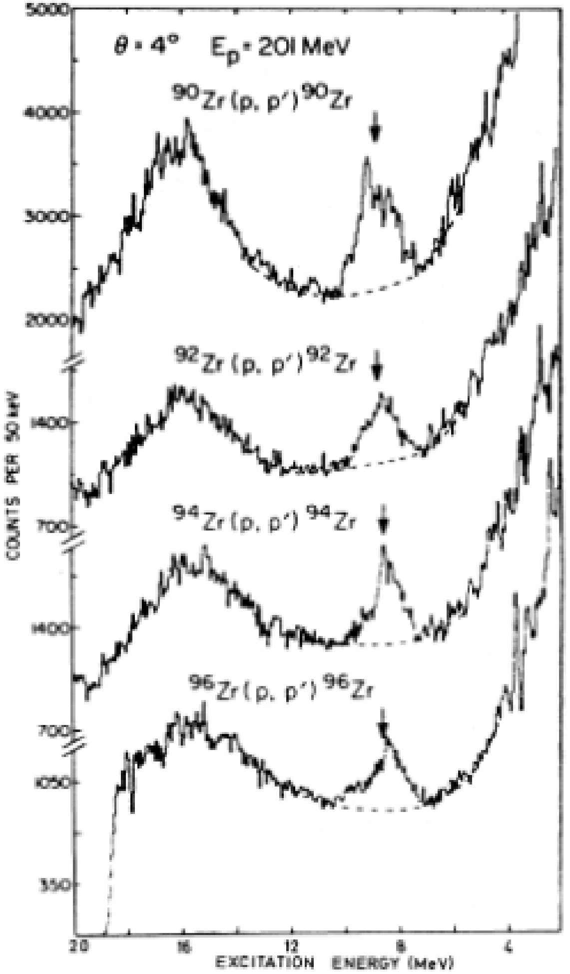
1. Systematics of the PDR may be used to constrain the density dependence of the symmetry energy, a property which has a strong impact on neutron-star properties such as composition, radius and cooling mechanisms.
2. The existence of low-energy dipole strength in neutron-rich nuclei significantly enhances the cross section for radiative capture of low-energy (~10 MeV) neutrons, important for r-process nucleosynthesis.
3. The PDR may aid the supernovae explosion mechanism. Neutrinos (99% of E) interact with neutrons (weak vector charge) and can therefore couple to the neutron rich skin of the PDR allowing for a significant energy transfer to the nuclear medium. This could revive the supernovae shock.

Recent Publications from HIγS

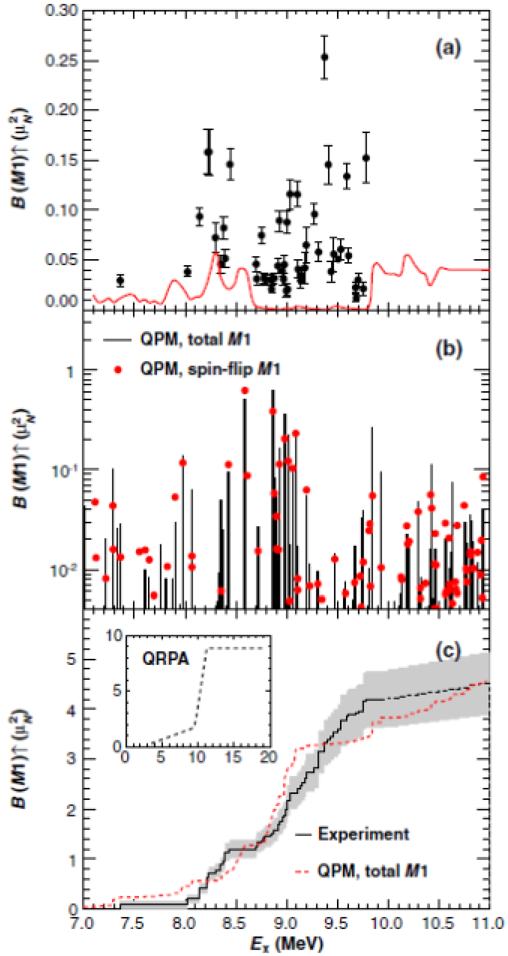
- *Decay Pattern of the Pygmy Dipole Resonance in ^{60}Ni*, M. Scheck *et al.*, Phys. Rev. C **87**, 051304(R) (2013).
- *Fine Structure of the Giant M1 Resonance in ^{90}Zr*, G. Rusev *et al.*, **Phys. Rev. Lett. 110**, 022503 (2013).
- *Pygmy dipole strength in ^{86}Kr and systematics of N = 50 isotones*, R. Schwengner *et al.*, Phys. Rev. C **87**, 024306 (2013).
- *Electromagnetic dipole strength of ^{136}Ba below neutron separation energy*, R. Massarczyk *et al.*, Phys. Rev. C **86**, 014319 (2012).
- *Spectral Structure of the Pygmy Dipole Resonance*, A.P. Tonchev *et al.*, **Phys. Rev. Lett. 104**, 072501 (2010).

Example of a recent NRF Measurement

The Giant M1 Resonance in ^{90}Zr observed via inelastic proton scattering, G. Crawley et al., Phys. Lett. B 127, 322 (1983).



Fine Structure of the Giant M1 Resonance in ^{90}Zr, G. Rusev *et al.,* **Phys. Rev. Lett. 110**, 022503 (2013).

