Nuclear Physics Research at the High Intensity Gamma-ray Source (HIγS) at TUNL

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Duke University
and
Triangle Universities Nuclear Laboratory (TUNL)
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International Meeting on Laser-Driven Radiation Sources for Nuclear Applications

Outline

• Basic Research

• Applications of Photonuclear Reaction Measurements
  1. Nuclear Resonance Fluorescence (NRF)
  2. Photofission
     – real-time detection of neutrons
     – fission product yields
H\textsubscript{\textgamma}S: Intracavity Compton-back Scattering

**How it works**

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

**Example:** \( E_e = 500 \text{ MeV} \Rightarrow \gamma = 978 \)

- \( \lambda_{\text{FEL}} = 400 \text{ nm} \)
- \( \hbar \omega = 3.11 \text{ eV} \)
- \( E_\gamma = 11.9 \text{ MeV} \)
Most intense Compton $\gamma$-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 ($>10^6 \gamma$/s @ $\Delta E/E = 5\%$)
• >95% beam polarization (linear and circular)

1.2 GeV Storage Ring FEL

Energy resolution by collimation

$E_\gamma = 2032$ keV
$\Delta E_\gamma = 26$ keV
$\Delta E/E = 1.3\%$
Studies of Strongly Interacting Matter at H\(\gamma\)S

From 2007 Nuclear Science LRP

- **Physics of Hadrons**
  - Degrees of Freedom: quarks, gluons
  - Energy (MeV): 940 neutron mass
  - Constituent quarks
  - Degrees of Freedom: baryons, mesons
  - Energy (MeV): 140 pion mass
  - Quark masses

- **Physics of Nuclei**
  - Degrees of Freedom: protons, neutrons
  - Energy (MeV): 8 proton separation energy in lead
  - Nuclear densities and currents
  - Energy (MeV): 1.32 vibrational state in tin
  - Degrees of Freedom: collective coordinates
  - Energy (MeV): 0.043 rotational state in uranium

**Compton Scattering**
- Nucleon electric and magnetic polarizabilities
- Nucleon spin polarizabilities

**Photo-pion Production**

**Nuclear Structure**
- NRF, \((\gamma,\gamma')\), Compton Scattering
- \((\gamma,n)\) reactions, photofission

**Nuclear Astrophysics**
- \((\gamma,\alpha)\), \((\gamma,n)\) reactions

**Milestones (2007 LRP):**
- NS6: collective modes in many-body nuclei
- HP10: ab initio microscopic studies
- NA4: 

GDH Sum Rule
- \(^2\text{H}\)
- \(^3\text{He}\)

Few-nucleon Systems
- photodisintegration

Duke University
NC State University
The University of North Carolina at Chapel Hill

LDRE - Dec, 2015
### HλγS Users (2010-2014)

<table>
<thead>
<tr>
<th>US Collaborating Institutions</th>
<th>Non-US Collaborating Institutions</th>
<th>Total</th>
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<tbody>
<tr>
<td>23</td>
<td>17</td>
<td>40</td>
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**Collaborating Institutions at HIGS**

- **US Collaborating Institutions (57%)**
  - American Science and Engineering (AS&E)
  - Argonne National Laboratory, Argonne, IL
  - European Space Agency (ESA)
  - Fakultat fur Physik, LMU München, Garching, Germany
  - Fermi National Accelerator Laboratory, Batavia, IL
  - Frankfurt Institute for Advanced Studies FIAS, Frankfurt, Germany
  - George Washington University, Washington, DC
  - GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
  - Hebrew University of Jerusalem, Israel
  - IKP, TU Darmstadt, Darmstadt, Germany
  - Institut für Strahlenphysik, Dresden, Germany
  - James Madison University
  - Japanese Atomic Energy Agency (JAEA)
  - Kayoto University
  - Lawrence Berkeley National Laboratory
  - Lawrence Livermore National Laboratory
  - Los Alamos National Laboratory
  - National Aeronautics and Space Administration (NASA)
  - National Ignition Facility (NIF)
  - NSC Kharkov Institute of Physics and Technology, Kharkov, Ukraine

- **Non-US Collaborating Institutions (43%)**
  - North Carolina Central University, Durham, NC
  - Pacific Northwest National Laboratory
  - PTB, Braunschweig, Germany
  - Rutgers, The State University of New Jersey, Piscataway, New Jersey
  - Temple University
  - Thomas Jefferson National Accelerator Facility
  - Universität zu Köln, Köln, Germany
  - University of California Berkeley
  - University of Connecticut, CT
  - University of Illinois, Urbana-Champaign, Illinois
  - University of Kentucky, Lexington, Kentucky
  - University of Lund, Lund, Sweden
  - University of Massachusetts, Amherst MA
  - University of New Hampshire, Durham, NH
  - University of Notre Dame
  - University of Saskatchewan
  - University of Saskatchewan, Saskatoon, SK, Canada
  - University of Virginia, Charlottesville, VA
  - Weizmann Institute, Israel
  - WNSL, Yale University, New Haven, CT
HlγS: Topical groups (collaborators with TUNL faculty)

