Research Opportunities at the Upgraded HIGS Facility

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HIGS PROGRAM

H.R. Weller et al.,

Nuclear Materials Workshop-
USASK-April 2010
HI$_\gamma$S

• *Nearly Mono-energetic $\gamma$-rays*
  — Tunable Energies
  — Energy resolution selected by collimator size

• *Linearly and Circularly Polarized $\gamma$-rays*

• *High Beam Intensities*

• *Pulsed Beam*
  — TOF Techniques to reduce non-beam related backgrounds
One Bunch Mode

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Created by Brent Pardoe, 2006
Two Bunch Mode

RF Cavity

Linac Injector

Upstream Mirror

OK-4 FEL

Downstream Mirror

Created by Brent Pardue, 2006

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High Intensity Gamma-ray Source (HICyS)

Compton Backscattering Source

Duke Free Electron Laser Laboratory

Nearly Monoenergetic: $\Delta E_\gamma / E_\gamma > 1\%$
Tunable: $E_\gamma = 2 - 65$ MeV
>90% Linear and Circular Polarization
$E_\gamma < 20$ MeV: $\gamma$-ray beam flux > $5 \times 10^7$ $\gamma$/s

Beam time structure:
(a) Standard pulse mode: $R = 5.58$ MHz and $\Delta t = 100$ ps
(b) Giant high-peak power pulse mode: $R = 1 - 60$ Hz, $\Delta t = 40 - 200$ ms

TUNL and Duke Univ.
HIγS γ-ray beam generation

Provides circularly and linearly polarized, nearly monoenergetic γ-rays from 2 to 60 MeV
Utilizes Compton backscattering to generate γ-rays
Ok-4 is a linear array, which produces linearly polarized beams. Ok-5 is a helical wiggler which provides circularly polarized beams.
### Some typical beam intensities

<table>
<thead>
<tr>
<th>$E_\gamma$ (MeV)</th>
<th>Beam on target ($\Delta E/E = 3%$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 2</td>
<td>$2 \times 10^7 \ \gamma/s$</td>
</tr>
<tr>
<td>8 – 16</td>
<td>$8 \times 10^7$ (total flux of $2 \times 10^9$)</td>
</tr>
<tr>
<td>20 – 45</td>
<td>$8 \times 10^6$</td>
</tr>
<tr>
<td>50 – 95</td>
<td>$4 \times 10^6$ (by 2011)</td>
</tr>
</tbody>
</table>
The research program at HIγS

There is a very broad program of research underway at HIγS. This is expected to take over five years to execute, and will require over 2000 hrs. per year of beam time. The program includes:

• Few Body Physics
• Nuclear Structure studies using NRF
• Nuclear Astrophysics
• Applications
• GDH Sum rule for deuterium and $^3$He
• Compton scattering from nucleons and few body nuclei
• Pion Threshold studies using polarized targets
Few-Body Physics @ HIγS

Use the intense polarized beams at HIγS to perform double polarization experiments on 2, 3 (and 4) body systems.

Resolve long standing cross section problems.
Measure fundamental properties such as nuclear polarizabilities.
Perform Precision tests of few-body theory including EFTs and 3-body force models.
Photodisintegration of the deuteron

The E1 gammas are absorbed on the $1^+ (^3S_1)$ state, exciting 0-, 1-, and 2- strength, which then decays into n+p having $S=1$ (since $\Delta S=0$) and $l=1$ (p-waves). There are 3 different p-wave terms corresponding to $J= 0^-, 1^-$, and $2^-$. No information about the splittings of these has been available—until now.
d(γ,n)p at 14 and 16 MeV

(Dissertation topic of Dr. Matthew Blackston)

- Used the 88 neutron detector array Blowfish (had TOF and PSD).
- Heavy water target.
- 100% linearly polarized beams.

A full simulation was performed using Geant4 to correct the data for finite geometry and multiple scattering effects.
• The upgraded *BLOWFISH* array
The first determination of the p-wave splittings

Accurate cross section and analyzing power data allowed for a determination of the 3 different p-wave terms corresponding to J= 0-, 1-, and 2-.
Phases were fixed using the n-p scattering phase shifts (Fermi-Watson Theorem).
Cross section and analyzing power were fit to s-wave, 3 p-wave and 3 d-wave amplitudes using phases from n-p scattering.

Figure 6.11: Fits to the observables with splittings. The error bars are statistical only. The blue curve is the fit and the red curve is from the SAPM calculation.
• First determination of the splittings in the p-wave (E1) amplitudes in photodisintegration of the deuteron at 16 MeV.
The Gerasimov Drell Hearn Sum Rule

\[
\int_{\text{th}}^{\infty} (\sigma_p - \sigma_A) dE / E = \frac{4\pi^2 \alpha}{m^2} \kappa^2 S = I_{GDH}
\]
• The Gerasimov-Drell-Hearn (GDH) Sum
• Rule for

\[ I_{GDH}^{\text{GDH}} = \int_{2.2 \text{ MeV}}^{\infty} (\sigma_P(E) - \sigma_A(E)) \frac{dE}{E} = 4\pi^2 \kappa^2 \frac{e^2}{M^2} \]

\[ \vec{M} = (Q + \kappa) \frac{e}{M} \hat{S}; \]

