Measurements of Fusion-Reaction–Yield Ratios in Ignition-Relevant Direct-Drive Cryogenic Deuterium–Tritium Implosions

C. J. Forrest
University of Rochester
Laboratory for Laser Energetics

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Summary

The $Y_{DT}/Y_{DD}$ ratio in cryogenic inertial confinement fusion (ICF) experiments can be used to diagnose multi-fluid effects

- Multi-fluid effects can alter the inferred fuel composition caused by species separation during peak neutron production
- The $Y_{DT}/Y_{DD}$ ratio has been measured for ignition-relevant direct-drive cryogenic DT implosions at the OMEGA laser facility
- The measured yield ratio is consistent with both the calculated values of the nuclear-reaction rates and the pre-shot target-fuel composition
- This measurement indicates that mechanisms that have been proposed to alter the fuel composition are not observed in ignition-relevant direct-drive cryogenic DT implosions
Collaborators


University of Rochester
Laboratory for Laser Energetics

M. Gatu-Johnson
Plasma Science and Fusion Center
Massachusetts Institute of Technology
Motivation

Mass diffusion can separate the fusing ions during peak neutron production in laser-driven inertial confinement fusion implosions

Barodiffusion theory*

- Thermodynamic forces such as pressure and temperature gradients can lead to species separation in an initially homogenous plasma
- The diffusive mass flux in a plasma with two ion species take the form,

\[ T = -\rho D \left( \frac{\text{classical diffusion}}{\text{baro diffusion}} + \frac{\text{thermal diffusion}}{\text{diffusion}} \right) = -D \]

- Since the D-T and D-D fusion reactivities are well known, this effect on ignition-relevant implosions can be empirically verified

The process for neutron production near peak compression is different for highly kinetic and strongly hydrodynamic-like implosion designs.

![Graph showing neutron production and ion temperature over distance and time for two different times: 0.8 and 2.6. The graph on the left indicates the remaining SiO2 shell at Time = 0.8, while the graph on the right shows the ablation ice layer at Time = 2.6.](image-url)
The mean-free-path length ($\lambda_{ii}$) and diffusion time ($T_{\text{diff}}$) are different during peak neutron production for these different implosion designs.
A high-dynamic-range neutron time-of-flight diagnostic has the capability to measure both the DT and DD yield and ion temperature in a single line of sight.

- A relativistic equation* is used to forward the experimental data to infer the yield and ion temperature from the primary peaks.
- The DT and DD neutron yield uncertainty is 5%** and 9%,† respectively.
- The $\frac{Y_{DT}}{Y_{DD}}$ ratio uncertainty is given by
  \[
  \frac{\Delta Y_{DT}}{Y_{DD}} = \sqrt{\frac{\Delta Y_{DT} Y_{DT}}{Y_{DT}} + \frac{\Delta Y_{DD} Y_{DD}}{Y_{DD}}} \approx 10\%
  \]
- The uncertainty in the ion temperature is driven by the instrument response function used in the forward-fit approach‡
  \[
  \Delta T_{i}^{DT} = \pm 250 \text{ eV} \\
  \Delta T_{i}^{DD} = \pm 200 \text{ eV}
  \]

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The fusion-yield evaluation includes a correction for the neutron attenuation caused by the areal density of the cold-fuel assembly

- The D-D neutron has approximately a factor of $3\times$ more attenuation as compared to the D-T neutron
- With the areal densities achieved on OMEGA (<300 mg/cm²), multiple scattering can be neglected
  - ideal platform to study the effects of fuel-species separation in ignition-relevant implosions
- In higher areal-density implosions, detailed simulations are required to correct for multiple scattering

\[
\Delta \eta_{Y_{DT}/Y_{DD}} = \sqrt{\frac{\Delta \eta_{Y_{DT}} \eta_{Y_{DT}}}{\eta_{Y_{DT}}} + \frac{\Delta \eta_{Y_{DD}} \eta_{Y_{DD}}}{\eta_{Y_{DD}}}} \approx 1\%
\]
The calculated $Y_{DT}/Y_{DD}$ ratios show good agreement with the nuclear measurements.

- The calculated reaction yield ratios follow the form
  \[ Y_{DT}/Y_{DD} \sim 2T_{i}^{0.4} (f_t/f_d)^{*} \]
- The uncertainty in the reactivity rate is given by
  \[ \Delta \langle \sigma v \rangle_{DT} \sim 1\% \]
- Three different fuel adjustments took place over a several-year period
  - Initial measurement of the fuel inventory
  - Final measurement of the fuel inventory

Fluid motion is not considered in this analysis.

The measured pre-shot fuel composition for ignition-relevant implosions show good agreement with the inferred fuel fractions.

- The uncertainty in inferred fuel fractions from the nuclear measurements is given by

\[
\Delta f_d = \sqrt{(\Delta Y_{DT}/Y_{DD})^2 + (\Delta \eta_{DT}/Y_{DD})^2 + \langle \sigma v_{DT} \rangle^2} \sim 10\%
\]

- A gas chromatography technique is used to measure the pre-shot fuel composition*

\[
\Delta f_d = 1.5\%
\]

A significant disagreement is observed between the measured pre-shot fuel composition for exploding pusher implosions.

![Graph showing the comparison between assay and nuclear measurements for different ablator materials. The graph plots \( f_t/f_d \) assay measurement against \( f_t/f_d \) nuclear measurement. The data points represent different ablator materials: 20-\( \mu \)m CH ablator, 16-\( \mu \)m CH ablator, 27-\( \mu \)m CH ablator, and 3-\( \mu \)m SiO\(_2\) (exploding pusher).]
Summary/Conclusions

The $Y_{DT}/Y_{DD}$ ratio in cryogenic inertial confinement fusion (ICF) experiments can be used to diagnose multi-fluid effects.

- Multi-fluid effects can alter the inferred fuel composition caused by species separation during peak neutron production.
- The $Y_{DT}/Y_{DD}$ ratio has been measured for ignition-relevant direct-drive cryogenic DT implosions at the OMEGA laser facility.
- The measured yield ratio is consistent with both the calculated values of the nuclear-reaction rates and the pre-shot target-fuel composition.
- This measurement indicates that mechanisms that have been proposed to alter the fuel composition are not observed in ignition-relevant direct-drive cryogenic DT implosions.