1. Nuclear Structure and Nuclear Astrophysics:
   (a) Volker Werner, Yale University
   (b) Deniz Savran, Univ. Frankfurt and GSI
   (c) Norbert Pietralla, Univ. Darmstadt
   (d) R. Schwengner, Helmholtz-Zentrum Dresden-Rossendorf
   (e) Moshe Gai, Univ. Conn.
   (f) Ernst Rehm, ANL
   (g) Michael Wiescher, Univ. of Notre Dame
   (h) Steve Yates, Univ. of Kentucky

2. Compton Scattering: Nucleon and Nuclear Polarizabilities
   (a) J. Feldman, GWU
   (b) B. Norum and D. Crabb, UVA
   (c) D. Hornidge, Mt. Allison Univ., Canada
   (d) R. Miskimen, U. Mass

3. Gerasimov-Drell-Hearn (GDH) Sum Rule
   (a) B. Norum and D. Crabb, UVA
   (b) R. Pywell, Univ. of Saskatchewan
The mass of the iron core at the end nuclear energy generation has a critical influence on the fate of a massive star, i.e., $M > 15 \, M_\odot$, core mass $> 2.0 \, M_\odot \rightarrow$ black hole
lower mass cores explode easier $\rightarrow$ neutron stars

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

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

\[ ^{12}\text{C} + \alpha \rightarrow ^{16}\text{O} + \gamma \; ; \text{converts } ^{12}\text{C} \text{ to } ^{16}\text{O} \]

\[ \rightarrow \text{determines } ^{12}\text{C}/^{16}\text{O} \]

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

Collaboration 1: M.W. Ahmed (NCCU), M. Gai (U. Conn.) and H.R. Weller (Duke)
Technique: CO$_2$ gas target (Optical Time Projection Chamber)

Collaboration 2: E. Rehm (ANL), C. Ugalde (ANL) and A.E. Champagne (UNC)
Technique: Superheated liquid bubble chamber

Faculty: M.W. Ahmed, H.R. Weller
Collaborator: M. Gai (Univ. Connecticut)

Technique: CO$_2$ filled Optical Time Project Chamber (OTPC)
Collective Excitations of Nuclei

- M1
- E1
- Xλ ?
- p,n
- E1
- NRF
- Compton scattering
- Pygmy Dipole Resonance
- Isovector Giant Quadrupole Resonance

Cross Section

- 1
- 5
- 10
- 20

E_x

- (γ,γ)
- (γ,n)
- (γ,2n)
- (γ,p)
- (γ,3n)
- (γ,Xn)
- (γ,abs)
Nuclear Resonance Fluorescence (NRF): Spin and Parity Determination in Even-Mass Nuclei

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

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

$^{138}\text{Ba}(\gamma,\gamma') \ E_\gamma = 5.40 \text{ MeV}$
Nuclear Resonance Fluorescence (NRF): Spin and Parity Determination in Even-Mass Nuclei

138Ba(\gamma,\gamma') E_\gamma = 5.40 MeV

\[ 0^+ \rightarrow 1^{(+,-)} \rightarrow 0^+ \]
\[ 0^+ \rightarrow 2^+ \rightarrow 0^+ \]

Precise Determination of the Isovector Giant Quadrupole Resonances


### Experiment Setup

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

### Nuclear Equation of State

\[
E(\rho, \beta) = E(\rho, \beta = 0) + S(\rho)\beta^2
\]

\[
\rho = \rho_n + \rho_p; \quad \beta = (\rho_n - \rho_p)/\rho
\]

\[
S(\rho) = E(\rho, \beta = 1) - E(\rho, \beta = 0)
\]

\[
S(\rho) = \left[ S_v + \frac{L}{3} \frac{\rho - \rho_s}{\rho_s} + \frac{K_{sym}}{18} \left( \frac{\rho - \rho_s}{\rho_s} \right)^2 \right] + \ldots
\]

\[
S_v = \frac{1}{8} \left[ \frac{\partial^2 E}{\partial \beta^2} \right]_{\rho_s, \beta = 1}
\]

\[
L = \frac{3}{8} \frac{\partial^3 E}{\partial \rho \partial \beta^2} \bigg|_{\rho_s, \beta = 1}
\]

\[
K_{sym} = \frac{9}{8} \frac{\partial^4 E}{\partial \rho^2 \partial \beta^2} \bigg|_{\rho_s, \beta = 1}
\]
Measure/determine quantities that can be calculated both by Lattice QCD and \( \chi \)EFT