- \( \sigma_{P/A}(E) \) are the total cross sections for the absorption of circularly polarized photons on a target with spin Parallel/Antiparallel to the spin of the photon;
- \( \kappa = \) anomalous magnetic moment (of the deuteron).
- \( \kappa_d = -0.143 \ \mu_m \rightarrow I_{GDH}^{\text{GDH}} \text{ Predicted} = 0.65 \ \mu\text{b} \)

\[ I_{GDH}^{\text{total}} = \int_{2.2 \text{ MeV}}^{E_{\pi}} \ldots + \int_{E_{\pi}}^{\infty} \ldots \]

\( E_{\pi} = \) pion production threshold

\[ \int_{E_{\pi}}^{\infty} = \int_{E_{\pi}}^{E_{\pi}} (\text{proton}) + \int_{E_{\pi}}^{E_{\pi}} (\text{neutron}) = 436 \ \mu\text{b} \]
\[
\int_{E_{\pi}}^{2.2\text{ MeV}} \ldots \approx -436\ \mu\text{b}
\]
The GDH integrand can be written in terms of the contributing T-matrix elements

[if no p or d-wave splitting, \( \sigma_p - \sigma_A = -3 \sigma(M1) \)]

\[
\sigma_p - \sigma_A = \frac{\pi \hbar^2}{2} \left[ -|M1(S_0)|^2 - |E1(P_0)|^2 \\
-\frac{3}{2}|E1(P_1)|^2 + \frac{5}{2}|E1(P_2)|^2 - \frac{3}{2}|E2(D_1)|^2 \\
-\frac{5}{6}|E2(D_2)|^2 + \frac{7}{3}|E2(D_3)|^2 \right], \quad (9)
\]
Indirect determination of the GDH integrand for the deuteron using the *no-splitting* approximation.
Results for the GDH integral at low energies

The solid black curve was a fit to the data using a Lorentzian line shape parameterized by amplitude, centroid and width. The GDH integral of this function up to 6 MeV gave a value of

\[ \text{GDH (thresh} \rightarrow 6 \text{ MeV)}_{\text{exp}} = -603 \pm 43 \mu b \]

(note: already much larger than -436 \( \mu b \))

Theory (Arenhoevel et al.) gives \(-627 \mu b \) (full)
and \(-662 \mu b \) (s-wave only)
Predicted behavior (Ahrenhovel) of the GDH integrand. Solid line includes a relativistic correction.
Relativistic contributions

- Leading order relativistic contributions are required to give the correct form of the term linear in photon momentum in the low-energy expansion of the Compton amplitude.

- The relativistic spin-orbit current effects the splitting of the p-wave amplitudes, leading to a positive value of the GDH integrand. (*It increases the relative strength of the $^3p_2$ term.*)
• First determination of the splittings in the p-wave (E1) amplitudes in photodisintegration of the deuteron at 16 MeV.
• The GDH integrand can be written in terms of the contributing T-matrix elements

[if no p or d-wave splitting, \( \sigma_P - \sigma_A = -3 \sigma(M1) \)]

\[
\sigma_P - \sigma_A = \frac{\pi \lambda^2}{2} \left[ -|M1(^1S_0)|^2 - |E1(^3P_0)|^2 \\
- \frac{3}{2}|E1(^3P_1)|^2 + \frac{5}{2}|E1(^3P_2)|^2 - \frac{3}{2}|E2(^3D_1)|^2 \\
- \frac{5}{6}|E2(^3D_2)|^2 + \frac{7}{3}|E2(^3D_3)|^2 \right], \quad (9)
\]
Results for the GDH integrand from the two solutions. Without p-wave splittings the value at 14 MeV is predicted to be -50 μb (from the s-wave M1 term). Positive values are predicted only when the relativistic contribution is included.
• Requirements for direct measurements of The GDH integrand on the Deuteron

• *Circularly Polarized gamma rays*—available NOW!

• *Neutron detection array—Blowfish*—ready to go!

• *Polarized frozen-spin* target—Under construction in collaboration with *Don Crabb* and *Blaine Norum* of U. Va.
**Frozen Spin Polarized Deuterium Target** -- target and installation (loading dock system) are **fully funded**.

- Butanol
- Polarization \(\sim 80\%\)
- Polarizing Field \(\sim 2.5\) T
- Holding Field \(\sim 0.6\) T
- Thickness \(\sim 3.5 \times 10^{23} \) d/cm\(^2\)
The GDH integrand for deuterium

- A 300 hour run will allow us to measure the GDH integrand between 5 and 50 MeV to an overall accuracy of about 5% or better, assuming a beam of $1 \times 10^7 \gamma/s$ with ~5% energy spread.

- Besides being a crucial piece of the world’s data on the GDH sum rule, the integrand will provide important tests of potential and EFT calculations, being more sensitive to spin physics and relativistic contributions than any previously measured observable.
Anticipated schedule

The HIFROST target will be installed by mid-2011.

We (the GDH @HIγS Collaboration) expect to begin taking data in late 2011, with preliminary results between 5 and 50 MeV by the end of the year.
Nuclear Structure@HIγS

- The HIγS Facility has advanced the method of NRF to a new level of precision and sensitivity.

Utilize the 100% polarized beams at HIγS to study nuclear structure primarily by means of the technique of nuclear resonance fluorescence.
Understanding the nuclear dipole response, especially near particle emission threshold, is of broad current interest.