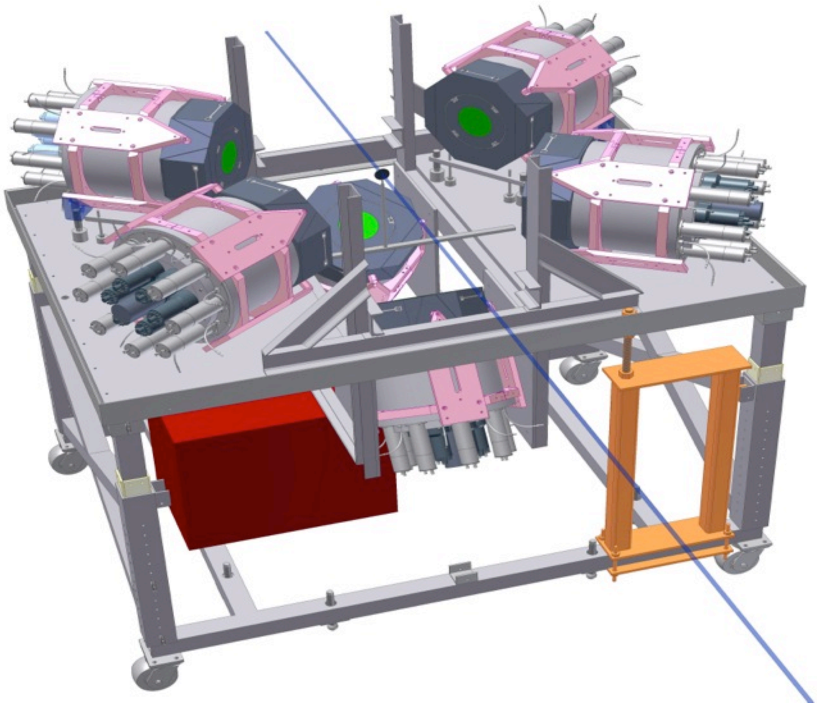


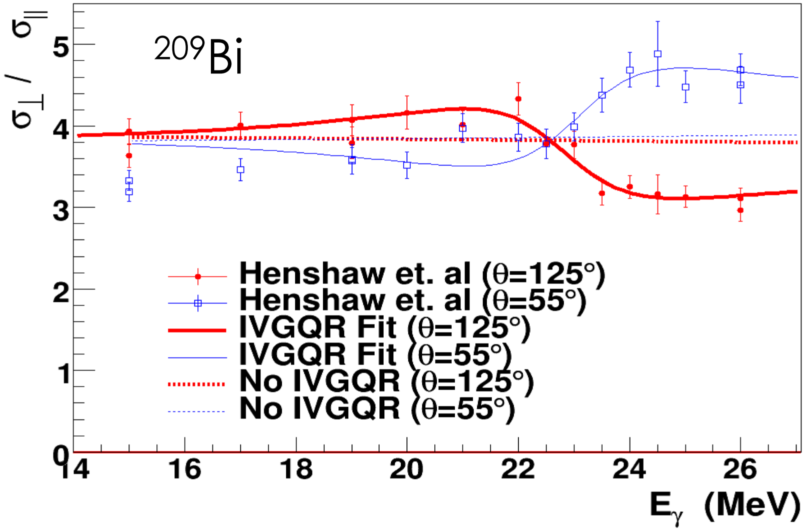
New Method for Precise Determination of the Isovector Giant Quadrupole Resonances

New Method for Precise Determination of the Isovector Giant Quadrupole Resonances in Nuclei, S.S.Henshaw et al., PRL **107**, 222501 (2011).

$$\frac{\sigma_{\parallel}}{\sigma_{\perp}} = \cos^2\theta + \frac{2|f_{E2}|\cos(\phi_{E2} - \phi_{E1})[\cos^3\theta - \cos\theta]}{|f_{E1} + D(E_\gamma, \theta)|}$$

Experiment Setup





First Measurements of Spin-Dependent Cross Sections for $^3He(\gamma,n)pp$

First measurements of the Spin-Dependent Double-Differential Cross Sections and the GDH Integrand from $^3He(\gamma,n)pp$ at Incident Photon Energies of 12.8 and 14.7 MeV, G. Laskaris *et al.*, Phys. Rev. Lett. **110**, 202501 (2013).

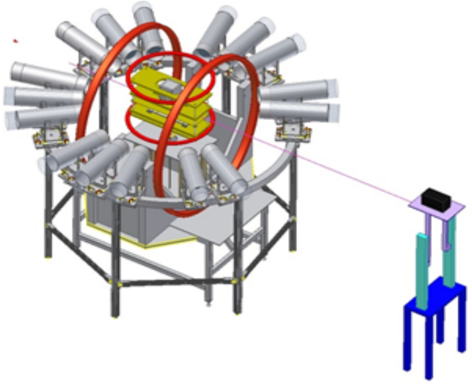
Faculty: M.W.Ahmed, H. Gao, H.R.Weller

Gerasimov-Drell-Hearn (GDH) sum rule

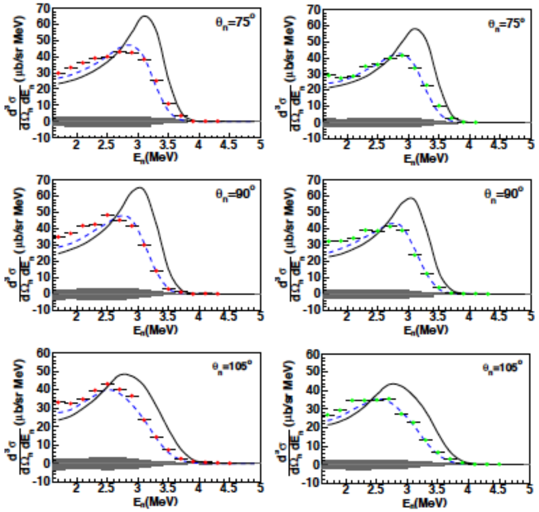
$$I^{GDH} = \int_{\nu_{thr}}^{\infty} (\sigma^P - \sigma^A)\frac{d\nu}{\nu} = \frac{4\pi^2 e^2}{M^2}\kappa^2 I,$$

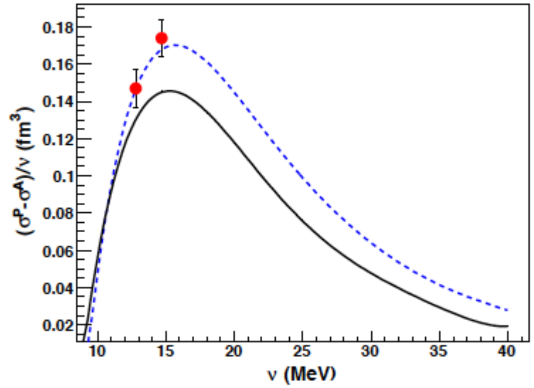
Experimental Setup:

☐ Circularly Polarized Gamma rays at 12.8 and 14.7 MeV
☐ An optically pumped polarized ^{3}He target
☐ Neutron Detector Array



Results





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Calc. by Deltuva et al. (AGS eqns., CD-Bonn+Delta with Coulomb)

—

Calc. by Skibinski et al. (Faddeev eqns., AV18+UIX 3NF, no Coulomb)

