Low-energy neutrons and the prospects for neutron capture nucleosynthesis measurements using NIF

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Collaborators – We need lots of them!


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K.-H. Langanke - GSI
NIF allows studies of nuclear physics in a plasma environment.

Neutron Capture Nucleosynthesis

Charged-particle reactions (McNabb, Petrasso)

Dense $1-1000 \text{ g/cm}^3$

Hot $kT=1-100 \text{ keV}$

High Neutron Flux

$\approx 10^{27-33} \text{ cm}^{-2} \text{ s}^{-1}$ (fluence=$10^{17-22}\text{cm}^{-2}$)

We have results from two different diagnostics showing that neutron capture experiments can be done at NIF right now.
Nuclear Physics @ NIF Philosophy

“Only do things at NIF that can’t be done anywhere else”

“Experiments that complement NIC and WCI program goals are more likely to get shot time and diagnostic support sooner”

*Neutron Capture Nucleosynthesis*

(...asking to be ride-along means you probably won’t be turned down...
Step #1: Are stellar-like (< 1 MeV) neutrons present at NIF? Predictions are that shots with $\rho R_{\text{fuel}} > 1 \text{ g/cm}^2$ make many

HYDRA (Cerjan/Sepke)

146 J Pure D-filled capsule

$10^9$ Neutrons/MeV

$10^3$ Neutrons/MeV

$10^1$ Neutrons/MeV

$10^0$ Neutrons/MeV

0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5

Neutron Energy (MeV)

MCNP (Hagmann)

DD m = 200 ug

Escaped Neutrons / 10 kev / Src Neutron

$10^8$

$10^7$

$10^6$

$10^5$

$10^4$

$10^3$

$10^2$

$10^1$

$10^0$

0.001

0.01

0.1

1

10

Neutron Energy [MeV]

But these are only predictions...
This huge *predicted* neutron fluence ($10^{18}\text{ cm}^{-2}$) suggests neutron capture nucleosynthesis could be studied at NIF.

(n,γ) cross sections on branch-point nuclei in a thermal distribution of excited states cannot be measured with even the most intense neutron beams.

*NIF crams 2800 years* of neutron capture into every shot

The Thulium reaction network is important for both Astrophysics and Stockpile Radchem.

The Thulium reaction network is important for both Astrophysics and Stockpile Radchem. F. Kappeler et al., has shown that modeled \((n,\gamma)\) cross sections have large uncertainties.

- These states have been left out of network calculations.
  - Their population depends on plasma conditions \((T\) and \(\rho)\).

Thulium was the most fielded radchem tracers in UGTs.
We have two ways to simultaneously measure sub-MeV \((n,\gamma)\) on samples loaded into a NIF capsule.

\(\leq 10^{17}\) atoms can be implanted in a NIF capsule (Kucheyev, Hamza)

Collect “debris” & count Gostic, Shaughnessy, Moody, Greife

Measure prompt \(\gamma\)-rays following capture (Stoeffl, Herrmann)

I will show data from both approaches

7x10^{16} Ge atoms in layers 2 & 3
Diagnostic #1: $\gamma$-rays from $(n,x\gamma)$ are measured using a Gas Cherenkov-based system: GRH (Gamma Reaction History)

$E_{\gamma} = 0.3 - 0.5$ MeV

Gas pressure determines $E_{th}$

\begin{itemize}
  \item CO$_2$ or SF$_6$
  \item Pressure Window
  \item Fiber light insertions
  \item 6 m from TCC
  \item W Shield
  \item Mach Zehnder
  \item Off-axis Parabolic Mirror
  \item PMT
  \item Al-Converter
  \item Snout n-$\gamma$ Cherenkov
\end{itemize}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{diagram.png}
\caption{Diagram of the experiment setup and components.}
\end{figure}

(\textbf{H. Herrmann & W. Stoeffl})
Interpreting GRH data requires good knowledge of the $(n_{14},x\gamma)$ cross sections on materials near TCC (Al, Si, Au etc.)