A knowledge of the dipole strength and mode (E1 vs M1) is important in understanding nuclear structure phenomena such as:

- halo structures,
- clustering,
- local isospin resonances,
- pygmy resonances,
- proton-crust oscillations,
- dynamical M1 scissors mode,
- mixed symmetry states,
- two-phonon excitations,
- etc.

Nuclear Resonance Fluorescence is a powerful means for studying the dipole strength in nuclei.
Nuclear Resonance Fluorescence-(NRF) Experiments at HIγS

The analyzing power for dipole excitations in a nucleus with a $0^+$ ground state is:

$$\Sigma(90^0) = +1 \text{ for } J^\pi = 1^+$$
$$-1 \text{ for } J^\pi = 1^-$$

where $\Sigma(90^0) = \frac{I(\phi=0) - I(\phi=90)}{I(\phi=0) + I(\phi=90)}$

Four 60% High purity Germanium detectors
Parity assignments to strong dipole excitations of $^{92}$Zr and $^{96}$Mo
(Phys Rev C70, 044317 (2004))

Crucial for identifying two-phonon excitations originating from inhomogeneous phonon coupling.

Confirmed the 3472 keV state in $^{92}$Zr as the dominant fragment of the M1 excitation strength function.

Identified 3 strong M1 states in $^{96}$Mo as fragments of the 1$^+$ member of the mixed-symmetry 2-phonon multiplet of this nucleus.
Example of an E1 and an M1 transition in $^{96}$Mo
M1 Resonance Excitation in $^{92}\text{Zr}$ at 3471.7 keV
(Beam on target 5.5 hr)

Horizontal     Vertical

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The HIGS experiment identified 25 dipole states, finding one 1+ state at 9.757 MeV, with $B(M1)=0.14(3)$ nm. (The target was a 4500 psi gas cell!)
A shell model calculation predicts that the proton $d_{5/2} \rightarrow d_{3/2}$ spin-flip transition strength dominates the M1 matrix elements for the states at 6.882 (0.44 $\mu_N^2$) and 9.465 MeV (0.105 $\mu_N^2$).

The $1^+$ state observed at 9.757 MeV (0.148(59) $\mu_N^2$) is identified as the first spin-flip M1 strength observed in $^{40}$Ar.
Nuclear Data Measurements on Actinides Using the High Intensity Gamma-ray Source

Collaborative Research: ARI-MA


*Duke University, Durham, NC*


*University of North Carolina, Chapel Hill, NC*

*A. Harrell* and R. S. Pedroni

*North Carolina A&T State University, Greensboro, NC*

In collaboration with:

*NC State University, Lawrence Livermore National Laboratory and Los Alamos National Laboratory*

ARI Conference, April 12-14, 2010
Dennis McNabb et al. (LLNL) tested the *FINDER concept using HI\(\gamma\)S beams* (T-REX will use terawatt lasers to produce \(\sim 2\) MeV \(\gamma\)s with intensities of \(10^6/\text{eV/s.}\))

Fluorescent imaging with Thomson radiation is a new concept for isotopic detection of SNM

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**FINDER:** Fluorescence Imaging in the Nuclear Domain with Extreme Radiation

**FINDER** has quantifiably low false positive and false negative rates – concept details are published: Pru et al., *J. Appl. Phys.* 99, 123102 (2006).
**Basic idea:**

- Use an array of detectors to measure the rate of resonant scattering within a sample to determine the flux of resonance photons exiting the cargo.

- Measure the flux of off-resonant photons with a transmission detector placed in the beam.

- *A disparity between the attenuation suffered by resonant and off-resonant photons indicates the presence of the material.*
FIG. 2. (Color online) Schematic representation of the detection system studied here. A photon beam is sent to interrogation cargo. After passing through the container the flux of resonant and off-resonant photons is measured. Resonant flux is measured by “notch detectors” that observe NRF within a small sample foil made of the isotope that is being looked for. The flux of off-resonant photons is measured with a simple transmission or current detector.
NRF Setup at HIGS

Typical sample mass = 3 to 8 g
HIGS: Pushing the Limit of Sensitivity

$^{138}\text{Ba}(\gamma,\gamma')$ $E_\gamma = 5.40$ MeV

High detection sensitivities: resonance states with $\Gamma_{\text{tot}} \geq 1\text{meV}$
NRF Measurements on $^{238}\text{U}$

$E_\gamma = 2.0 - 5.5$ MeV

PhD thesis project of Samantha Hammond at UNC-Chapel Hill
See poster by S. Hammond et al. for details
### $^{238}$U Level Diagram with the New Dipole States

