Gamma-Ray Spectroscopy
2011 OMEGA Laser Users’ Group Workshop
APS Briefing
Nov 15, 2011

H.W. Herrmann
Los Alamos National Laboratory
The γ-Ray Spectrum at NIF is complicated, but holds a wealth of information.

Simulated indirect-drive, prompt DT spectrum

- DT
- D
- C
- Au
- Al
- Si
- Total

Gamma-Ray Energy (MeV)

Gammas/Source_neutron/(0.1 MeV/bin)

- $^{12}$C(n, n$'$)
- $^5$He
- $^{12}$C(n, y)
- $^5$He
- $^4$He

H.W. Hermann, 11/1/2010
Gamma-Ray Spectroscopy

- Gas Cherenkov Detectors are currently being used at OMEGA to perform energy-thresholded γ-ray spectroscopy in the 3-20 MeV range
  - DT Fusion γ-ray spectrum has been mapped out (C. Horsfield NO6-10)
  - DT Fusion γ/n Branching Ratio has been determined in ICF conditions (~3e-5 γ/n, Y. Kim NI3-6)
  - $^{12}$C(n,n') γ is being used to infer CH ablator γR (N. Hoffman CO8.10, H. Herrmann NO6.9)
- However, a true energy-resolving γ-ray spectrometer could be used for much more to support NIC, such as:
  - D(n, γ) at 15.6 MeV γ γ fuel γR diagnostic
  - $^{12}$C(n, γ) at 17.9 MeV γ γ CH ablator γR diagnostic
  - HT fusion γ-ray at 19.8 MeV γ Hot Spot H/D ratio in THD
- And for general Nuclear Plasma Science:
  - Additional fusion reactions (e.g., T+T $^{6}$He+ γ(12MeV); $^3$He+ γ(5.5MeV), A. Zylstra)
  - Measure nuclear cross-sections on materials placed in extreme neutron flux (e.g., pucks of known γR)
  - Ablator dopants for S-process or possibly as mix indicators
    - Stellar-like environment provides excited state nuclei
Gamma-Ray Compton Spectrometer

- Recommendations of the 2nd OLGU Meeting:
  - “The community felt that a new gamma-ray spectrometer needs to be designed, validated and commissioned for the facility. Users requested that the spectrometer have a spectral range up to 20 MeV.”
- Design study underway in conjunction with LANL, LLNL, GA & NSTec
Backup Slides
Reactions emitting gammas sensitive to stopping power with $s_g \gtrsim 10$ mb/sr/gamma-ray

**Energetic $g$-rays as Probes of Mixing and Stopping Powers at NIF (A. Hayes, LANL)**

MeV alpha-particles born in the DT burn and MeV knockon deuterons and tritons interacting with ablator material (C or Be)

<table>
<thead>
<tr>
<th>reaction</th>
<th>$E_g$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{13}$C(d,n)$^{14}$N*</td>
<td>3.94, 4.91, 5.1, 5.69, 7.0, 8.06</td>
</tr>
<tr>
<td>$^{9}$Be(d,n)$^{10}$B*</td>
<td>2.8, 3.4, 4.49, 6.03</td>
</tr>
<tr>
<td>$^{9}$Be(a,n)$^{12}$C*</td>
<td>4.4</td>
</tr>
</tbody>
</table>

\[
\frac{d\psi_{k.o.}(E_f)}{dE} = \frac{Q_0}{|dE/dx(E_f)|} \int_{E_f}^{E_{max}} dE_0 q(E_0)
\]

Shape of K.O. fluence determined by stopping $\Rightarrow$ g-ray yields can determine form of stopping
Studies of the HD reaction: Next step in HEDP laboratory nuclear astrophysics

Alex Zylstra

3rd OMEGA Laser User’s Group Workshop
Rochester, NY, April 27-29 2011

Proton-proton chain in hydrogen-burning stars

Second step of stellar pp chain
The astrophysical S-factor for the HD reaction is poorly know at low energies.

