Prompt gamma-ray measurements in ICF experiments

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ICF Gamma Ray Physics
a LANL-led collaboration across multiple institutions
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Outline

- Intro to Gas Cherenkov Detectors (GCD)
- Gamma Reaction History
- Future Gamma Diagnostics
Gamma-rays provide the most un-perturbed nuclear signature of ICF performance

\[ D + T \rightarrow {}^5\text{He}^* \begin{cases} \overset{\sim 1}{\text{no escape (hopefully)}} \\ \overset{\sim 4e^{-5}}{\text{Doppler Broadened (}T_i\text{)}} \end{cases} \rightarrow n (14.1 \text{ MeV}) + \alpha (3.5 \text{ MeV}) \rightarrow 5\text{He} + \gamma (16.75 \text{MeV}) \rightarrow n + \alpha

- **Bang Time** - used to establish laser energy coupling to target (shell velocity)

\[ ITF = I_0 S^3 \left( \frac{\nu}{\nu_0} \right)^8 \left( \frac{\alpha}{\alpha_0} \right)^{-4} \left( 1 - 1.2 \frac{\Delta R_{hotspot}}{R_{hotspot}} \right)^{4+\epsilon} \left( \frac{M_{clean}}{M_{DT}} \right)^{0.5} \]

- **Burn Width & other RH features** - used for failure mode correlation
Gas Cherenkov Detectors (GCD) convert MeV gammas to UV/Visible for easy detection

Variable Energy Thresholding

Fast Time Response

GCD Impluse Response
(CO2 at 100 psi = 6.3 MeV threshold)

fwhm = 11 ps
Gamma Ray Diagnostic capability at OMEGA & NIF

**OMEGA-60**
- 3 GCDs (20cm), 1 GRH (187cm)
  - Coax (40ft) & Mach Zehnders
  - Only GRH absolutely timed

**NIF**
- 4 GRHs (607 cm)
  - Mach Zehnders only (160 ft)
  - All absolutely timed

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Gamma Reaction History (GRH) is optimized to operate outside target chamber.

1 gas cell at Omega, 4 at NIF
Single-channel GRH prototype performance demonstrated at OMEGA (U. of Rochester) in 2009

Installed on OMEGA

GRH

Gas Cell

Tungsten Shielding

PMT Housing

Front Flange

Domed Port Cover

Electronics Enclosure

CO₂/Vacuum Connection

Fill Valve

Pressure Gauge

Fiber Optic Connectors

Data from OMEGA

1 ns square Laser Pulse

DT-γ

6.3 MeV Threshold

(100 psia CO₂)

Background

(no gas)

Background

(no gas)

t₀
NIF has produced Interesting Direct-Drive Reaction Histories

- Ablatively-driven implosion with shock & compression yields having burnwidths ~600 ps

CH-coated Glass Capsule

- N110924
  $Y_n = 4.4 \times 10^{13}$
  GRH at 4.5 MeV

Xe-doped Exploding Pusher

- N120815
  $Y_n = 1.4 \times 10^{13}$

- Comparable shock & compression yield
- Low-threshold signals (2.9 & 4.5 MeV) more dominant at Compression due to higher shell $\rho R$
**DT γ-ray Spectrum consists of 2 prominent lines**

\[ D + T \rightarrow ^5\text{He}^\ast \rightarrow ^4\text{He} (3.5 \text{ MeV}) + n (14.1 \text{ MeV}) \]

\[ \rightarrow ^5\text{He} + \gamma_0 (16.75 \text{ MeV}) \]

\[ \rightarrow ^5\text{He}^\ast + \gamma_1 (~13.5 \text{ MeV}) \]

\[ 16.75 \text{ MeV} \]

\[ \gamma_1 / \gamma_0 \approx 2.9 \]

* Courtesy C.J. Horsfield (AWE), assuming lines shapes offered by R-Matrix analysis (G. Hale, LANL)
GCD & GRH have provided great HED & Burn Physics results at OMEGA