**Level diagram (not to scale!)**

<table>
<thead>
<tr>
<th>$J^\pi$</th>
<th>$E_x$ (keV)</th>
<th>$J^\pi$</th>
<th>$E_y$ (keV)</th>
<th>$J^\pi$</th>
<th>$E_y$ (keV)</th>
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<tr>
<td>0+</td>
<td>2557</td>
<td>1-</td>
<td>3298</td>
<td>1-</td>
<td>3820</td>
</tr>
<tr>
<td>1+</td>
<td>2468</td>
<td>1-</td>
<td>3254</td>
<td>1-</td>
<td>3809</td>
</tr>
<tr>
<td>1+</td>
<td>2410</td>
<td>1+</td>
<td>3171</td>
<td>1-</td>
<td>3738</td>
</tr>
<tr>
<td>1+</td>
<td>2295</td>
<td>1+</td>
<td>3165</td>
<td>1-</td>
<td>3651</td>
</tr>
<tr>
<td>1+</td>
<td>2245</td>
<td>1+</td>
<td>3153</td>
<td>1-</td>
<td>3639</td>
</tr>
<tr>
<td>1+</td>
<td>2209</td>
<td>1+</td>
<td>3093</td>
<td>1-</td>
<td>3622</td>
</tr>
<tr>
<td>1+</td>
<td>2176</td>
<td>1+</td>
<td>3076</td>
<td>1-</td>
<td>3607</td>
</tr>
<tr>
<td>1+</td>
<td>2163</td>
<td>2+</td>
<td>2952</td>
<td>1+</td>
<td>3593</td>
</tr>
<tr>
<td>1+</td>
<td>2163</td>
<td>1-</td>
<td>2897</td>
<td>1+</td>
<td>3575</td>
</tr>
<tr>
<td>1+</td>
<td>2176</td>
<td>1+</td>
<td>2791</td>
<td>1-</td>
<td>3501</td>
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<tr>
<td>1+</td>
<td>2209</td>
<td>1+</td>
<td>2773</td>
<td>1-</td>
<td>3488</td>
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<tr>
<td>1+</td>
<td>2245</td>
<td>1+</td>
<td>2760</td>
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<tr>
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<td>2295</td>
<td>1+</td>
<td>2754</td>
<td>1-</td>
<td>3473</td>
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<tr>
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<td>1+</td>
<td>2738</td>
<td>1-</td>
<td>3468</td>
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<tr>
<td>1+</td>
<td>2468</td>
<td>0+</td>
<td>45</td>
<td>1+</td>
<td>3463</td>
</tr>
<tr>
<td>1+</td>
<td>2557</td>
<td>0+</td>
<td>0</td>
<td>1+</td>
<td>3447</td>
</tr>
</tbody>
</table>

35 new states have been identified and characterized in the present work.

**TUNL and HIGS**
NRF Measurements on $^{235}\text{U}$

$E_\gamma = 1.7 - 3.0 \text{ MeV}$

See poster by E. Kwan et al. for details
Summary

Progress

- NRF measurements on $^{238}$U at $E_{\gamma} = 2.0 - 5.0$ MeV
  - Data taking is complete
  - Observed 35 new low-spin states $E_x = 2.0$ to $5.0$ MeV
  - Data analysis nearly complete

- NRF measurements on $^{235}$U at $E_{\gamma} = 1.7 - 4.2$ MeV
  - Data taking for $E_{\gamma} = 1.7$ to $3.0$ MeV complete
  - Observed 21 transitions to the ground state for $E_x = 1.7$ to $3.0$ MeV
  - Data analysis nearly complete

- Started NRF measurements on $^{232}$Th at $E_{\gamma} = 2.0 - 3.9$ MeV

- Started precision $\gamma$-ray attenuation measurements

Next Year

- NRF measurements on $^{232}$Th and $^{239}$Pu at $E_{\gamma} = 2.0 - 5.0$ MeV

- Precision $\gamma$-ray attenuation measurements at $E_{\gamma} > 3$ MeV

- Continue R&D on detector for delayed neutron measurements
Nuclear Astrophysics $@HI\gamma S$

- Use the intense-low energy $\gamma$ beams in order to perform precision measurements of key capture cross sections using the inverse reaction process.
The \( ^{16}\text{O}(\gamma,\alpha)^{12}\text{C} \) reaction at HI\( \gamma \)S

The inverse of the \( ^{12}\text{C}(\alpha,\gamma)^{16}\text{O} \) capture reaction, termed the holy grail of nuclear astrophysics by Willie Fowler.

The ratio of carbon to oxygen at the end of helium burning is crucial for understanding the fate of Type II Supernovae and the nucleosynthesis of heavy elements.

An oxygen rich star is predicted to end up as a black hole, while a carbon rich star leads to neutron star. And a minor change in the S-factor of the \( ^{12}\text{C}(\alpha,\gamma)^{16}\text{O} \) capture reaction (from 170 to 200 keV-b) can make all the difference.

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**S-factors for CTAG**

This reaction is dominated by two amplitudes at low energies corresponding to E1 and E2 absorption. E1 comes from p-wave capture, while E2 is the result of d-wave capture.

Since we have to extrapolate to 300 keV, both must be determined, since they will have different E-dependence and extrapolate differently.

Need to ultimately know them at the 10-20% level at 300 keV.
World data on the $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ cross section
• Motivation for the $^{16}$O(γ,α)$^{12}$C experiment
CTAG@HI$_\gamma$S

Measurement of the $^{16}$O($\gamma,\alpha$)$^{12}$C reaction at and below $E_\alpha$(cm) = 2.6 MeV. (Co-spokesperson: Dr. Moshe Gai.)

An optical readout Time Projection Chamber (TPC) has been constructed (Collaboration with UConn, Physikalisch Technische Bundesanstalt, Braunschweig, Germany and Weizmann Institute, Israel).

This one-meter long high-resolution (2%) TPC allows for simultaneous detection of $\alpha$’s and $^{12}$C’s. Uses N$_2$ + CO$_2$ admixture for the scintillating gas.
• Schematic diagram of the Optical Time Projection Chamber @ HIγS
  (a UConn, PTB, Weizmann, Duke collaboration)
• Tracks from 3.18 MeV alphas (\(^{148}\text{Gd}\) collimated source)
• The TPC will provide a target thickness of $\sim 10^{20}$ nuc/cm$^2$ operating at 100 Torr. A beam intensity of $9 \times 10^7$ will require the following running times to obtain 10% accuracy for both the $E_1$ and the $E_2$ S-factors.