- GDH sum rule on the deuteron (spin-dependent cross section)
- Electric and magnetic polarizabilities of the nucleons
- Spin dependent polarizabilities of the nucleons
- \( m_u/m_d \) via polarized photopion production (test of \( \chi \)PT)
- Hadronic weak low-energy parameter in EFT (parity violating measurement of photodisintegration of the deuteron)
GDH (Gerasimov-Drell-Hearn) Sum Rule

Relates the helicity dependence of the photoabsorption cross section of a nucleon/nucleus to its static properties, i.e., magnetic moment, mass and spin: provides opportunities to gain insight about the dynamical response of the internal dof of nucleons to EM impulses over a broad frequency band

\[ I_{GDH} = \int_0^\infty \frac{\sigma_P^N - \sigma_A^N}{\omega} d\omega = 4\pi^2 \left( \frac{e}{M} \right)^2 \kappa^2 S \]

Derived by applying dispersive analysis and assuming:
- Lorentz invariance
- Gauge invariance
- Crossing symmetry
- Rotational invariance
- Causality and
- Unitarity

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

Forward spin polarizability:
\[ \gamma_0 = -\frac{1}{4\pi^2} \int_0^\infty \frac{\sigma_P^N - \sigma_A^N}{\omega^3} d\omega \]
Recent accomplishments and plans for GDH on $^2\text{H}$

$$^2\text{H} + \gamma \rightarrow n + p$$

$$\int_0^\infty \frac{\sigma_p^d - \sigma_A^d}{\omega} d\omega = \int_0^{\omega_x} \frac{\sigma_p^d - \sigma_A^d}{\omega} d\omega + \int_{\omega_x}^{\omega_{\text{max}}} \frac{\sigma_p^d - \sigma_A^d}{\omega} d\omega + \int_{\omega_{\text{max}}}^{\infty} \frac{\sigma_p^d - \sigma_A^d}{\omega} d\omega$$

0.6 $\mu$b Measurements at HI$\gamma$S

Calculated -14 $\mu$b

Measurements at HI$\gamma$S:
Recent measurements and plans for GDH on $^3$He

$^3$He + γ → n + p + p (3-body channel)

Data taken on 2-body channel; analysis underway

$^3$He + γ → p + d

**Future:** push to higher energies, up to ~50 MeV


Collective responses of internal structure of nucleons

Focus is on $E_\gamma < 500$ MeV

$$\lambda = \frac{\hbar c}{E_\gamma} \Rightarrow \lambda > 0.4 \text{ fm}$$

Most sensitive to the nucleon-(virtual pion cloud) DoF

Pion-cloud physics

Compton Scattering: Nucleon Polarizabilities

Multipole expansion

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

Scalar polarizabilities

\[ \alpha_{E1}(\omega) = \left[ 2 f_{EE}^{1+}(\omega) + f_{EE}^{1-}(\omega) \right] / \omega^2, \]
\[ \beta_{M1}(\omega) = \left[ 2 f_{MM}^{1+}(\omega) + f_{MM}^{1-}(\omega) \right] / \omega^2, \]
\[ \alpha_{E2}(\omega) = 36 \left[ 3 f_{EE}^{2+}(\omega) + 2 f_{EE}^{2-}(\omega) \right] / \omega^4, \]
\[ \beta_{M2}(\omega) = 36 \left[ 3 f_{MM}^{2+}(\omega) + 2 f_{MM}^{2-}(\omega) \right] / \omega^4. \]

Spin-dependent polarizabilities

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

Compton Scattering: Nucleon Polarizabilities

$d = 4\pi\alpha\Delta E1(\omega)E(\omega)$

$m = 4\pi\beta\Delta M1(\omega)B(\omega)$

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

Expt. goals:
- sum-rule independent meas. of $\beta_p$
- reduce $\Delta\beta_n$ by $\sim$ factor of 2

Measuring spin polarizabilities

\( E_\gamma > 110 \text{ MeV} \)

Beam and target polarization

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

Circular polarization

\[
\Sigma_{2z} = \frac{\sigma^\to - \sigma^\leftarrow}{\sigma^\to + \sigma^\leftarrow}
\]

Circular polarization

\[
\Sigma_3 = \frac{\sigma^\parallel - \sigma^\perp}{\sigma^\parallel + \sigma^\perp}
\]

Linear polarization

Sensitive to \( \gamma_{E1E1} \)

Sensitive to \( \gamma_{M1M1} \) and \( \gamma_\pi \)

Sensitive to \( \gamma_{E1E1} \) and \( \gamma_{M1M1} \)
H\(\gamma\)S: Nuclear Physics Applications

A. National Nuclear Security
   • Stockpile Stewardship
   • Nuclear weapons non-proliferation treaty verification

B. Homeland Security
   • Technologies for screening cargo for special nuclear materials
   • Development of particle detection technologies