Compton Scattering

The T-matrix for the Compton scattering of incoming photon of energy ω with a spin (σ) ½ target is described by six structure functions

$$
\begin{aligned}
T(\omega, z) = {} & A_1(\omega, z)(\vec{\epsilon}'^* \cdot \vec{\epsilon}) + A_2(\omega, z)(\vec{\epsilon}'^* \cdot \hat{\vec{k}})(\vec{\epsilon} \cdot \hat{\vec{k}}') \\
& + \mathrm{i} A_3(\omega, z)\, \vec{\sigma} \cdot (\vec{\epsilon}'^* \times \vec{\epsilon}) + \mathrm{i} A_4(\omega, z)\, \vec{\sigma} \cdot (\hat{\vec{k}}' \times \hat{\vec{k}})(\vec{\epsilon}'^* \cdot \vec{\epsilon}) \\
& + \mathrm{i} A_5(\omega, z)\, \vec{\sigma} \cdot [(\vec{\epsilon}'^* \times \hat{\vec{k}})\,(\vec{\epsilon} \cdot \hat{\vec{k}}') - (\vec{\epsilon} \times \hat{\vec{k}}')(\vec{\epsilon}'^* \cdot \hat{\vec{k}})] \\
& + \mathrm{i} A_6(\omega, z)\, \vec{\sigma} \cdot [(\vec{\epsilon}'^* \times \hat{\vec{k}}')(\vec{\epsilon} \cdot \hat{\vec{k}}') - (\vec{\epsilon} \times \hat{\vec{k}})(\vec{\epsilon}'^* \cdot \hat{\vec{k}})],
\end{aligned}
$$

ε = photon polarization, *k* is the momentum

H.W. Grießhammer, et al., Progress in Particle and Nuclear Physics (2012), doi:10.1016/j.ppnp.2012.04.003

Compton Scattering

Electric and Magnetic Polarizabilities (order of ω^2)

$$\bar{A}_1(\omega, z) = 4\pi\,[\alpha_{E1}(\omega) + z\,\beta_{M1}(\omega)]\omega^2 + \cdots$$

$$\bar{A}_2(\omega, z) = -4\pi\,\beta_{M1}(\omega)\omega^2 + \cdots$$

$$\bar{A}_3(\omega, z) = -4\pi\,[\gamma_{E1E1}(\omega) + z\,\gamma_{M1M1}(\omega) + \gamma_{E1M2}(\omega) + z\,\gamma_{M1E2}(\omega)]\omega^3 + \cdots$$

$$\bar{A}_4(\omega, z) = 4\pi\,[-\gamma_{M1M1}(\omega) + \gamma_{M1E2}(\omega)]\omega^3 + \cdots$$

$$\bar{A}_5(\omega, z) = 4\pi\,\gamma_{M1M1}(\omega)\omega^3 + \cdots$$

$$\bar{A}_6(\omega, z) = 4\pi\,\gamma_{E1M2}(\omega)\omega^3 + \cdots,$$

Spin Polarizabilities (order of ω^3)

$$\gamma_1 = -\gamma_{E1E1} - \gamma_{E1M2}, \qquad \gamma_2 = \gamma_{M1E2} - \gamma_{M1M1}, \qquad \gamma_3 = \gamma_{E1M2}, \qquad \gamma_4 = \gamma_{M1M1}$$

$$\gamma_0 = -\gamma_{M1E2} - \gamma_{M1M1} - \gamma_{E1E1} - \gamma_{E1M2}, \qquad \gamma_\pi = \gamma_{M1E2} + \gamma_{M1M1} - \gamma_{E1E1} - \gamma_{E1M2}.$$

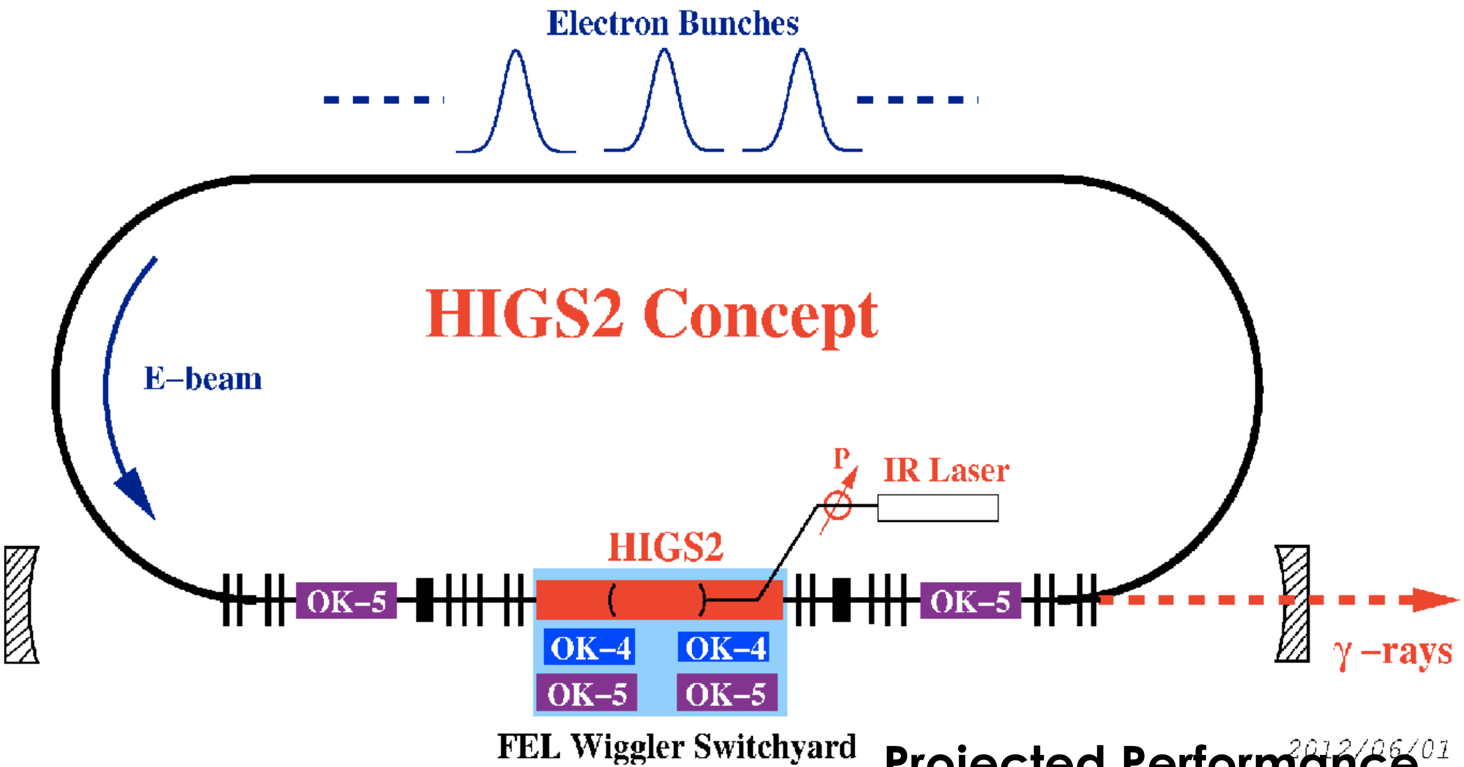
$$\gamma_0 = -\frac{1}{8\pi^2}\int_{\omega_{\mathrm{th}}}^{\infty} (\sigma_P(\omega) - \sigma_A(\omega))\frac{d\omega}{\omega^3}.$$