There were hints of the existence of sub-MeV neutrons about 1 year ago.

$\sim \frac{1}{2}$ ns

$\leq 10^8$ gammas

$T/H/D$: 74/24/2, $t_0 \pm \frac{1}{4}$

$\leq 10^8$ gammas
Our plan (Dan Sayre) is to perform a multi-shot analysis of NIF GRH data.

**Input**
4 \( I_\gamma(t) \) for lowest 2 lowest GRH channels (2.9 and 4.5 MeV) for 5 shots (≈40 observables)

**Model**
4\(^{th}\) order poly. IRF for 2.9/4.5 chan.: 8
Gamma source terms for 2.9/4.5: 2
\( \rho R_{\text{ablato}} \) for 2.9 MeV channel: 5
1 gaussian RH \((X_0, W, H):15\)
(30 variables)

All we need is a mass model (MCNP) for the 575 hohlraum.
Chamber diameter: 10 meters (Drawing not to scale)

Diagnostic #2: Solid radchem (SRC)
Dawn Shaughnessy, Julie Gostic, Ken Moody

Polar Diagnostic Insertion Module (DIM)

- Disposable Debris Shield (DDS) + Final Optics Assembly
- Equatorial DIM
- 7 m
- 25-50 cm
- 50 cm
- 8-10 cm

Al Shields: covered Neutron Activation Diagnostic
Ta Collimators: part of x-ray diagnostic assembly
Glass DDS: covered the final optics assembly

Pasive Particle Detector
Blast Shield removed post-shot & counted
Gold debris, mainly from the Hohlraum/TMP was identified via SEM/EDS & neutron activation

Secondary Electron Microscopy & Energy Dispersive Spectroscopy

USGS Federal Center TRIGA Reactor

≈120(25)% of Solid Angle collection efficiency obtained

Thanks to Julie Gostic, Dawn Shaughnessy and Ken Moody!
196,198\textsuperscript{Au} from the hohlraum has been observed on Ta plates 50 cm from TCC at NIF\textsuperscript{*}

\[
\text{Ratio of Au, Ta (n,\gamma) to (n,2n) activity determined to } \approx \pm 20\%
\]

Thanks to Julie Gostic, Dawn Shaughnessy and Ken Moody!
A Gold foil was then behind the Ta collector @ 50 cm to see the \( (n,\gamma) \) activation from scattered neutrons.

The foil shows that low-energy from neutrons scattered off of material in the target chamber do not contribute to \( (n,\gamma) \) from the hohlraum.

Thanks to Julie Gostic, Dawn Shaughnessy and Ken Moody!
The N111103 post-shot simulated neutron spectrum* is consistent with measured Gold ratio

Predicted ratio of Gold \((n,\gamma)\) to \((n,2n)\): \(4.46 \times 10^{-3}\)

Observed ratio: \(4.28\pm1.1 \times 10^{-3}\)

*Thanks to C. Cerjan & O. Jones
We not only saw $\gamma$-rays from the decay of the $^{196}$Au ground state but also from a 9.7 hour isomer ($J^\pi=12^-$)

Isomer-to-ground state ratio previously measured as being $8(2)^\%$
Nuclear-plasma interactions on $E<6$ MeV states could change the isomer-to-ground ratio in $^{196}$Au

This experiment requires a “thinned Gold” hohlraum (2-3 μm)

Here there be dragons…
Tri-doped capsules (Si, Ge and Cu) (16 February+) offer the first opportunity to observe γ-rays/debris from *in situ* capsule dopants

**Layer** | **Dopants (at%)**
--- | ---
1 (inside) | No Si (<0.05)<br>No Ge (<0.02)<br>Cu 0.10 ± 0.02
2 | Si 0.7±0.2<br>Ge 0.15±0.02<br>No Cu (<0.02)
3 | Si 1.7±0.2<br>Ge 0.15±0.02<br>No Cu (<0.02)
4 | Si 1.0±0.2<br>No Ge (<0.02)<br>No Cu (<0.02)
5 (outside) | No Si (<0.05)<br>No Ge (<0.02)<br>No Cu (<0.02)

…and Oslo just measured the γ-ray spectrum for Ge, Al and Si (last week)…

**Thanks to Hye-Sook Park!**

**Thanks to Therese Renstrøm and everyone at the Univ. of Oslo!**
External “targets” can now be loaded on the Hohlraum for cross section measurements (NIC ride-along).

