Low-Energy QCD Research at H1γS

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**Program Components:**

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

- Nucleon structure in terms of collective degrees of freedom: *Compton scattering at $E_\gamma > 60$ MeV*

Most intense Compton γ-ray source in the world

Features that enable basic and applied research
- Wide beam energy range: 1 to 100 MeV
- Selectable beam energy spread (by collimation)
- High beam intensity on target (>10⁷ γ/s @ ΔE/E = 5%)
- E < 20 MeV; ~10³ γ/s/eV
- >95% beam polarization (linear and circular)

1.2 GeV Storage Ring FEL

Energy resolution by collimation

\[ E_γ = 2032 \text{ keV} \]
\[ ΔE_γ = 26 \text{ keV} \]
\[ ΔE/E = 1.3\% \]
HIGS operates about 1800 hours/year for nuclear physics research

Low-Energy QCD:

- Compton Scattering
- nucleon electric and magnetic polarizabilities
- nucleon spin polarizabilities
- Few-nucleon 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

Figure from 2007 USA Nuclear Science LRP
Duke University and TUNL


North Carolina Central University and TUNL

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Smoluchowski Institute of Physics, Jagiellonian University

H. Witała

Vilnius University

A. Deltuva
Long-term Goal of Nuclear Physics: connect nuclei to QCD

Hierarchy of theoretical treatments of nuclear systems

Schematic diagram for coherent theoretical treatment of nuclear systems starting from high energies where perturbative QCD can be applied going to low-energy nuclear phenomena where mean-field potential models are most efficient.
Color Interaction:
- Quarks bound by color force
- Strong interaction forms colorless hadrons

Nuclear Force:
interaction of colorless hadrons \( \rightarrow \) must be due to residential and dynamic interactions analogous to Van der Waals forces.

Van der Waal interaction, e.g., London dispersive force

\[
V_{LD} \propto -\frac{\alpha_A \alpha_B}{R^6}
\]
Few nucleon systems and light nuclei provide a laboratory for analyzing nuclear structure and reaction dynamics in the context of QCD.

**TUNL few-nucleon program with γ-ray beams:**
- Contribute to development of *ab-initio* few-nucleon calculations
- Evaluate theoretical treatment of meson exchange currents and 3N interactions
Long-term Goal of Nuclear Physics: connect nuclei to QCD

Univ. Bonn, $E_n=26$ MeV

CIAE, $E_n=25$ MeV

nd breakup
nn QFS

$E_p=0$

Witała: Must increase the accepted $nn \, ^1S_0$ strength to fit data by $\lambda = x \, 1.09$

- **Consequence**: Large CSB in NN force
- **Conjecture**: (1) uncertainties in data too small and/or (2) long-range 3NI not included in the models

Two-pronged approach

Neutron beam at tandem lab
Measure nn-QFS

$\gamma$ beam at HI\gamma S

np and nn FSI via
$\gamma + ^3\text{He} \rightarrow n + p + p$
$\gamma + ^3\text{H} \rightarrow n + n + p$
$^3\text{He}(\gamma,n)pp$ total cross section

Figure from thesis of R. Skibinski, Jagiellonian Univ., 2002. The MECs are treated using the Siegert theorem. The experimental data are from Berman et al., PRC 10, 2221 (1974) (LLNL) and Faul et al., PRC 24, 1791 (1981) (LLNL).
Ab-initio Calculations of 3-Body Photodisintegration of $^3$He

$$E_\gamma = 15.0 \text{ MeV}: \theta_p = 87.0^\circ, \theta_n = 84.0^\circ, \phi_{pn} = 180^\circ$$

Graph showing data for different calculations and configurations.