Timeline for Experiment at HIGS

Time (years)

	Beam Road Map	Targets/Detector	Measurements
2017			Photopion
2016			Photopion
2015		XBox-NMS	nucleon spin polarizabilities
2014	150 nm (150+ MeV, C)	ST-HIFROST	nucleon spin polarizabilities
2013	170 nm (120 MeV, C)	ST-HIFROST S-HIFROST	α,β
2012	190 nm (82 MeV, L) 190 nm (100 MeV, C) OK-5 Upgrade	Active Targets HIFROST	He-3 GDH Li-6 (80 MeV) D-GDH
2011	190 nm (100 MeV,C) 265 nm (60 MeV, C)	HINDA Blowfish	Li-6 (60 MeV) He-3 GDH

Next Generation
High Intensity Gamma-ray Source (HIγS2)



Projected Performance

~2 μm FP cavity

E_γ = 2 – 12 MeV

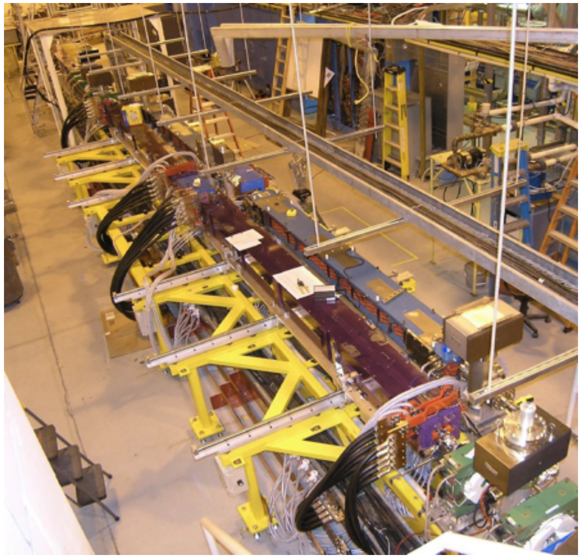
Total flux = $10^{11} – 10^{12}$ γ/s

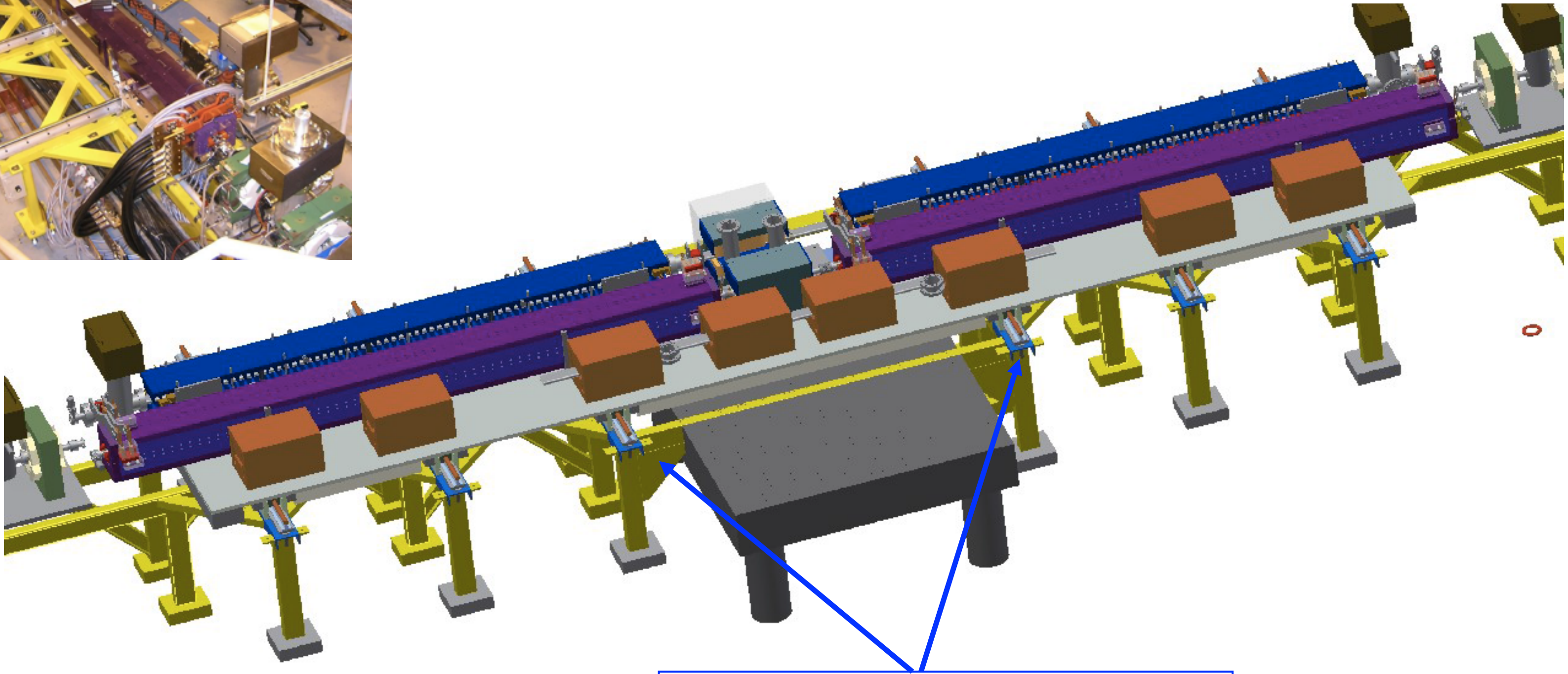
Polarization: linear or circular (rapid switch)