Decay $\gamma$-rays using RAGS

10-50% of $4\pi$
200-1000 mg
($\approx$1.5-7.5 x current $M_{Au}$)

Prompt $\gamma$-rays using GRH

Modeling by Dan Sayre

<table>
<thead>
<tr>
<th>Quantity</th>
<th>NIF (&lt;225 keV)</th>
<th>NIF (&lt;1 MeV)</th>
<th>NIF (13-15 MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td># of neutrons in bin</td>
<td>6.96E+11</td>
<td>1.30E+12</td>
<td>8.88E+13</td>
</tr>
<tr>
<td>Collected atoms/shot/barn</td>
<td>2.48E+05</td>
<td>4.63E+05</td>
<td>3.16E+07</td>
</tr>
<tr>
<td>Observed gammas/shot/barn</td>
<td>6.20E+03</td>
<td>1.16E+04</td>
<td>7.91E+05</td>
</tr>
<tr>
<td>Ratio to DANCE (per day)</td>
<td>1.34</td>
<td>25.06</td>
<td>85623.59</td>
</tr>
</tbody>
</table>

NIF is complementary to existing state-of-the-art (n,x) measurements facilities.
Future Improvements

• Improve the existing/add new diagnostics
  • $\gamma$-rays: Super-GCD (increased solid angle)
  • Highly-segmented detector “Furlong”
  • Compton Spectrometer/Bent Crystal
  • Low-energy neutron spectrometer (LENS)
  • Increased/faster solid radchem (SRC)
    • Including capsule debris!

• “Ride-along” nuclear physics experiment
  • External hohlraum “targets”
  • Thinned-out Gold hohlraums (treasure hunt!)
Next Step for Diagnostics – Greater Efficiency

- **Solid Radchem**: Simple - More real estate near TCC
  - Chemical separation of debris prior to counting would help w/bkgnd.
- **Prompt Gammas**: “Super GCD”

Real $\gamma$-ray spectroscopy (Energy resolved)

- Compton Spect.
- Pixilated Single-Hit at a “Furlong”
- Bent Crystal (<1.5 MeV)

M. Moran, RSI 56, 1066 (1985)
A spectrally resolved measurement of the low-energy neutron spectrum is now essential.

- **Approach #1**: CVD diamond + a layer of $^{235}$U or $^6$Li ($E_n=250$ keV resonant break-up to $T+\alpha$) to enhance low-energy response.

- **Approach #2**: $^6$Li scintillator in the 20 m alcove.

GEANT Models by D. Sayre
Conclusions

- Simulations have predicted large numbers of sub-MeV neutrons at NIF from multiple scatter in the cold, dense fuel.
- These neutrons allow studies of the $(n,\gamma)$ reactions responsible for heavy element formation in stellar cores (s-process).
- Recent results from both GRH and Solid Radchem suggest the presence of a large NIF-thermal neutron component in DT and THD capsules.
- The role of nuclear-plasma interactions on neutron capture rates can now be explored using NIF ($^{196m}\text{Au}/^{196}\text{Au}$).
- NIC ride-along nuclear physics experiments can now be considered.
- Often these experiments provide valuable info for NIC.
  - Example: $\rho R_{\text{fuel}}$ from the $^{198}\text{Au}/^{196}\text{Au}$ ratio.

We are poised to perform unique neutron capture measurements on material on the hohlraum, and possibly in the capsule itself.
This work has *many* different parts – Lots of room for collaboration!

*Thanks for your attention*