Data obtained in accelerator experiments differ by a factor of ~3 at energies relevant to ICF; accelerator data must also be corrected for electron screening effects using unreliable nuclear models.

Most of the heaviest elements (A>56) are made via “slow” neutron capture (s-process) in the cores of massive stars

S-process conditions

\[ k_B T \approx 8, 30 \text{ keV} \]

\[ \rho \approx 50-100 \text{ g/cm}^3 \]

s-process path near Tm

\begin{align*}
^{170}\text{Yb} &\rightarrow ^{171}\text{Yb} &\rightarrow ^{172}\text{Yb} &\rightarrow ^{173}\text{Yb} \\
^{169}\text{Tm} &\rightarrow ^{170}\text{Tm} & & &\rightarrow ^{172}\text{Tm}
\end{align*}

L. Bernstein, LLNL
Many important\(^*\) s-process branch point nuclei have HEDP-populated low-lying excited states

S-process (n,\(^{[n]}\)) enhancement due to excited states\(^*\)

\[
SEF(kT) = \frac{\sigma_{HEDP}}{\sigma_{GS}} = \frac{\sum_{i=0}^{\infty} (2J_i + 1) \sigma(E_x = E_i) e^{-E_i/kT}}{\sigma_{GS} \sum_{i=0}^{\infty} (2J_i + 1) e^{-E_i/kT}}
\]


<table>
<thead>
<tr>
<th>Branch Point</th>
<th>Gnd State J(^\pi)</th>
<th>1(^{st}) Exc. State E(_x) (keV)</th>
<th>1(^{st}) Exc. State J(^\pi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{79})Se</td>
<td>7/2(^+)</td>
<td>95.77</td>
<td>1/2(^-)</td>
</tr>
<tr>
<td>(^{85})Kr</td>
<td>9/2(^+)</td>
<td>304.871</td>
<td>1/2(^-)</td>
</tr>
<tr>
<td>(^{147})Pm</td>
<td>7/2(^+)</td>
<td>91.1</td>
<td>5/2(^+)</td>
</tr>
<tr>
<td>(^{151})Sm</td>
<td>5/2(^-)</td>
<td>4.821</td>
<td>3/2(^-)</td>
</tr>
<tr>
<td>(^{163})Ho</td>
<td>7/2(^-)</td>
<td>100.03</td>
<td>9/2(^-)</td>
</tr>
<tr>
<td>(^{170})Tm</td>
<td>1(^-)</td>
<td>38.7139</td>
<td>2(^-)</td>
</tr>
<tr>
<td>(^{171})Tm</td>
<td>1/2(^+)</td>
<td>5.0361</td>
<td>3/2(^+)</td>
</tr>
<tr>
<td>(^{179})Ta</td>
<td>7/2(^+)</td>
<td>30.7</td>
<td>9/2(^+)</td>
</tr>
<tr>
<td>(^{204})Tl</td>
<td>2(^-)</td>
<td>414.1</td>
<td>4(^-)</td>
</tr>
<tr>
<td>(^{205})Pb</td>
<td>5/2(^-)</td>
<td>703.3</td>
<td>7/2(^-)</td>
</tr>
<tr>
<td>(^{185})W</td>
<td>3/2(^-)</td>
<td>23.547</td>
<td>1/2(^-)</td>
</tr>
</tbody>
</table>

NIF (or LMJ) are the only places where (n,\(^{[n]}\)) might be measured on ground+excited states

L. Bernstein, LLNL
Gamma spectrum at NIF provides a wealth of information

- GRH is useful to infer spectral information, but better resolution is required.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Gamma-ray Energy (MeV)</th>
<th>Cross-section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha-particle Physics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{9}\text{Be}(\text{n},\text{n}'\text{g})^{12}\text{C}$</td>
<td>5.7</td>
<td>~ 50 mb</td>
</tr>
<tr>
<td>Aneutronic Fuel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{D(p,}^{3}\text{He)}^{3}\text{He}$</td>
<td>5.5</td>
<td>~ 10 nb</td>
</tr>
<tr>
<td>$\text{D}(^{3}\text{He},\text{X})^{5}\text{Li}$</td>
<td>16.4</td>
<td>~ 1 b</td>
</tr>
<tr>
<td>Stellar Nucleosynthesis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{12}\text{C}(\text{X},\text{X})^{16}\text{O}$</td>
<td>7.12</td>
<td>1 – 10 nb</td>
</tr>
</tbody>
</table>