Energy resolution (FWHM) < 0.5%

http://www.tunl.duke.edu/higs2.php

HIγS2 Layout

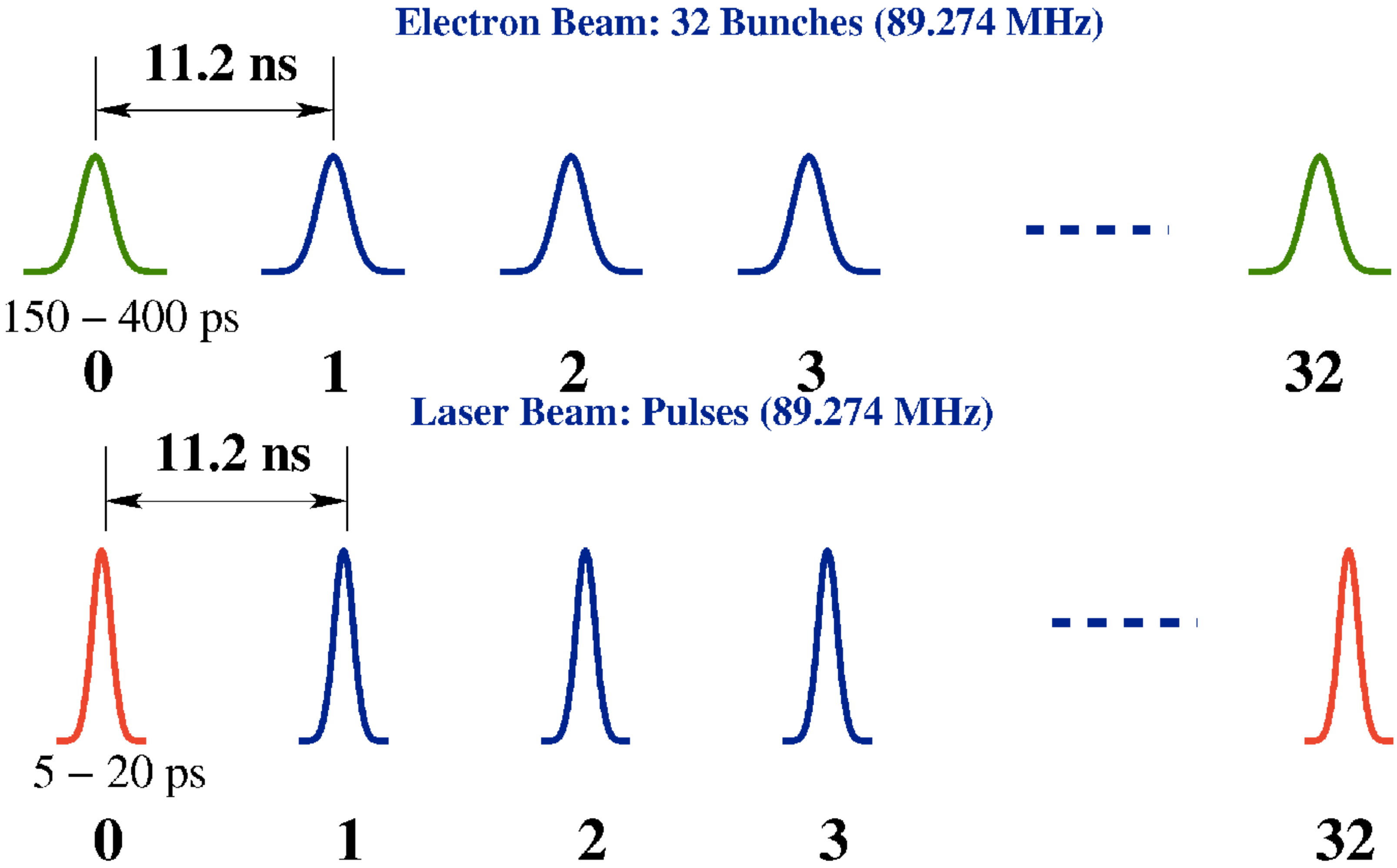




Mirrors of FP optical cavity
$L_{cav} = 1.679$ m
P_{FB} (avg) > 10 kW, 90 MHz

Collaborators: Jun Ye, JILA and U. of Colorado at Boulder

Time Structures of Electron and Laser Beams



HIγS2 Workshop: June 3 – 4, 2013
Duke University, Durham, NC USA
http://higs2.phy.duke.edu

Research Topics:

- Hadronic Parity Violation
- Nuclear Astrophysics
- Nuclear Structure
- Search for Exotic Particles (dark light)

Workshop Sponsors:

The Duke University Office of Global Strategy and Programs through the Phillips Endowment
The Department of Physics, Duke University
The Triangle Universities Nuclear Laboratory

HIγS2 Contacts:

(when sending email use "HIGS2" as the subject)

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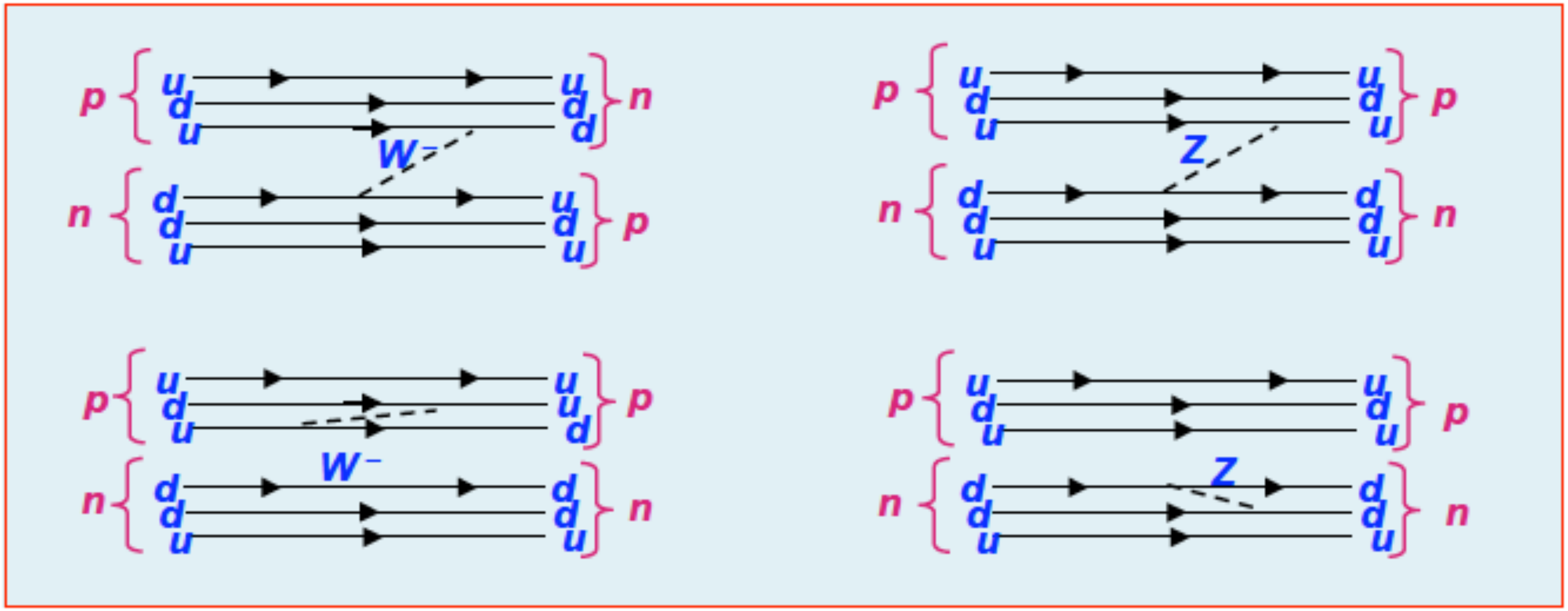
Calvin Howell, howell@tunl.duke.edu