Accomplished:
- DT Branching Ratio = \((4.2 \pm 2)e^{-5}\) \(\gamma/n\)
- Characterization of other fusion gammas (\(D^3He, HT, T_2, T_3He, ^3He^3He, HD,\ldots\))
- \((n,n')\) gammas from pucks of various materials → ablator areal density of CH & SiO2 implosions

In Progress:
- Kinetic Plasma Effects
  - Fuel Ion Segregation
  - Knudsen Reactivity Reduction
  - Transport validation (mass, momentum, energy)
- Charged-Particle Stopping Power
- Charged-Particle induced gammas for Mix diagnosis
The Prompt $\gamma$-Ray Energy Spectrum from Indirect-Drive, Cryo-Layered Implosions is full of information!

### Calculated $\gamma$-Ray Spectrum

- **TOTAL $Y_{DT}$ ($\rightarrow$TDSF)**
  - $Y_{DT} = B_{\gamma/n} Y_{DT\gamma}$
  - TDSF = $1 - (Y_{n(13-15)}/Y_{DT})$
- **Ablator $\rho R$**
  - $12C(n,n'\gamma)$
  - $12C(n,\gamma)$?
- **Cold fuel $\rho R$**
  - $D(n,\gamma)$
- **Goals**
  - Hohl/TMP
  - Mix?
  - $^9$Be($\alpha,n)^{12}C^*$
  - $^{13}C(d,n)^{14}N^*$
- **Other**
  - Pucks
  - Dopants
  - Surprises!

![Graph showing calculated $\gamma$-Ray spectrum](image-url)
GRH isolates DT fusion and $^{12}$C(n,n’)$ \gamma$-rays
14 MeV neutron-induced $\gamma$-Rays from CH Capsule & Hohlraum assembly are simulated in MCNP

544 Hohlraum

Prompt $\gamma$-Ray Temporal History
BT+$\frac{1}{4}$ ns, $\delta$(t=0) 14 MeV n-source
Gaussian forward fit decomposition into spectral components provides Total DT & $^{12}\text{C}(n,n'\gamma)$ yields and absolute timing (BT, BW, $t_{C\gamma}$)

10 MeV

8 MeV

4.5 MeV

2.9 MeV

$\Gamma > BT$
Indirect Drive: DT Symcap produces discernible “Re-Shock flash”, Cryo-layered implosions do not

- Symcap uses surrogate CH layer in place of DT ice
  - provides harder boundary for shock reflection
- Re-Shock flash occurs before Fall Line reaches core
  - $Y_{\text{Compr}} / Y_{\text{Re-Shock}}$ is a measure of mix

HYDRA courtesy N. Meezan

1130 µm
CH: 193 µm
Ice: 69 µm
866 µm

DT gas 0.3 mg/cc
DT ice
Symcap $\rightarrow$ CH

Operated by Los Alamos National Security, LLC for the U.S. Department of Energy’s NNSA
Future gamma diagnostics will add significant capability

- Gas Cherenkov Detectors (temporal detectors):
  - **“Super” GCD**
    - 400 psia $C_2F_6$
    - Low Threshold, High Sensitivity
      - $\sim 2$ MeV threshold
      - 20 cm from TCC (TIM mounted)
  - **GRH-15m**
    - 15m from TCC
    - Shielded Streak Cameras
    - PMTs
    - High Temporal Resolution
      - Streak Camera for $\sim 10$ps resolution
      - Camera behind 6’ bio shield wall
“Super” GCD (GCD-3 at $\Omega$) provides High-Sensitivity, Low-Threshold capability now at OMEGA and eventually at NIF

“Super” GCD

- Low Threshold, High Sensitivity
  - $\approx$ 2 MeV threshold
  - 20 cm from TCC (TIM mounted)

Physics Driven Requirements:

- Low Threshold ($\leq$ 2 MeV) to reveal new portions of gamma-ray spectrum
  - High pressure (400 psia) $\rightarrow$ redesigned pressure boundary
  - Fluorinated gases $\rightarrow$ metal seals to achieve $<1e^{-9}$ scc/s leak rate to avoid damage to TRS catalyst

- High Sensitivity
  - TIM-based to capture solid angle
  - Modular optics package to optimize SNR

- Absolute Timing & Dry Run capability
  - $2\omega$ fidu injection

- Improved SNR
  - better shielding
  - additional precursor to signal delay
Lower Energy Threshold (~ 2 MeV) opens up new portions of gamma-ray study

- New gamma-ray detection (too low E for GCD-1, too dim for GRH):
  - $^{16}\text{O}(n,n'\gamma)$ at 6.1 MeV ($\text{SiO}_2 \rho \text{R}$)
  - $^{13}\text{C}(d_{ko},n)^{14}\text{N}^*$ at 5.69 MeV (CH Mix)
  - $^9\text{Be}(\alpha,n)^{12}\text{C}^*$ at 4.44 MeV (Be Mix)
  - $^9\text{Be}(d_{ko},n)^{10}\text{B}^* 3.4$ MeV (Be Mix)
  - $^{10}\text{B}(d_{ko},n)^{11}\text{C}^*$ at ~7 MeV ($\text{B}_4\text{C}$ or BH Mix)
  - HD-$\gamma$ at 5.5 MeV (MIT Zylstra PhD)
The p+D reaction relevant to BBN, formation of proto stars, and brown dwarfs, is being investigated at OMEGA in July-August.

\[ p + D \rightarrow ^3\text{He} + \gamma (5.5 \text{ MeV}) \]

LANL’s new GCD-3 uniquely identified HD fusion gammas at 5.5 MeV for the first time (as well as $^3\text{He}-\gamma$ & $D_2-\gamma$)
Integral puck holder allows study of 14 MeV neutron interactions with materials placed near implosion

6 cm

Y. Kim, et al., JoP, 2010
Gamma Rays may illuminate “Dark Mix”

$^{12}$C vs $^{13}$C pucks at OMEGA will determine feasibility

- To determine where carbon ablator mix is coming from and when
- Sensitive to Dark Mix (unlike x-rays & separated reactants)

Concept by W. Stoeffl

**Carbon Energy Level Diagrams**

- Low Adiabat
- Hi Adiabat

**$^{12}$C layer depth (um) from interface**

- Min detectable (~50 mg/cm$^2$)

MCNP predicts ~6x less signal for $^{13}$C, but large uncertainty

$^{4.44}$ MeV Strong!

$^{3.1-3.9}$ MeV (how weak?)

**$^{12}$C gamma signal ($\gamma$)**

- $^{12}$C layer buried in $^{13}$C-based ablator (CH or HDC)

Response $\Rightarrow$ $^{13}$C

Operated by Los Alamos National Security, LLC for the U.S. Department of Energy’s NNSA
Future gamma diagnostics will add significant capability

- Spectroscopic detectors:
  - Gamma-to-Electron Magnetic Spectrometer (GEMS)
Gamma Spectroscopy will be an enabling technology for NIF

GEMS (Gamma-to-Electron Magnetic Spectrometer)

- Total Yield (no Total Yield measurement currently exists!) \( D(t, \gamma_0) \)
- Total Down Scatter Fraction (TDSF) when combined w/ primary \( Y_n \)
- \( 4\pi \) Global Fuel \( \rho R \) (Fuel \( \rho R \) currently line-of-sight) \( D(n, \gamma) \)
- Ablator \( \rho R \) (reduced uncertainty relative to GRH) \( ^{12}\text{C}(n, n'\gamma) \)
- Mix studies (e.g., \(^9\text{Be}(\alpha, n\gamma)\), \(^{13}\text{C}(d_{ko}, n\gamma)\), \(^{11}\text{B}(d_{ko}, n\gamma)\) )
- Neutron Interactions on materials (i.e., pucks)
- Astrophysical studies (e.g., s & r-processes)