Y. Kim, LANL
NIF GCS design goals:
• broad-energy-range (1-20 MeV)
• high sensitivity (NIF Yields > $10^{14}$ DT-n to isolate HTg)
• modest energy resolution (1-2 MeV)
• modest temporal resolution (~1 ns)
• high signal to background ratio

Preliminary Concept:
• electromagnet & detector array attached outside NIF chamber.
• two modes of operation:
  1) Chamber-mounted converter foil for high-yield (> $10^{16}$ DT-n)
  2) DIM-mounted converter foil & electron optics for low-yield (<$10^{16}$ DT-n).
GRH is useful as a 4-channel, energy-thresholded spectrometer. However, a true energy-resolving spectrometer is highly desired.

- “Prompt” γ-rays of interest from indirectly-driven, THD:
  - 16.75 MeV DT fusion γ-ray
    - Total DT Yield
  - 19.8 MeV HT fusion γ-ray
    - Hot Spot H/D ratio?
  - 4.44 MeV $^{12}$C(n,n’) γ-ray
    - Ablator ρhR
  - Hohlraum/TMP n-γ continuum
    - Effective n-to-g convertor for low yield BT determination
LANL built WHEBY 25 years ago. Design and Calibration data is still useful to GCS

**WHEBY 10-24**

<table>
<thead>
<tr>
<th>Components</th>
<th>Parameters</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design goal</td>
<td>Energy range (MeV)</td>
<td>10-24</td>
</tr>
<tr>
<td></td>
<td>Momentum resolution (%)</td>
<td>1-2</td>
</tr>
<tr>
<td></td>
<td>Time resolution (ps)</td>
<td>100</td>
</tr>
<tr>
<td>Magnet</td>
<td>B-field (G)</td>
<td>2400, uniform</td>
</tr>
<tr>
<td></td>
<td>Size (cm)</td>
<td>57x26x13</td>
</tr>
<tr>
<td></td>
<td>Weight (lbs)</td>
<td>300</td>
</tr>
<tr>
<td>Converter</td>
<td>Material</td>
<td>Be</td>
</tr>
<tr>
<td></td>
<td>Diameter (cm)</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>Thickness (cm)</td>
<td>0.2</td>
</tr>
<tr>
<td>Detector</td>
<td>Photoconductive</td>
<td>GaAs</td>
</tr>
</tbody>
</table>

Y. Kim, LANL
T. Hilsabeck, GA
NIF needs a Total DT Yield measurement during high rhoR implosions

- Existing yield measurements compromised by:
  - $Y_n$: neutron downscattering
  - GRH: presence of HT-

- DT$_{2}^{0}$-rays could provide Total DT yield ($= Y_{DT_n}^{0}/BR_{\gamma_0}^{0}$)
  - Negligible DT-\(\gamma\) down-scattering (unlike DT-n)
  - Either need to know BR & have a good absolute calibration
  - Or, perform in-situ calibrations using DT Expl Pshr ($\gamma_0$)

\[
TDSF = 1 - \frac{Y_{DTn}(13 - 15 \text{ MeV})}{Y_{DT\gamma_0}/BR_{\gamma_0}}
\]
Separation of DT-\( ^{\text{2}}\text{He} \) and DT-\( ^{\text{3}}\text{He} \) resolves 5He nuclear status issue and impacts on BR\( ^{\text{3}}\text{He} \)