Accelerator:
Ying Wu, wu@fel.duke.edu

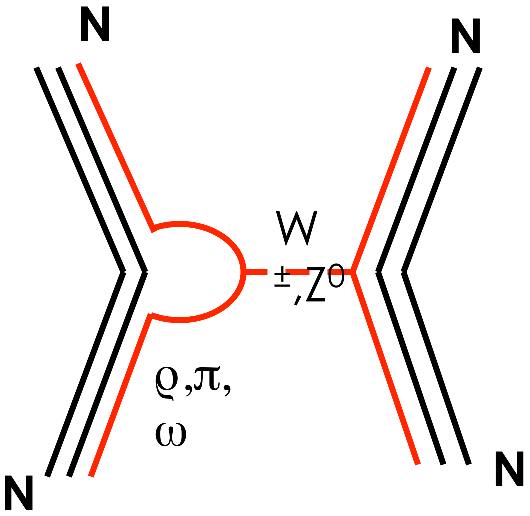
Parity Violation in the Nucleon-Nucleon Interaction

From talk by Mike Snow at HIGS2 workshop



HPV as a probe of QCD:
- probes nucleon in their ground state;
- short-ranged compared to the size of the nucleon, 1st order sensitive to q-q correlations in hadrons
- Only way to probe non-lepton strangest conserving q-q weak current
- provides fundamental constants for lattice QCD calculations in few-nucleon systems

NN Weak Interaction: 5 Independent Elastic Scattering Amplitudes at Low Energy



Organize by isospin:

I_{tot} = 1

- Even L, $S_{tot} = 0$ ➔ $^1S_0$, $^1D_2$, $^1G_4$, …
- Odd L, $S_{tot} = 1$ ➔ $^3P_{0,1,2}$, $^3F_{2,3,4}$

I_{tot} = 0

- Even L, $S_{tot} = 1$ ➔ $^1P_1$, $^1F_3$, …
- Odd L, $S_{tot} = 0$ ➔ $^3S_1$, $^3D_{1,2,3}$, …

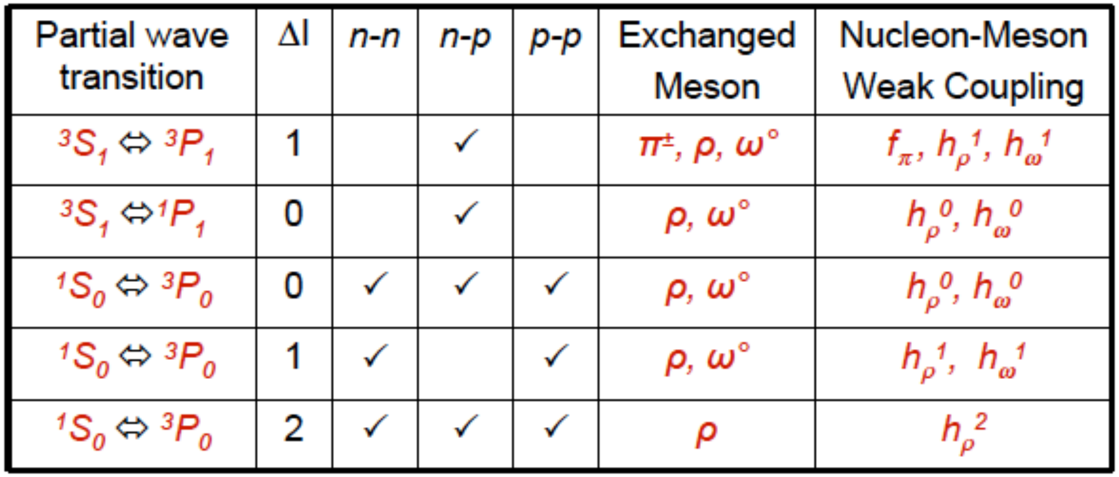
Consider only low energies, i.e., only L=0 (s-wave) are important for strong interaction, then parity violation is dominated by S-P interference.
➔ 5 independent NN parity-violating transition amplitudes

ΔI = 0	$^3S_1$ ⇔ $^1P_1$ (np)
ΔI = 1	$^3S_1$ ⇔ $^3P_1$ (np)
ΔI = 0, 1, 2	$^3S_0$ ⇔ $^1P_0$ (nn, pp, np)

Hadronic weak couplings:

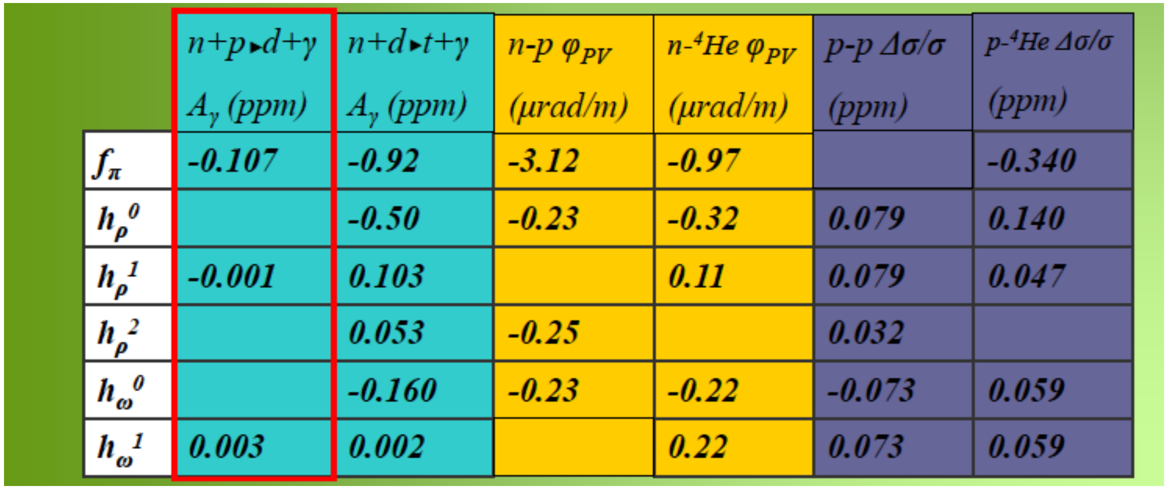
in terms of meson exchange picture

Unified treatment of the parity violating nuclear, Force,
B. Desplanques, J.F. Donoghue, B.R. Holstein, Ann. Phys. 124, 449 (1980)



