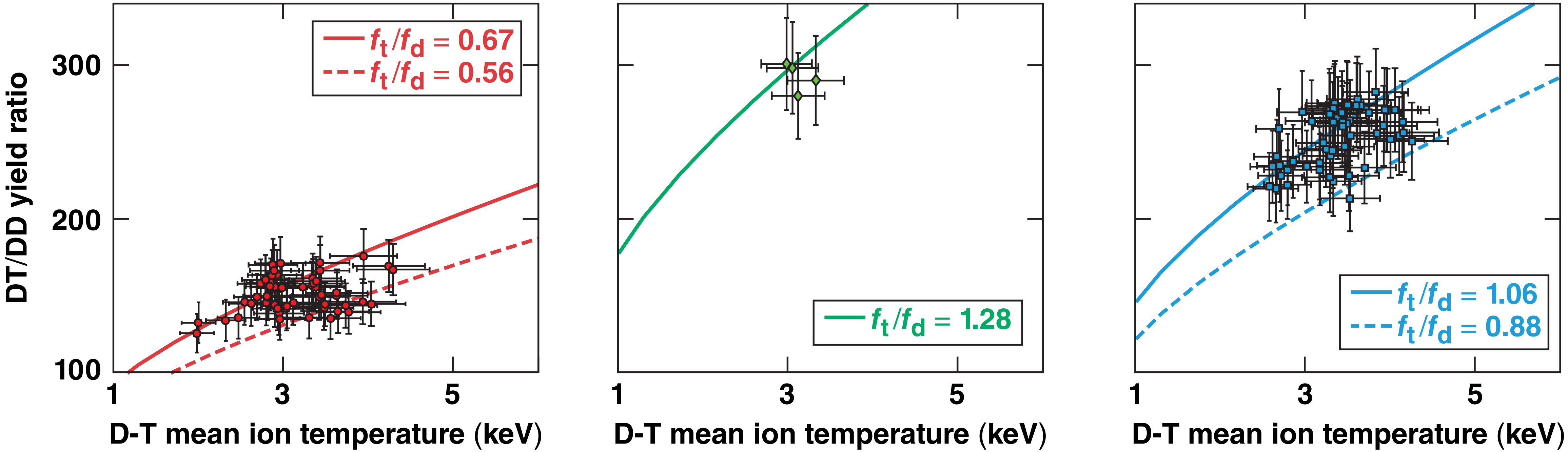
Measurements of Fusion-Reaction–Yield Ratios in Ignition-Relevant Direct-Drive Cryogenic Deuterium–Tritium Implosions



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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

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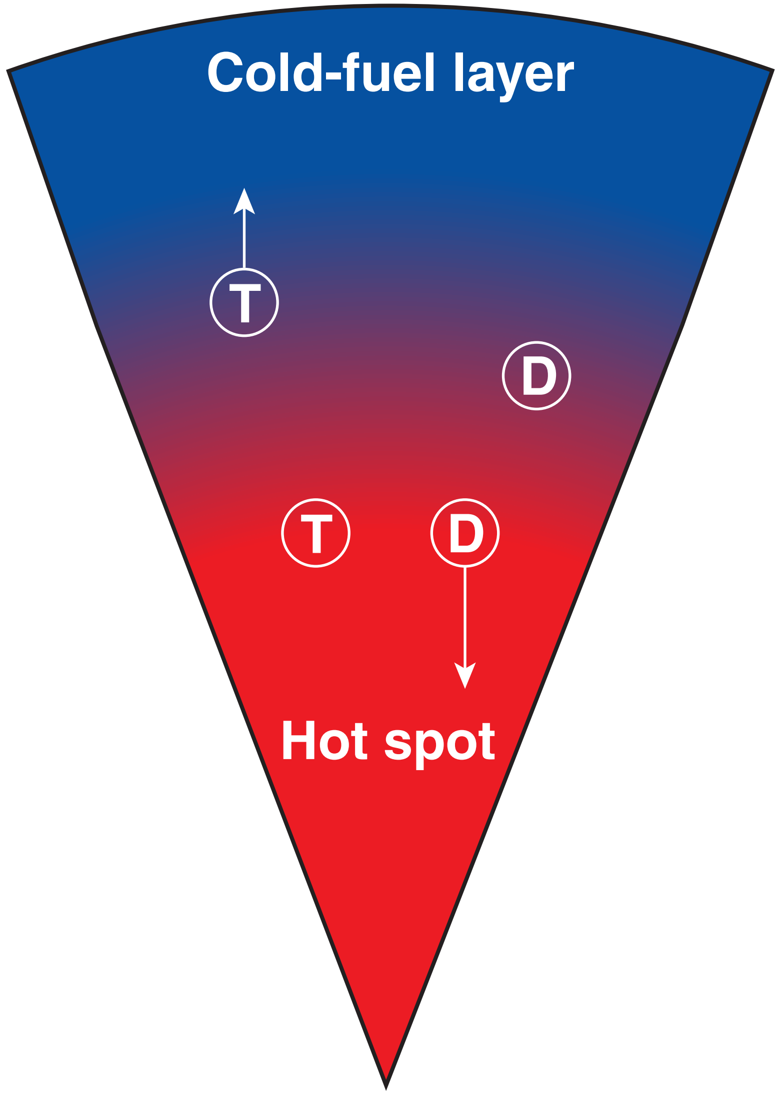
Mass diffusion can separate the fusing ions during peak neutron production in laser-driven inertial confinement fusion implosions