• (Note: Data will be binned into 7 angular bins, with about 1000 counts per angular distribution.)

<table>
<thead>
<tr>
<th>$E_{cm}$</th>
<th>$E_\gamma$ (MeV)</th>
<th>$Y$(cph)</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.58</td>
<td>9.68</td>
<td>133</td>
<td>6 hrs</td>
</tr>
<tr>
<td>2.07</td>
<td>9.23</td>
<td>37</td>
<td>32 hrs</td>
</tr>
<tr>
<td>1.82</td>
<td>8.98</td>
<td>8</td>
<td>120 hrs</td>
</tr>
<tr>
<td>1.57</td>
<td>8.7</td>
<td>3</td>
<td>300 hrs</td>
</tr>
</tbody>
</table>

• Best measurements to date are Kunz et al. (PRL 86,3244(2001)) which achieved 30% uncertainties.

• The three most recent capture measurements invested almost 8000 hrs. of beam time. Even so, their results for $S(E2)$ disagree by a factor of $\sim 2.5$!
Phases obtained from recent (EUROGAM) angular distributions disagree with those from elastic scattering (PRC 73, 055801 (2006))
A New Method for Identifying Special Nuclear Materials Based Upon Polarized ($\gamma$,n) Asymmetries

A TUNL/Hi$\gamma$S Project funded by the NSF/DNDO through their Academic Research Initiative program

H. R. Weller—PI
M. Ahmed and Y. Wu -- Co PIs

Collaborators:
B. Davis and D. Markoff—NCCU
G. Feldman—GWU
L. Myers—UIUC
M. S. Johnson--LLNL

USASK-April 2010
Introduction

• Premise: Linearly polarized $\gamma$ rays having energies between threshold and 20 MeV can be a useful tool for the interrogation of materials

• Induce the emission of several MeV neutrons which can then be detected as a function of energy and emission angle relative to the plane of polarization

• In fissionable nuclei, energetic neutrons are produced even at energies effectively below ($\gamma$,n) threshold
Formalism

• For unpolarized $\gamma$-ray beams, the angular distribution of the outgoing neutrons assuming pure electric dipole absorption can be written as:

$$\sigma(\theta) = A_0(1 + a_2 P_2(\cos \theta))$$

where $a_2 = A_2/A_0$, $P_2$ is the second Legendre polynomial.

• Using Satchler’s expressions for linearly polarized $\gamma$-rays (Proc. Phys. Soc., 68A:1041, 1955), when both detectors are at 90 degrees:

$$I_{\text{par}} = A_0(1 - 2a_2)$$

$$I_{\text{perp}} = A_0(1 + a_2)$$

• $I_{\text{par}}/I_{\text{perp}}$ depends only on $a_2$.
Overview of $a_2$

$a_2$ varies from -0.1 to -0.7 for $Z$ between 23 (Vanadium) and 92 (Uranium)

Leads to a range of $I_{\text{par}}/I_{\text{perp}}$ from 1.0 to 8.0

$I_{\text{par}}/I_{\text{perp}}$ has not been measured before this project began.

• These are the targets that were used in our initial measurements.


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Sensitivity when using 2-detectors

- Linearly polarized beam increases sensitivity over unpolarized measurement
Experiment Setup—Four detectors left, right, up and down at 90°.

γ-ray beam direction into the screen

Using 1” collimator
Approximate flux: $1 \times 10^7 \gamma/s$

Target at $\theta=45^\circ, \phi=45^\circ$
to make the out-going path material length similar for all $\theta=90^\circ$ detectors

BC-501A
Liquid scintillators

1 meter flightpath

$I_{\text{par}}$

$I_{\text{perp}}$

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Experimental Setup

Top view

γ-ray beam

BC-501A
Liquid scintillators

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$^{238}$U target: 15.5 MeV Circular pol.

Same shape both in- and out-of-plane
$^{238}\text{U}$ target: 15.5 MeV Linear pol.

Peaking seen in-plane only
$^{238}$U target: 15.5 MeV Linear pol.

Average from 5 MeV to max $E_n$

1 at lower energies

Peaking at 2.5 near max $E_n$

Uncertainties are from statistics and a detector efficiency correction
Elemental identification: 15.5 MeV

- Targets:
  - $^{238}\text{U}$
  - $\text{natPb}$
  - $\text{natFe}$
  - $\text{natCu}$
  - $^{209}\text{Bi}$
  - $\text{Cr}$
Comparison with $a_2$ calculation

- Comparison of calculation using $a_2$ with measurements at 15.5 MeV
- Expect some deviations due to previous data having an end point $\gamma$ ray energy of 22 MeV

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>$I_{\text{par}}/I_{\text{perp}}$ (Calc)</th>
<th>$I_{\text{par}}/I_{\text{perp}}$ (Meas)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{238}\text{U}$</td>
<td>1.6</td>
<td>$1.79 \pm 0.03$</td>
</tr>
<tr>
<td>$^{208}\text{Pb}$</td>
<td>3.2</td>
<td>$3.30 \pm 0.09$</td>
</tr>
<tr>
<td>$^{209}\text{Bi}$</td>
<td>3.5</td>
<td>$3.11 \pm 0.09$</td>
</tr>
<tr>
<td>Cu</td>
<td>2.2</td>
<td>$1.62 \pm 0.03$</td>
</tr>
<tr>
<td>Fe</td>
<td>1.6</td>
<td>$1.48 \pm 0.03$</td>
</tr>
<tr>
<td>Cr</td>
<td>1.2</td>
<td>$0.98 \pm 0.04$</td>
</tr>
</tbody>
</table>
Conclusion

• $I_{\text{par}}/I_{\text{perp}}$ has been measured at HI$\gamma$S at 15.5 MeV for various targets

• Ratio has a strong dependence on outgoing neutron energy which differs from element to element.