Partial wave transition	ΔI	*n-n*	*n-p*	*p-p*	Exchanged Meson	Nucleon-Meson Weak Coupling
$^3S_1 \Leftrightarrow {}^3P_1$	1		✓		$\pi^\pm$, ρ, ω°	f_π, h_ρ^1, h_ω^1
$^3S_1 \Leftrightarrow {}^1P_1$	0		✓		ρ, ω°	h_ρ^0, h_ω^0
$^1S_0 \Leftrightarrow {}^3P_0$	0	✓	✓	✓	ρ, ω°	h_ρ^0, h_ω^0
$^1S_0 \Leftrightarrow {}^3P_0$	1	✓		✓	ρ, ω°	h_ρ^1, h_ω^1
$^1S_0 \Leftrightarrow {}^3P_0$	2	✓	✓	✓	ρ	h_ρ^2

From talk by Mike Snow at HIGS2 workshop

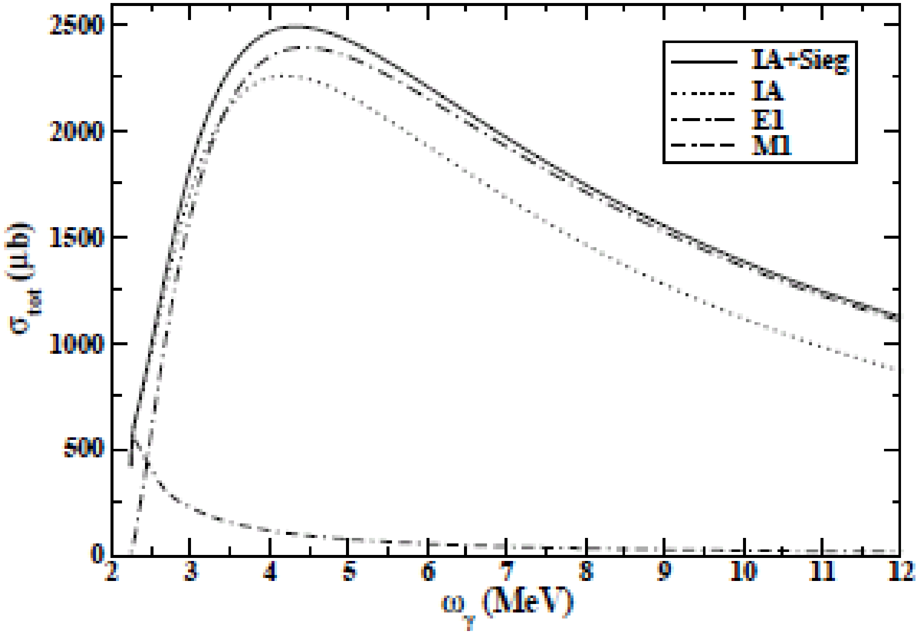


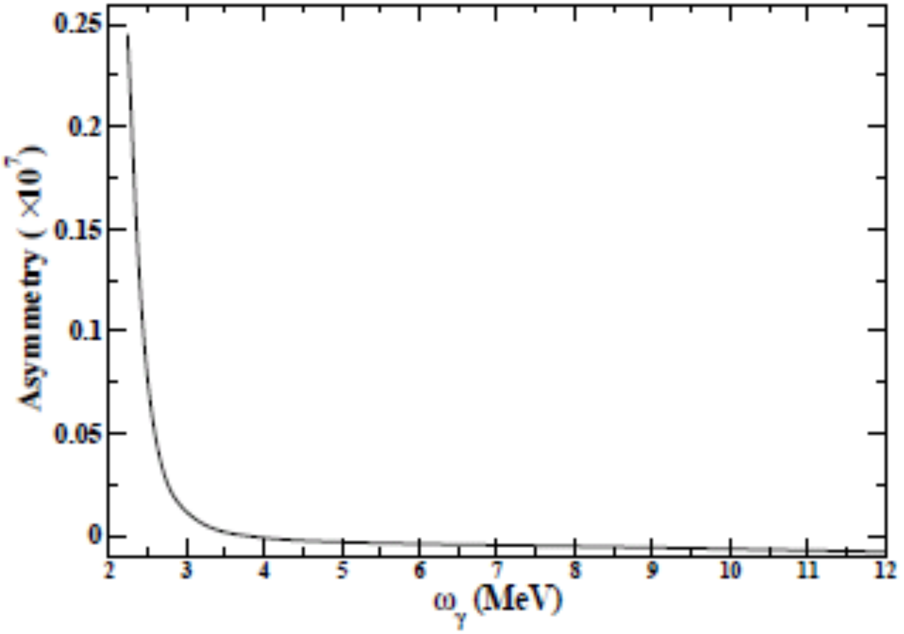
	$n+p \to d+\gamma$ A_γ (ppm)	$n+d \to t+\gamma$ A_γ (ppm)	n-p φ_{PV} (μrad/m)	n-^4He φ_{PV} (μrad/m)	p-p $\Delta\sigma/\sigma$ (ppm)	p-^4He $\Delta\sigma/\sigma$ (ppm)
f_π	-0.107	-0.92	-3.12	-0.97		-0.340
h_ρ^0		-0.50	-0.23	-0.32	0.079	0.140
h_ρ^1	-0.001	0.103		0.11	0.079	0.047
h_ρ^2		0.053	-0.25		0.032	
h_ω^0		-0.160	-0.23	-0.22	-0.073	0.059
h_ω^1	0.003	0.002		0.22	0.073	0.059