- Witala av18,UrbIX+MEC+3NF, Anp=-22.1
- Witala av18,UrbIX+MEC+3NF, Anp=-24.1
- Deltuva CD Bonn+Delta+rel.ch.corr.MEC
- Deltuva CD Bonn+Delta+rel.ch.corr.MEC+Coulomb
Exclusive Photodisintegration of $^3$He: Experimental Setup

**Setup Details:**
Number of target cells = 7  
Target cell pressure = 5 atm  
Number of neutron detectors = $14 \times 2 = 28$  
Silicon strip width = 5.9 mm
Exclusive Photodisintegration of $^3$He: Technique Features

**Experiment Features:**

- Detector signals fully digitized
- Single detector event triggers – no constraints on neutron detector coincidences
- Two methods for measuring $\gamma$-ray beam flux
  - 5-paddle system (eff. calibrated with large NaI detector)
  - $^2$H($\gamma$, n)p with D$_2$O target
- In-situ $^3$He($\gamma$, pd) reaction
  - Bench mark simulations of d$\Omega$
  - Monitor target thickness
Energy spectra for n-p coincidences: Example

\[ ^3\text{He}(\gamma, \text{n}p)p \]
\[ E_\gamma = 15 \text{ MeV} \]
\[ \theta_n = 87^\circ, \theta_p = 84^\circ, \]
\[ \Delta\phi_{np} = 180^\circ \]
Energy spectra for p-p and p-d coincidences: Example

$^{3}\text{He}(\gamma, \text{np})p$
$E_\gamma = 15 \text{ MeV}$
$\Theta_{p,d} = 87^\circ, \theta_{p,d} = 84^\circ$
$\Delta\phi_{pp/pd} = 180^\circ$

$p$-$d$ coinc.  
np FSI  
S = 0  

3B photodisintegration

2B photodisintegration
Experiment Design for P-02-13, $^3\text{H}(\gamma, \text{nn})p$

**Calculations by H. Witala**

- $a_{nn} = -19 \text{ fm}$
- $a_{nn} = -17 \text{ fm}$
- $\frac{\Delta \sigma/\sigma}{\Delta a_{nn}} = 9.3\%$
- $f_{nn} = -19 \text{ fm}$
- $f_{nn} = -17 \text{ fm}$

**Diagram Details:**
- **Secondary containment**
- **To tritium gas U-bed getter system**
- **$\gamma$-ray beam**

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Nuclear Photonics: March 15 – 16, 2018
Hi\gammaS Compton-Scattering Collaboration

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Nucleon Structure: in terms of collective degrees of freedom

\[ \rho_1 = \bar{e}^t \cdot \bar{e}, \quad \rho_2 = \bar{s}^t \cdot \bar{s}, \]
\[ \rho_3 = i \vec{\sigma} \cdot (\bar{e}^t \times \bar{e}), \quad \rho_4 = i \vec{\sigma} \cdot (\bar{s}^t \times \bar{s}), \]
\[ \rho_5 = i \left( \vec{\sigma} \cdot \vec{k} \right) (\bar{e}^t \times \bar{e}) - \left( \vec{\sigma} \cdot \vec{k} \right) (\bar{s}^t \times \bar{s}), \]
\[ \rho_6 = i \left( \vec{\sigma} \cdot \vec{k} \right) (\bar{s}^t \times \bar{e}) - \left( \vec{\sigma} \cdot \vec{k} \right) (\bar{s}^t \times \bar{s}) \]

Nucleon Dipole Polarizabilities

Stiff core + pliable pion cloud

Scalar polarizabilities:

\[ \alpha = \frac{2 f_{EE}^{1+}(\omega) + f_{EE}^{1-}(\omega)}{\omega^2}, \]
\[ \beta = \frac{2 f_{MM}^{1+}(\omega) + f_{MM}^{1-}(\omega)}{\omega^2}. \]

