Nuclear Diagnostics at the National Ignition Facility

Presentation to

Third Workshop on Nuclear Level Density and Gamma Strength
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(et. a lot of al.)
NIF is the culmination of a long line of glass laser systems developed at LLNL.

- **Janus, 1973**: 100J IR
- **Argus, 1976**: 1kJ IR
- **Shiva, 1977**: 10kJ IR
- **Nova, 1984**: 30kJ UV
- **NIF, 2009**: 1.8MJ UV
NIF concentrates all 192 laser beam energy in a football stadium-sized facility into a mm$^3$.

Matter
Temperature $>10^8$ K
Radiation Temperature $>3.5 \times 10^6$ K
Densities $>10^3$ g/cm$^3$
Pressures $>10^{11}$ atm
Target Chamber
June 1999
...In the target chamber
How NIF/ICF Works

Shock/compression

Laser power

Laser pulse

~20ns

“Ignition”: this is the goal
“Layered-cryo” w/ hohlraum (indirect drive) vs. “Exploding pusher” (direct drive)

**“Layered-Cryo”**
- Laser energy produces ~300 eV x-rays in hohlraum “can,” heating CH or Be capsule wall
- Cryogenic DT “layered” fuel shell with gas interior
- “Hot spot” ignites high ρR layer burn
- Yield up to $10^{19}$ n

**“Exploding Pusher”**
- Laser energy produces ~10 keV electrons: heats thin Si capsule wall
- Low ρR (no n scatter)
- Isotropic
- Yield up to $5 \times 10^{15}$ n

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CH or Be ablator shells
solid cryo DT layer
DT gas

Laser beams
Hot core, 'point' source of neutrons + soft x-rays

Wall explodes driving shock into DT

Cryogenic, x-ray driven, layered targets

DT gas
Lofty goal of the National Ignition Campaign (NIC): “Ignition”

Need to compress capsule adiabatically (isentropically) to 1/30th the size ($\rho \times 1000$)
Pitfalls to achieving ignition

Asymmetric implosion
Diagnose with:
Yield, $\rho R$, temperature, imaging (n, x-ray)

Shock Timing
Diagnose with:
$\gamma$-ray reaction history

Ablator/Fuel mix
Diagnose with: radchem?

Goal!
Ignition: Hotspot initiates outward “burn” into dense outer layer

(Etc….)
Neutron Spectra Diagnostics must span 9 orders of magnitude

Atypical measurement challenge: All neutrons born within <100 ps.
Activation: Zr Neutron activation (NAD) measures yield for DT shots to absolute accuracy of ± 7%

Activation Foil cross sections

Cross section (b)

Neutron energy (MeV)

14 MeV n

10 MeV n

\( ^{90}\text{Zr}(n,2n) \Rightarrow ^{89}\text{Zr} \quad (t_{1/2}=3.3 \text{ d}) \)

\( ^{63}\text{Cu}(n,2n) \Rightarrow ^{62}\text{Cu} \quad (t_{1/2}=9.74 \text{ m}) \)

3 samples with different thickness

Placed in a well 4.5m from TCC

Exp.Pusher: Raw Data, 8.7mm sample

24 hours counting

Counts

\( ^{89}\text{Zr} \)

\( Y = 2.3 \times 10^{14} \pm 7 \% \)
Neutron Activation Detectors
MRS: The MRS has been designed and implemented for simultaneous measurements of $\rho R$, $Y_{1n}$ and $T_{ion}$.

- **Med-Res**
  - $t_f = 125 \mu$m
- **Low-Res**
  - $t_f = 275 \mu$m

- $R_f = 26$ cm
- $R_a = 570$ cm
- $A_a = 20$ cm$^2$

**MRS Spectrum THD-3**

- **Primaries Yield**
- **DS-n**
- **TT-n**
- **Downscatter from 10-12MeV neutrons**
- **Deconvolved width = $T_{ion}$**

**Accuracy requirement for the MRS absolute yield measurement < 10% for $Y_{1n} > 10^{14}$**
GRH: Gamma Reaction History (GRH) measures Bang Time (w/in 30 ps) and Burn Width (w/in 15 ps) with Gas Cherenkov Detectors

- 4 Gas Cherenkov cells
- Detectors installed with Ultra-fast MCP PMTs and optical Mach Zehnders

- Bang time agrees with Ntof_BT data to within 100 ps
- Energy threshold of each cell set by gas pressure /composition
- 3-10MeV GRH will be fielded on DT implosions for yield and 4.4MeV carbon $\gamma$ (ablator density measurement)
Gamma Reaction History Detector (GRH)
**nToF**: Ion temperatures, yields, and $\rho R$ from ~6 nToF detectors are calculated by an iterative process

- Neutron energy determined by time to reach detector
- To measure downscattered neutrons after 100x primary 14MeV signal, must choose detector with fast recovery time (p-xylene, CVD diamond…)