From presentation by N. Fomin, CIPANP 2012

EFT calculation of deuteron PV photodisintegration

$$\vec{\gamma}d \rightarrow np$$



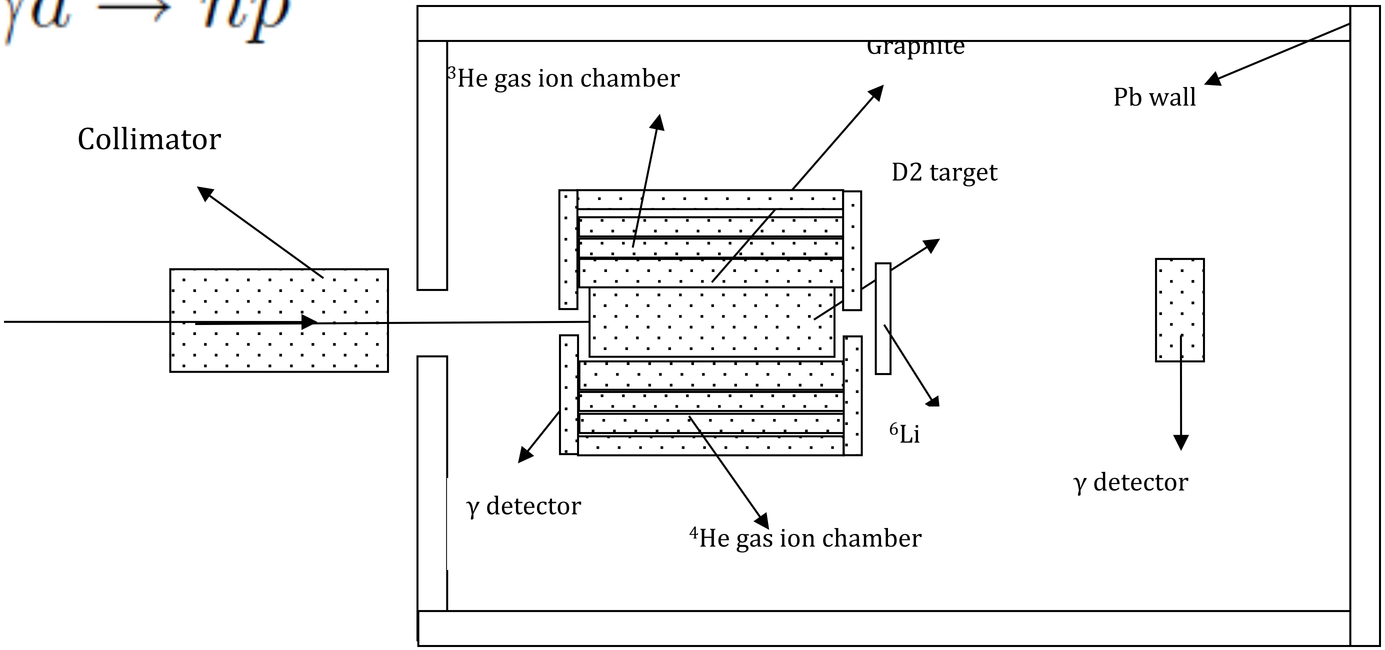


C.-P. Liu, C.H. Hyun and B. Desplanques, arXiv:nucl-th/0403009v1.

E_γ = 2.5 MeV
σ = 800 μb
A ~ 10^{-8}

Concept of the Experiment Setup for PV Photodisintegration of the Deuteron at HIGS2

$$\vec{\gamma} d \rightarrow np$$



For 10^{-8} statistical accuracy, need to detect about 10^{16} neutrons
➔ 4 x 10^{18} gammas.

Target thickness = 5 x 10^{24} deuterons/cm^2
Gamma-ray flux on target = 10^{11} γ/s
Production beam time = 450 days = 10,800 hours

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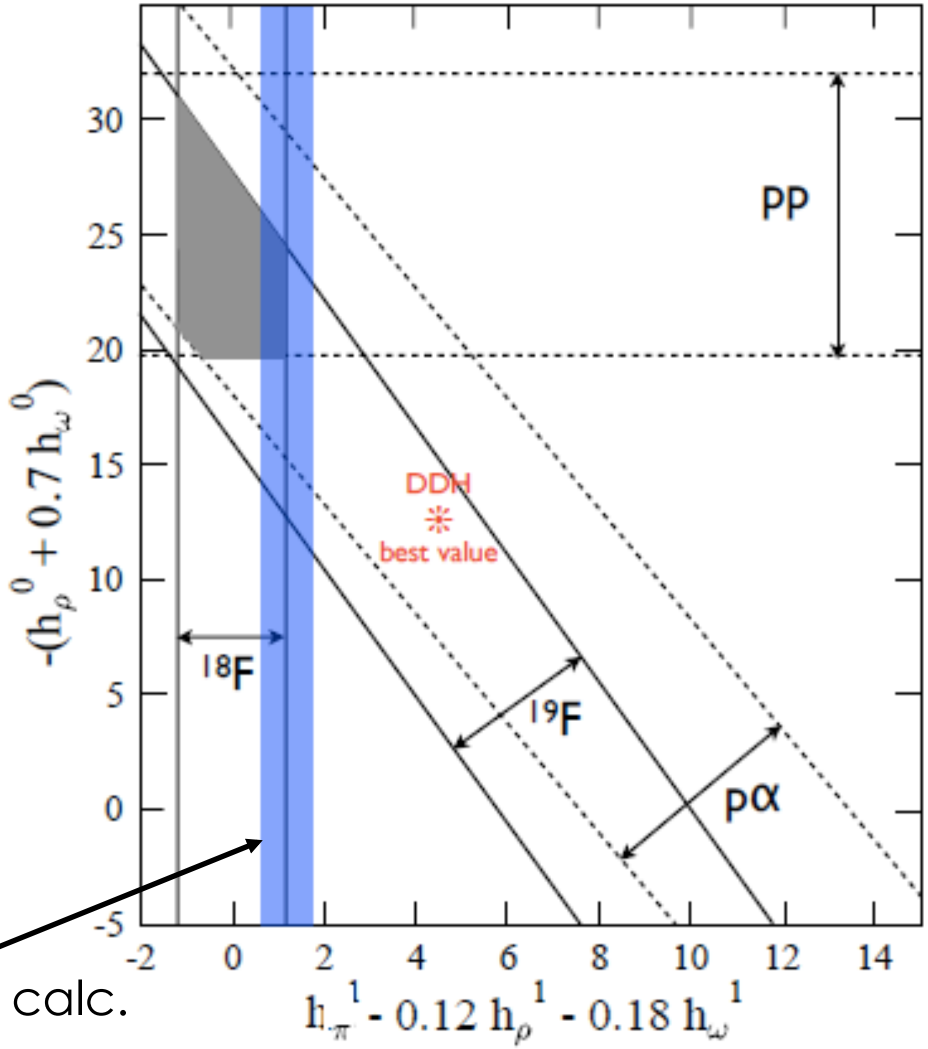
The Organizers of this workshop for inviting me

Backup Slides

Status of ΔI = 0 and 1 weak couplings



Haxton and Holstein, arXiv:1303.4132, March 2013

Lattice QCD calc.