_The NSF/DNDO (ARI) funded program began in October 2009. This allowed us to begin construction of a new neutron detector array._
Flight path is one meter. Up, down, left and right detectors at 55, 90 and 125 degrees.
Preliminary results from the Feb. 22-28, 2010 run for $^{238}$U
New data were obtained on Pb, $^{235}\text{U}$, and $^{238}\text{U}$; results at 15.5 MeV are shown here and compared to previous results at 90°.
10g target of $^{238}$U and $10^7 \gamma/s$ gives 600 counts in 10 minutes @ $E_\gamma = 6.2$ MeV—all fission neutrons
Running at a $\gamma$-ray energy of ~6.0 MeV and looking at neutrons above 2 MeV only produces counts for fissionable nuclei, except for d, Li and $^9$Be. These can be identified by their unique spectra.

This provides a very promising tool for interrogation which will receive further study.
Structure observed below \((\gamma,n)\) threshold using a nearly mono-energetic beam.  
5g \(^{238}\text{U}\) target and \(10^7 \gamma/s\) gives 5% stats in 12 min.
First measurement of photo-fission neutron polarization asymmetries
Summary

We have begun to create a catalogue (graphical and tabular) of polarization asymmetries both for incident $\gamma$-ray energies from 11 to 15.5 MeV and in the threshold region where photofission neutrons can be isolated.

Targets to date include Pb, Bi, Fe, Cr, Cu, $^{238}$U, $^{235}$U.

Next: $^{239}$Pu, $^{232}$Th, $^{233}$U, $^{237}$Np, $^{241}$Am, Be, B, N, Ni, Al, Ta, W, V, As, Rb, Sr, Ag, Cd, Ba, La, Ce, Hg.
Future Plans

Will use data in a simulation to determine how to maximize sensitivity to the presence of fissionable nuclei. Use both below \((\gamma,n)\) threshold energies (where only fission neutrons are observed) and higher \(\gamma\)-ray energies (~15 MeV) where large yields and large asymmetries are present.

Measurements on composite phantom targets to test accuracy and reliability will follow.
Two Bunch Mode

Created by Brent Pardue, 2006
The FEL equation

The wavelength of the FEL photons in OK-4 is given by:

\[ \lambda_{\text{FEL}} = \frac{\lambda_w [ 1 + K_w^2 ]}{2 \gamma^2} \]

\[ \lambda_w = 10 \text{ cm} \]

\[ \lambda_{\text{FEL}} = \frac{10 \text{ cm} [ 1 + K_w^2 ]}{2 \gamma^2} \]

\[ \lambda_w^2 = 10 \text{ cm}^2 \]

\[ K_w \] is called the wiggler parameter. It is varied by changing the magnetic field, is dimensionless, and varies between 0 and 5.4 for OK-4.

So the wavelength produced is varied by changing the magnetic field and the electron energy.
\( \gamma \)-ray Production at H\( \gamma \)S

**Two modes of operation:**
- No electron loss (\( E_\gamma < 20 \) MeV)
- Electron loss (\( E_\gamma > 20 \) MeV)
HI\textsubscript{\gamma}S

• High Intensity $\gamma$-ray Source (HI\textsubscript{\gamma}S)

– Located at the Duke Free Electron Laser Laboratory
  -- part of the Triangle Universities Nuclear Laboratory (TUNL)

– Intra-cavity Compton Back Scattering of FEL photons by electrons circulating in the Duke Storage Ring
Compton backscattering

For a collision between a relativistic electron and a low E photon the energy of the scattered photons is peaked along the direction of the incident electrons with a max value at $\theta_f = 0$:

$$E_f = \frac{\gamma^2 (1 + \beta)^2 E_i}{1 + R_0}$$

When the recoil term $R_0 = 2\gamma^2 (1 + \beta) E_i/E_e$ is small:

$$E_f \sim 4 \gamma^2 E_i$$

Ex.: For a 1 GeV electron $\gamma = 2000$, so a 10 eV photon becomes a 160 MeV $\gamma$ ray.
Upgraded Facility

(1) RF System with HOM Damping

(2) 1.2-GeV Booster Injector

(3a) Building extension + booster radiation shielding

(3b) LTB Transfer Line

(3c) BTR Transfer Line

(3d) Modifications to SR NSS

(3e) Radiation shielding over SR east arc
Extending Gamma Energy Range (4 kA Wiggler Op)

Gamma–beam tuning with OK5 FEL, $I_{max} = 4$ kA in CIRCULAR polarization (Projected)

Extending Wiggler Current 4 kA max

Upgrades required:
Additional power supplies
Filter/bassbar system upgrades
1.2 GeV operation to reach 158 MeV with 150 nm mirrors

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(a) 14 MeV Unpolarized Cross Section.