Spin-dependent polarizabilities:

\[ \gamma_{E1E1}(\omega) = \frac{f_{EE}^{1+}(\omega) - f_{EE}^{1-}(\omega)}{\omega^3}, \]
\[ \gamma_{M1M1}(\omega) = \frac{f_{MM}^{1+}(\omega) - f_{MM}^{1-}(\omega)}{\omega^3}, \]
\[ \gamma_{E1M2}(\omega) = \frac{f_{EM}^{1+}(\omega)}{\omega^3}, \]
\[ \gamma_{M1E2}(\omega) = \frac{f_{ME}^{1+}(\omega)}{\omega^3}. \]

\[ H_{\text{eff}}^{(3), \text{spin}} = -\frac{1}{2} 4\pi \left( \gamma_{E1E1} \vec{E} \cdot \vec{E} + \gamma_{M1M1} \vec{B} \cdot \vec{B} - 2 \gamma_{M1E2} E_j \sigma_j H_j + 2 \gamma_{E1M2} H_j \sigma_j E_j \right) \]

Energy Dependence of Nucleon Scalar Polarizabilities


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. $m_n-m_p$
- $\beta_p$ input to Lamb-shift corr. In $\mu$H atoms
- Collective response of internal spin dof to em pulse

Goals of Compton-scattering Program at H\(\text{lyS}\):
- sum-rule independent meas. of $\beta_p$
- reduce $\Delta \beta_n$ by ~ factor of 2

Baldin sum rule:
\[\alpha_E + \beta_M = \frac{1}{2\pi^2} \int_0^\infty \frac{\sigma_P^N - \sigma_A^N}{\omega^2} d\omega\]

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PDG - 2013: HGW, JAM, DRP, GF, PPNP, 67 (2012) 841-897
JAM, DRP, HGW, EJP, A 49 (2013) 12

[\text{EFT Extractions -- HWG, JAMcG, DRP, GF, PH,}\]

PDG - 2013: HGW, JAM, DRP, GF, PPNP, 67 (2012) 841-897
JAM, DRP, HGW, EJP, A 49 (2013) 12

Compton-scattering Experiment Setup at HIγS

Kendellen et al., NIMA 840 (2016) 174
Determination of Isocalar Polarizabilities by Compton Scattering from $^4$He

Follow-up $^4$He(γ,γ) Measurements

- HlyS data at $E_\gamma = 85$ MeV
These data will allow for the extraction of the proton polarizabilities using LEX. Along with the $\Sigma_3$ measurement, a new extraction of the proton EM polarizabilities will be available soon.

The data include both elastic and inelastic channels. The curves are EFT calculation for purely elastic Compton scattering cross section.
The overarching goal of the Compton-scattering program is to provide data that will enable a new and much improved extraction of neutron EM scalar polarizabilities.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Motivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-Resolution Compton Scattering on $^2$H @ 65 - 85 MeV</td>
<td>Combined with the existing HI$_3$S data and with the extraction of the elastic cross sections, these data will double the deuteron Compton scattering database for the extraction of the neutron scalar polarizabilities.</td>
</tr>
<tr>
<td>Compton Scattering on $^3$He at 100 - 115 MeV</td>
<td>First world data on Compton scattering on $^3$He for the extraction of nucleon scalar polarizabilities.</td>
</tr>
</tbody>
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Acknowledgement of Support for the HiγS LE QCD Program

U.S. Department of Energy, Office of Nuclear Physics
- Grant #: DE-FG02-97ER41033
- Grant #: DE-FG02-95ER-40907
- Grant #: DE-SC0015393
- Grant #: DE-SC0005367
- Grant #: DE-FG02-97ER41041
- Grant #: DE-FG02-97ER41
- Grant #: DE-FG02-06ER41422
- Grant #: DE-FG02-03ER41231
- Grant #: DE-SC0016512

U.S. National Science Foundation
- Grant #: 1301843

Polish National Science Center
- Grant #: DEC-2013/10/M/ST2/00420

Natural Sciences and Engineering Research Council of Canada

The Dean’s Research Chair programme of the Columbian College of Arts and Sciences, George Washington University
Thank You