C. Energy
   • Nuclear Fusion – Inertial confinement diagnostics (NIF)
     – gamma-ray detector R&D (LANL group)

D. Medicine and contraband detection
   • \(\gamma\)-ray beam biopsy, i.e., tissue isotopic assay
   • Isotopic imaging for medical diagnostics
Active Interrogation Systems
\(\sigma(\gamma,\gamma')\) data using Nuclear Resonance Fluorescence (NRF)

Need to identify J=1 states in actinides that can be photoexcited with 2 < \(E_\gamma\) < 4 MeV
The Challenge of finding low-spin states at $E_x > 2$ MeV in heavy nuclei
Challenge of finding low-spin states at $E_x > 2$ MeV (non band states)
NRF Measurement Strategy

• *Use Bremsstrahlung beam to conduct a search for dipole transitions over a broad $\gamma$-ray energy range, e.g. $(2 < E_\gamma < 4 \text{ MeV})$*

• *Next use monoenergetic $\gamma$-ray beam to make high sensitivity measurements at selected energies based on results obtained with bremsstrahlung beams. Use linear polarization to provide information about the multipolarity of the observed $\gamma$-ray transitions.*
H\(\gamma\)S: NRF on Radioactive materials

Target: \(^{240}\text{Pu}\)

\[ E_\gamma = 2.55 \text{ MeV, horizontal HPGe detector (5 hrs 21 min)} \]

\[ T = 180 \text{ ns} \]
240Pu: Determination of Spin and Parity

Runs 330, 334 (5 hr 21 min) - $^{240}\text{Pu} @ 2.55\text{ MeV}$

Horizontal and Vertical RF Subtracted

Energy (keV)

Counts

Energy (keV)

$J^\pi$

$E_x$

$2^+$

$0^+$

$42.8$

$0.0$

$^{240}\text{Pu}$
NRF at excitation energies above the particle separation thresholds, e.g., \((\gamma, \alpha), (\gamma, n), (\gamma, p)\)

\[
I_{s0} = \int_{0}^{\infty} \sigma_{\gamma,\gamma_{0}}(E)dE = \left(\frac{2J + 1}{2J_{0} + 1}\right) \left(\frac{\pi \hbar c}{E_{\gamma}}\right)^{2} \frac{\Gamma_{0}^{2}}{\Gamma}
\]

\[
\Gamma = \Gamma_{0} + \sum \Gamma_{i}
\]

Because \(g_{N} \sim x137\ \alpha\), expect \(\Gamma_{3} >> \Gamma_{0}, \Gamma_{1}, \Gamma_{2}\)

However, there are exceptions ➔ Isobaric analog states

Let thresholds for \((\gamma, \alpha)\) and \((\gamma, p)\) be higher than that for \((\gamma, n)\)
### NRF Measurements on Light Nuclei

<table>
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<tr>
<th>Targets</th>
<th>Isotopes</th>
<th>Energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH₄Cl, NaCl, KNO₃</td>
<td>¹⁴N, ³⁵Cl, ³⁷Cl, ³⁹K</td>
<td>1.7 – 3.1</td>
</tr>
<tr>
<td>natMg metal</td>
<td>²⁴Mg</td>
<td>9.4 – 10.7</td>
</tr>
<tr>
<td>natC (graphite)</td>
<td>¹²C</td>
<td>15.1 – 15.3</td>
</tr>
</tbody>
</table>

**Graphs:**

1. **NaCl - 2.99 MeV (8.4 hr)**
   - 90 Deg. In Plane
   - 90 Deg. Out of Plane
   - 135 Deg. In Plane

2. **NaCl - 2.99 MeV (8.4 hr)**
   - Gamma Beam
   - 60 Deg. In Plane
   - 60 Deg. Out of Plane
   - 135 Deg. In Plane

Counts vs. Energy (keV) for different angles and isotopes.
- Polarized $\gamma$-ray induces fission of target nuclei
- Prompt neutrons are detected both parallel and perpendicular to the plane of polarization of the incident $\gamma$-ray
Setup for photofission measurements

\( \gamma \)-ray beam
Typical energy range $E_\gamma = 5.8 - 7.0$ MeV

Only other stable isotopes which can produce neutrons at these energies are $^2$H and $^9$Be

The neutron energy detection threshold is 1.5 MeV (all neutrons are fission neutrons)
Example of neutron assembly of fissile vs nonfissile nucleus in Polarized Photofission

Counts/hr/g at 90° in θ, Eγ = 5.8 - 6.2 MeV, ~ 5×10^6 γ/s

- __235U parallel yield__
- __235U perpendicular yield__
- __238U parallel yield__
- __238U perpendicular yield__
Measurements of neutron assembly in polarized photofission

**Ratio at 90° in $\theta$, $E_n > 1.5$ MeV**

$R_n$

Non-fissile

Fissile


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