Convolve Brysk $dt_{\text{Brysk}} = c \times \text{distance} \times T^{1/2}$ with IRF
Neutron Time of Flight (NToF)
Neutron Imaging system has begun performance qualification process using exploding pusher shots

Exploding pusher

NIS Pinhole array

DATA

Compare to gated x-ray Image

Reconstructed Neutron Image

Raw Image

Yield = 2e14
First radiochemistry (RAGS) diagnostic utilizes $^{124}\text{Xe}(n,\gamma)$ and $^{124}\text{Xe}(n,2n)$ to measure average $\rho R$

NIF capsule w/$^{124}\text{Xe}$ implanted

- Outer Ablator (>95% normally ablated)
- Inner ablator (doped w/10$^{15}$ Atoms $^{124}\text{Xe}$)

NIF Target Chamber (600 m$^3$)

- Cryos (closed during shot)
- Turbos
- Pre-cleaner system

Radioactive $^{123,125}\text{Xe}$ Collected/counted post-shot

Neutron downscatter $\approx \rho R_{\text{fuel}}$ making $^{124}\text{Xe}(n,\gamma)^{125}\text{Xe}$

Normalized by Primary neutrons: $^{124}\text{Xe}(n,2n)^{123}\text{Xe}$

Ratio of Activities: $(^{125}\text{Xe}/^{123}\text{Xe})$
RAGS Precleaner (SNL)
Where we are now and where we’re going

• Primary purpose of these first two diagnostics phases are to achieve ignition
• We are now (≈3 weeks ago) beginning to think about science-enabling diagnostics, including:
  1. Solid-debris collection (fast and slow)
  2. Energy resolving $\gamma$-ray detectors (bent crystal)
  3. Fission-based low-energy neutron spectrometers (Supplements what Lee talked about)

Coming up with an idea for a new diagnostic is a great way to get involved
Nuclear Physics AT NIF (thanks Lee!)  
Nuclear Physics FOR NIF

• D-T fusion 16.7 MeV $\gamma$-ray branching ratio

• T-T neutron spectrum ($^6$He breakup)
  • Sequential, di-neutron, or two-body?

• Nuclear-plasma interactions/rates/thermal population
  • NEEC, NEET, etc.

• Reactions on highly-excited states

• Cross sections: (n,x) for radchem
NIF is providing opportunities to explore new areas of nuclear physics

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<th>DT produces n and fusion $\gamma$</th>
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<td>$D+T\rightarrow^5He^*$</td>
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<td>$\sim \overset{1}{\longrightarrow} n(14.1 \text{ MeV}) + \alpha(3.5 \text{ MeV})$</td>
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<th>Neutron spectrum inferred from MRS</th>
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<td><img src="image" alt="Neutron spectrum graph" /></td>
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- 16.7 MeV
- $\gamma_1$
- Isotropic
- $\rho r$ insensitive
- 4.5 MeV
- $\gamma_0$
- 0 MeV
- $He^5$

OMEGA measure $\gamma_1/\gamma_0 1.35 \pm 0.35$
THD suggest HT$_\gamma$ about 5x weaker than estimates $\rightarrow$ more accurate average yield measurement from GRH

Confirms recent OMEGA data in TT cross section region
- This information helps reduce uncertainties for RAGS
Nuclear physics needs T-T neutron spectrum at NIF-relevant energies (~10keV)

3 body reaction
\[ \text{T+T} \rightarrow \alpha + n + n \ (0-9.5 \text{ MeV}) \]

2 body reaction
\[ \text{T+T} \rightarrow ^5\text{He} + n \ (8.7 \text{ MeV}) \rightarrow \alpha + n \]

Could investigate by creating \(^6\text{He}\) at relevant energies via \(^6\text{Li}(d,^3\text{He})\), tag on \(^3\text{He},\alpha\) coincidences
Thanks…

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- lots and lots of others…
Nuclear Cross Sections for Charged Particles at Energies Relevant to Astrophysics are Difficult to Measure

\[ \text{Rate} = \langle \sigma v \rangle \frac{S(E)}{E} e^{-2\pi\xi} \]

By measuring reaction products at NIF the relevant cross sections are inferred.
The achievement of ignition will provide unique research opportunities in astrophysics, stewardship physics, and inertial fusion energy studies.

Screened reactions in dense plasma

- \(^{3}\text{He}(^{3}\text{He}, 2p)^{4}\text{He}\)
- Resonance?
- Solar Gamow peak

M. Junker et al., PRC 57, 2700 (1998)

- Strongly screened reactions are relevant to stellar evolution

Multi-hit reactions from \(10^{33} \text{n}/(\text{cm}^2 \cdot \text{s})\) flux

(vs \(10^{32} \text{n}/(\text{cm}^2 \cdot \text{s})\) for SNe)

- First hit gives excited nuclear state
- Reactions from excited states, relevant to r-process nucleosynthesis of heavy elements
- Second hit reaction cross section uncertain

S. Libby, IFSA proceedings (2004)