(b) 16 MeV Unpolarized Cross Section.

(c) 14 MeV Analyzing Power.

(d) 16 MeV Analyzing Power.
Argon gas target: 4500 psi, 12 cm long $\rightarrow$ 6.64 g/cm$^2$
TABLE II. The excitation energy $E_x$, total magnetic dipole excitation strength $B(M1)$, and strength contributed by the proton spin $B(M1_p)$ for the first two 1$^+$ states in $^{40}$Ar obtained from shell model calculations as described in the text.

<table>
<thead>
<tr>
<th>$E_x$ (MeV)</th>
<th>$B(M1)$ (µN²)</th>
<th>$B(M1_p)$ (µN²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.692</td>
<td>0.042</td>
<td>0.001</td>
</tr>
<tr>
<td>2.377</td>
<td>0.031</td>
<td>0.024</td>
</tr>
<tr>
<td>0.052</td>
<td>0.019</td>
<td>0.003</td>
</tr>
<tr>
<td>0.011</td>
<td>0.005</td>
<td>0.001</td>
</tr>
<tr>
<td>0.127</td>
<td>0.052</td>
<td>0.004</td>
</tr>
<tr>
<td>1.566</td>
<td>0.107</td>
<td>0.008</td>
</tr>
<tr>
<td>11.263</td>
<td>0.007</td>
<td>0.008</td>
</tr>
<tr>
<td>12.044</td>
<td>0.004</td>
<td>0.002</td>
</tr>
</tbody>
</table>

1$^+$ states. For the $M1$ operator we have used a quenching factor of 0.7 for the spin g-factors, 1.1 for the proton orbital g-factor and 0.1 for the neutron orbital g-factor. Figure 5 displays the $M1$ strengths measured in the experiment along with the predictions of this calculation. On the top part, the cross-hatched areas are meant to indicate that the energy regions below 7.7 MeV and above 11 MeV were not investigated in this experiment. A lower limit for the detection of $M1$ strength of 0.05 $\mu_N^2$ was estimated from Ref. [10] for energies between 7.7 and 11 MeV. Any $M1$ strength below this limit could not be detected and therefore this area is also cross-hatched in Fig. 4. The middle and bottom parts of the figure show the distribution of $M1$ strengths and compare the proton spin contribution to the total $B(M1)$ for the ten predicted 1$^+$ states in $^{40}$Ar. Among them, the third 1$^+$ state at 0.882 MeV has the largest proton spin contribution $B(M1_p) = 0.440$ $\mu_N^2$ to the total $B(M1)$. Unfortunately, the mirrors of the optical cavity at 130$^\circ$ made it impossible at the time of the experiment to cover the energy range below 7.7 MeV and, hence, that dominant fragment of the $\pi(d_{3/2} \rightarrow d_{5/2})$ spin-flip transition could not be investigated. The other state which was dominated by the $\pi(d_{3/2} \rightarrow d_{5/2})$ spin-flip transition is the sixth 1$^+$ state at 9.455 MeV, which has the second largest proton spin contribution $B(M1_p) = 0.105$ $\mu_N^2$ to the total $B(M1)$. The excitation energies of this predicted 1$^+$ state at 9.455 MeV and our experimentally identified 1$^+$ state at 9.757 MeV are very close. The experimental magnetic dipole excitation strength $B(M1_{exp}) = 0.14(8)$ $\mu_N^2$ agrees with $B(M1_{mod}) = 0.137$ $\mu_N^2$ (see Table II) within uncertainties. Based on the excellent agreement of both their $E_x$ and $B(M1)$, we interpret the origin of our experimentally identified 1$^+$ state at 9.757 MeV as one fragment of the $\pi(d_{3/2} \rightarrow d_{5/2})$ spin-flip transition in $^{40}$Ar at that excitation energy. Despite the fact that this is only a small part of the total $\pi(d_{3/2} \rightarrow d_{5/2})$ proton spin-flip strength (total = 2 $\mu_N^2$, expected), present experimental results have supported the shell model prediction that the proton spin-flip strength is not fully concentrated in the energy interval between 8 and 11 MeV. A similar situation has been observed for $^{37}$Ar and $^{38}$Ar [21] where the $M1$ strength is even more smoothly distributed between 6 and 15 MeV. To gain deeper insight into the structure of argon isotopes near neutron number $N = 20$ and to reveal the role of multiparticle-multiphole excitations across the $N = 20$ shell closure it is necessary to investigate experimentally whether the strength in neutron-rich argon isotopes is distributed according to the present shell model picture for $^{40}$Ar (Fig. 5, middle and bottom), which shows no cross-shell excitations, or whether it is even more strongly fragmented as in the case of $^{38}$Ar.

V. SUMMARY

$^{40}$Ar($^7$Li,$^7$Li)$^*$ photon scattering experiments have been performed using the nearly monochromatic, linearly polarized photon beam of $^7$Li. Eight beam energy settings have been used to cover the energy range from 7.7 to 11 MeV. 26 dipole excitations within this range were observed and their parity quantum numbers were unambiguously assigned from the azimuthal intensity asymmetry of nuclear resonance.
Non-Intrusive Active Interrogation Systems

$A(\gamma,\gamma')$ data using Nuclear Resonance Fluorescence (NRF)


Need to identify $J=1$ states in actinides that can be photoexcited with $E_\gamma > 3$ MeV
NRF Setup at HIGS

This project takes full advantage of the upgraded HIGS facility and cutting-edge gamma-ray detection system.