Calculated NIF Spectrum

NIF CDR held in July 2013

- Energy Resolution: \( \Delta E/E \leq 5\% \)
- Energy Range: \( E_0 \pm 33\% \) within 2-25 MeV
- Temporal response < 1.5 ns
- Viable at \( Y_{\text{DTn}} \geq 5\times10^{14} \)
High Resolution Mode (Goal)

Exploding pusher can be used to extract $^{12}\text{C}(n,\gamma)$ and $D(n,\gamma)$ from Ignition Capsule

![Graph showing energy spectrum with peaks at specific energies for $^{12}\text{C}(n,\gamma)$, $D(n,\gamma)$, and DT.]

Ignition capsule
Exploding pusher
Ignition - Exploding pusher
Hydro-dynamical Mixing of Ablator into Hotspot

\[^9\text{Be}(\alpha, n\gamma)^{12}\text{C}\] gamma-rays
(4.44 MeV)

<table>
<thead>
<tr>
<th>HS Radius (μm)</th>
<th>0.1 μg (^9\text{Be}) in HS</th>
<th>1 μg (^9\text{Be}) in HS</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1.2x10^-4</td>
<td>1.2x10^-3 γ/n</td>
</tr>
<tr>
<td>20</td>
<td>3.0x10^-5</td>
<td>3.0x10^-4</td>
</tr>
<tr>
<td>30</td>
<td>1.35x10^-5</td>
<td>1.35x10^-4</td>
</tr>
</tbody>
</table>

\[^{10}\text{B}(\alpha, p)^{13}\text{C}\] gamma-rays
(3.68, 3.86 MeV)

<table>
<thead>
<tr>
<th>HS Radius (μm)</th>
<th>0.1 μg (^{10}\text{B}) in HS</th>
<th>1 μg (^{10}\text{B}) in HS</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>1.34x10^-5</td>
<td>1.34x10^-4</td>
</tr>
</tbody>
</table>

Compare w/ 1.2x10^-3 γ/n at 100 mg/cm² \(^{12}\text{C}\)
Aerogel Cherenkov Detector (ACD) proposed for low-energy (0.2-2.5 MeV), course spectroscopy

Radiator: Aerogel-1 Aerogel-2 Aerogel-3 Aerogel-4 Aerogel-5 water quartz
Refractive index, n: 1.015 1.03 1.05 1.07 1.12 1.33 1.5
Threshold Energy (MeV): 2.47 1.62 1.16 0.93 0.62 0.26 0.17
Options for Future Gamma Diagnostics (cont.)

- **Spectroscopic detectors:**
  - Curved Crystal Gamma Spec (W.Stoeffl)
    - useful for <1.5 MeV
  - “Furlong” (W.Stoeffl)
    - Single-hit, pixelated scintillator detector array
    - ~200m from TCC

![Calculated DT γ-Ray Spectrum](image)
Gamma Imaging System (GIS)

Imaging of $^{12}\text{C}(n,n')\gamma$ would reveal ablator mass distribution at bang time

$\gamma$-Ray Imaging of Ablator ($^{12}\text{C}-\gamma$)  
(G. Grim, D. Lemieux (U.Ariz))
GRH boldly goes...

courtesy Scott Chambliss, Paramount Pictures and Bad Robot Productions
Backups
GRH continues to inform quest for Ignition at NIF

- ~500ps late BT indicative of reduced coupling → Drive Multipliers (~85%)
  - Scatter of nBT relative to GBT indicative of core velocity
- Wide GBW indicative of failure modes during NIC
- Large & late $^{12}$C$_\gamma$ peak indicative of improper stagnation
- Future: $^{12}$C layers in $^{13}$C capsules for Dark Mix studies

Simulation

GBW & $^{12}$C$_\gamma$ delay ($\Delta t$) are strong indicators of ignition failures