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,

$$T = -\rho D\left(\begin{matrix}\text{classical}\\ \text{diffusion}\end{matrix} + \begin{matrix}\text{baro}\\ \text{diffusion}\end{matrix} + \begin{matrix}\text{thermal}\\ \text{diffusion}\end{matrix}\right) = -D$$

ρ = total mass density
D = diffusion coefficient

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

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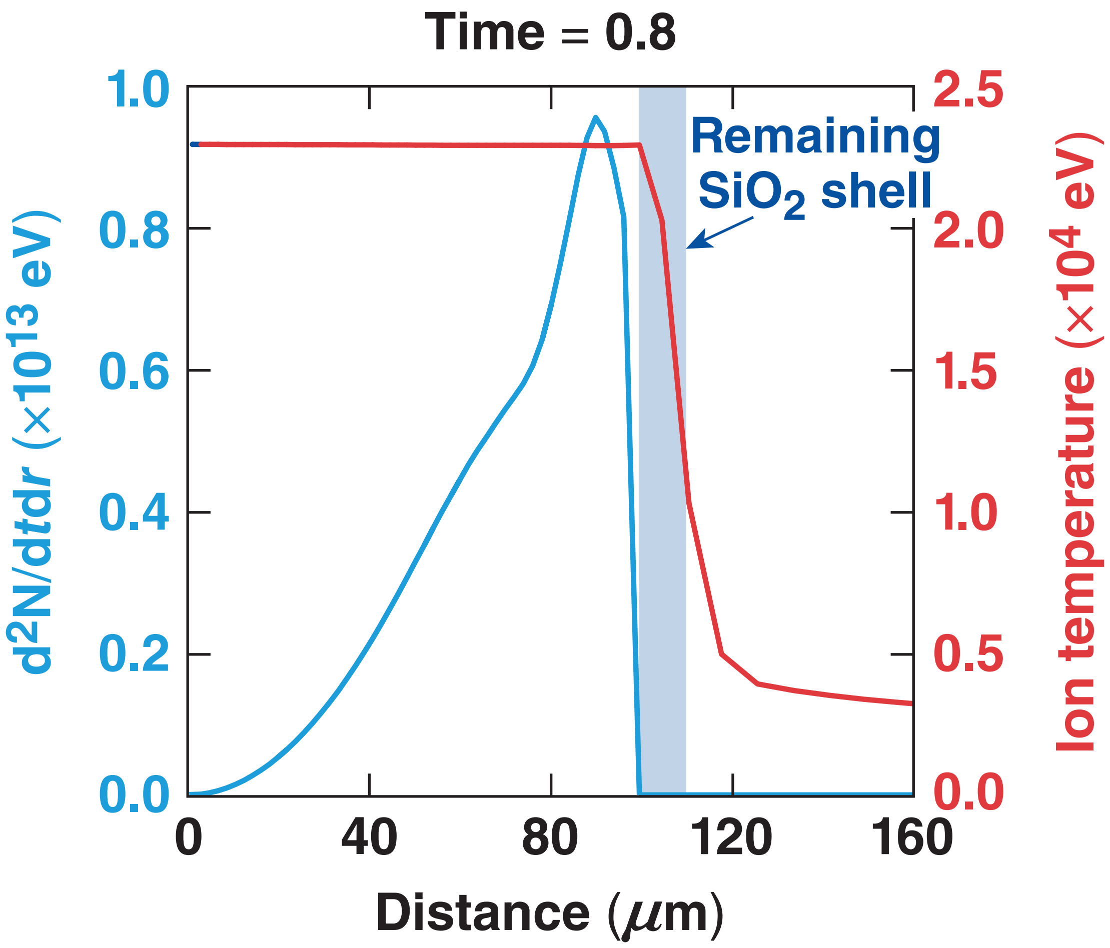
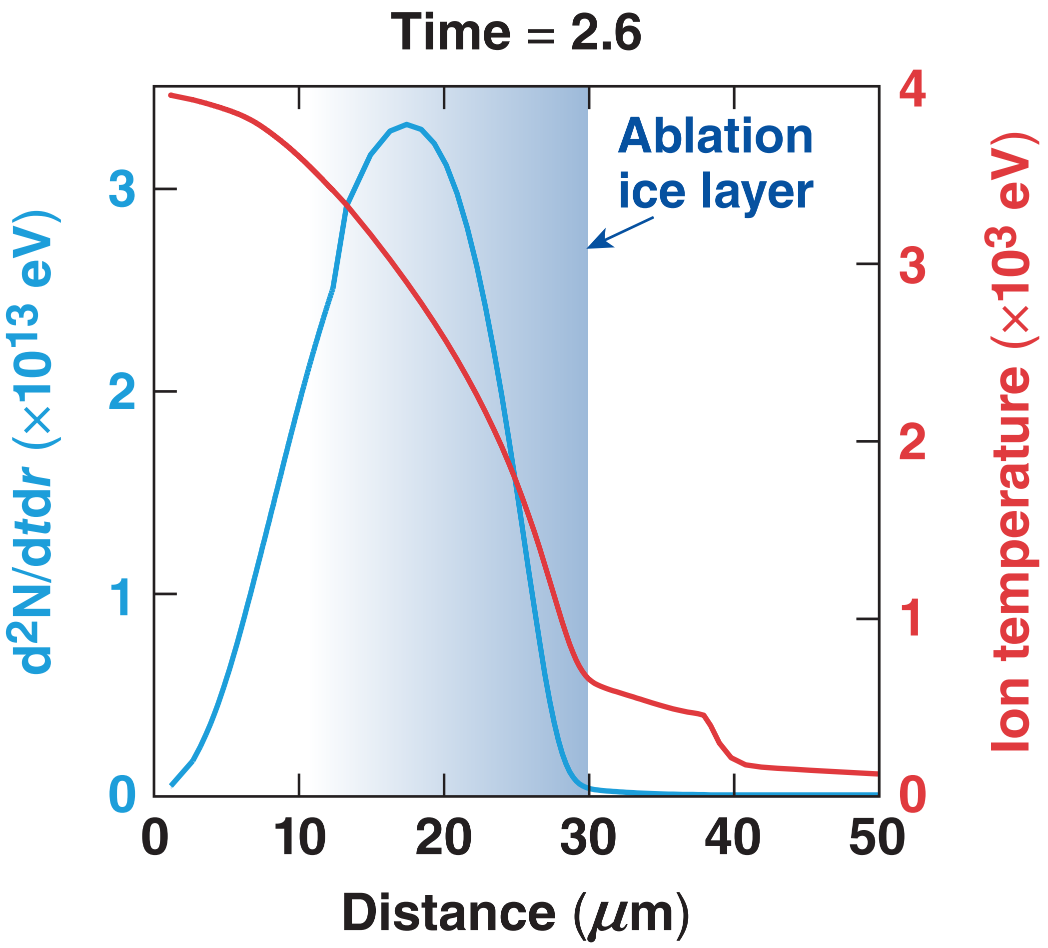
*P. Amendt *et al*., Phys. Rev. Lett. 105, 115005 (2010).