**Gamma beam**: $\Phi_\gamma > 10^8 \ \gamma/s$ (100 $\gamma/s/eV$).
FWHM=3\%, pulsed and polarized

**Detector system**: 4 Clovers + BGO; $\varepsilon_{array} = 1.4\%$
@ $E_\gamma = 1.33 \ MeV$

**NRF Capabilities at HIGS**: Excitation energies $E_x$; spin and parities $J, \pi$; branching ratio $\Gamma_f/\Gamma_0$ ground state widths $\Gamma_0$

**In completely model independent way!**

Clover Quartet
Results of the 3 most recent experiments were analyzed using R-Matrix theory to extrapolate to 300 keV. The resulting S-factor was assigned an uncertainty of +/-25%.


Extrapolation values $S_{E_1}^{300}$ and $S_{E_2}^{300}$ for the different combination of data sets A, B, and C ($A = EUROGAM, B = GANDI, C = Kunz et al.$). For all cases also data of elastic scattering [12–14] and $^{16}$N decay [20,21] were considered. The result of case $A+B+C$ yields the lowest uncertainty and is used for the calculation of the reaction rate.

<table>
<thead>
<tr>
<th>Data from :</th>
<th>A (keV b)</th>
<th>B (keV b)</th>
<th>C (keV b)</th>
<th>A + B (keV b)</th>
<th>B + C (keV b)</th>
<th>A + B + C (keV b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{E_1}^{300}$</td>
<td>81 (20)</td>
<td>77 (19)</td>
<td>76 (20)</td>
<td>77 (19)</td>
<td>76 (18)</td>
<td>77 (17)</td>
</tr>
<tr>
<td>$S_{E_2}^{300}$</td>
<td>80 (27)</td>
<td>78 (26)</td>
<td>85 (30)</td>
<td>80 (25)</td>
<td>81 (23)</td>
<td>81 (22)</td>
</tr>
<tr>
<td>$S_{tot}^{300}$</td>
<td>—</td>
<td>—</td>
<td>165 (50)</td>
<td>—</td>
<td>—</td>
<td>162 (39)</td>
</tr>
</tbody>
</table>
Projected $\text{HI}_\gamma\text{S}$ data for 32 hours of running. *Eurogam* result is from Assuncao et al. PRC 73, 055801 (2006).
$^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$
\[ A_0 = 0.25 \left| \rho_{M1} \right|^2 + 0.25 \left| \rho_{E1} \right|^2 + 0.75 \left| \rho_{E1} \right|^2 \]  
\[ + \ 1.25 \left| \phi_{E1} \right|^2 + 0.75 \left| d_{E2} \right|^2 + 1.25 \left| d_{E2} \right|^2 \]  
\[ + \ 1.75 \left| \phi_{E2} \right|^2 \]  

\[ \sigma_1 = 0.866 \left| \rho_{E1} \right| \left| \rho_{E2} \right| \cos(\delta_{\rho_{E1}} - \delta_{\rho_{E2}}) \]  
\[ + \ 0.640 \left| \rho_{E1} \right| \left| d_{E2} \right| \cos(\delta_{\rho_{E1}} - \delta_{d_{E2}}) \]  
\[ + \ 1.949 \left| \phi_{E1} \right| \left| d_{E2} \right| \cos(\delta_{\rho_{E1}} - \delta_{d_{E2}}) \]  
\[ + \ 0.043 \left| \rho_{E1} \right| \left| d_{E2} \right| \cos(\delta_{\rho_{E1}} - \delta_{d_{E2}}) \]  
\[ + \ 0.640 \left| d_{E2} \right| \left| \phi_{E1} \right| \cos(\delta_{d_{E2}} - \delta_{\phi_{E1}}) \]  
\[ + \ 3.837 \left| \rho_{E1} \right| \left| d_{E2} \right| \cos(\delta_{\rho_{E1}} - \delta_{d_{E2}}) \]  

\[ \sigma_2 = -0.187 \left| \rho_{E1} \right|^2 \]  
\[ - \ 0.438 \left| \rho_{E1} \right|^2 + 0.187 \left| d_{E2} \right|^2 \]  
\[ + \ 0.223 \left| d_{E2} \right|^2 + 0.857 \left| d_{E2} \right|^2 \]  
\[ - \ 0.500 \left| \rho_{E1} \right| \left| \rho_{E1} \right| \cos(\delta_{\rho_{E1}} - \delta_{\rho_{E1}}) \]  
\[ - \ 1.125 \left| \rho_{E1} \right| \left| \rho_{E1} \right| \cos(\delta_{\rho_{E1}} - \delta_{\rho_{E1}}) \]  
\[ + \ 0.025 \left| d_{E2} \right| \left| d_{E2} \right| \cos(\delta_{d_{E2}} - \delta_{d_{E2}}) \]  
\[ + \ 0.071 \left| d_{E2} \right| \left| d_{E2} \right| \cos(\delta_{d_{E2}} - \delta_{d_{E2}}) \]  
\[ + \ 0.714 \left| d_{E2} \right| \left| d_{E2} \right| \cos(\delta_{d_{E2}} - \delta_{d_{E2}}) \]  

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