G. Hale (2006)
C. Horsfield (2010)
GRH is a 4-channel, Time-resolved, Energy-thresholded, Gamma-Ray Spectrometer

- “Prompt” γ-rays of interest from indirectly-driven, THD:
  - 19.8 MeV HT fusion γ-ray
  - 16.75 MeV DT fusion γ-ray
  - 4.44 MeV $^{12}$C(n,n') γ-ray
  - Hohlraum/TMP n-γ continuum

- Relative abundances inferred from multiple threshold measurements on each shot
  - <1% of total prompt γ-rays are from fusion (DT + HT)
  - This is why we need a threshold detector!
  - >90% of GRH signal is from fusion γ-rays at 10 MeV threshold
Outline

- Why do we need GCS?
- How it works?
  - Review of LANL’s previous WHEBY
  - Broad-energy GCS
- Technical challenges at NIF
  - Shielding against hard radiation background
  - Improving detector sensitivity
- Summary
- Design ideas from previous work
- clean-up magnet
- collimator made of graphite
- beam dump
- vacuum box
- calibration data
Magnet Size would need to get Bigger to catch Low Energy Gamma

- WHEBY 10-24 @ 2400 G
- WHEBY 3-20 @ 1000 G
- WHEBY 1-20 @ 500 G

~ 60 cm

~ 2 meter
Electromagnet is the way to have broad-energy range with a compact system

Size = 50 × 20 cm
2 MeV lines @500 G

\[ B\rho [kG \cdot cm] = 3.3356 \cdot \sqrt{2m_c^2E_k + E_k^2} \]
Outline

- Why do we need GCS?
- How it works?
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- Summary
Technical Challenges: Indirect-drive creates a challenging hard x-ray background for close-in detectors

- ~100 kJ Hard x-rays from LPI-induced, hot-electron Bremsstrahlung
  - ~1e7x more energy than the ~10 mJ of DT fusion gamma-ray energy from a 1e14 DTn shot
- Ave Energy ~50 keV, but extends up to ~MeV
- Significant shielding needed!

Shielding requirement & NIF interference will be reduced by locating GCS outside target chamber

X-ray spectrum due to conversion of 33% of laser energy (1.8 MJ) into hot electrons

11th International Conference on Radiation Shielding
Hesham Khater, Sandra Brereton, and Mike Singh
LLNL-PRES-402778
April 17, 2008
Estimated Sensitivity at 1.5 MeV Resolution = \( Y_n \sim 5 \times 10^{15} \)

- Minimum neutron yield \((Y_n_{\text{min}})\) estimation

\[
Y_{n_{\text{min}}} \cdot BR_\gamma \cdot \Omega \cdot \eta_\gamma (\psi, t_c) \cdot \eta_{\text{mag}} = 100 \text{ electrons}
\]

<table>
<thead>
<tr>
<th>Branching ratio ([BR_{\gamma}])</th>
<th>5e-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid angle ([\Omega])</td>
<td>5e-7</td>
</tr>
<tr>
<td>Converter diameter = 1.7 cm, distance from TCC = 600 cm</td>
<td></td>
</tr>
<tr>
<td>(\gamma)-to-e conversion efficiency ([\eta_{\gamma e}])</td>
<td>1e-3</td>
</tr>
<tr>
<td>Converter thickness = 1 cm</td>
<td></td>
</tr>
<tr>
<td>Magnet efficiency ([\eta_{\text{mag}}])</td>
<td>0.8</td>
</tr>
<tr>
<td>Min Yield ([Y_n_{\text{min}}])</td>
<td>5e15</td>
</tr>
</tbody>
</table>
If we place magnet outside chamber, how can we improve efficiency?

Converter & focusing device in close to target can improve detector sensitivity

Option for focusing device
- Solenoid
- Quadrupole
- Permanent magnet array
Summary

- We need GCS to support NIC and beyond, e.g., gamma-based yield measurement

- Using existing WHEBY knowledge, design & calibration work previously demonstrated.

- Electromagnet design enables energy ranges of 1-20 MeV

- NIF background shielding will be simplified by locating magnet outside chamber
  - Detection efficiency may require enhancement
  - Converter & focusing device in close to target can improve detector sensitivity