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





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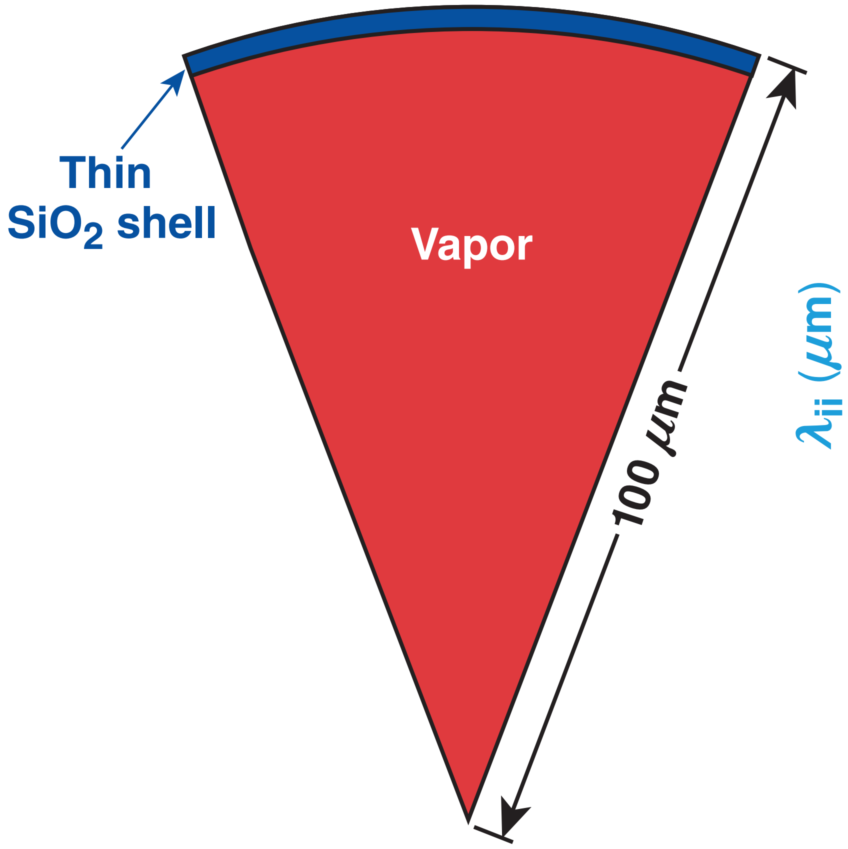
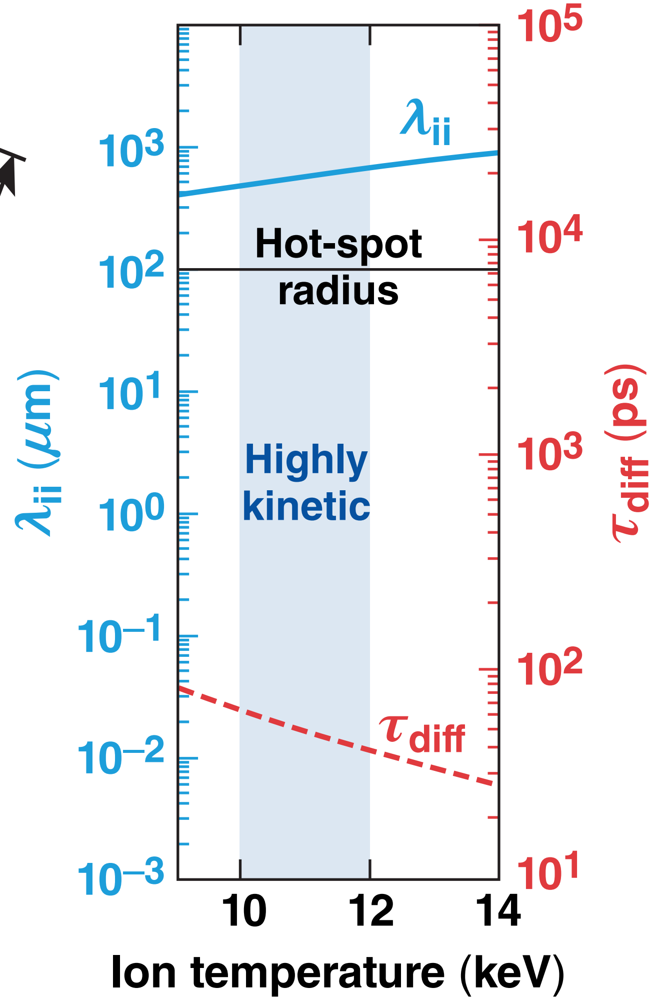
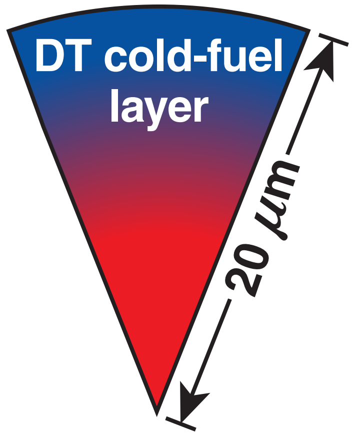
The mean-free-path length (λ_{ii}) and diffusion time (τ_{diff}) are different during peak neutron production for these different implosion designs

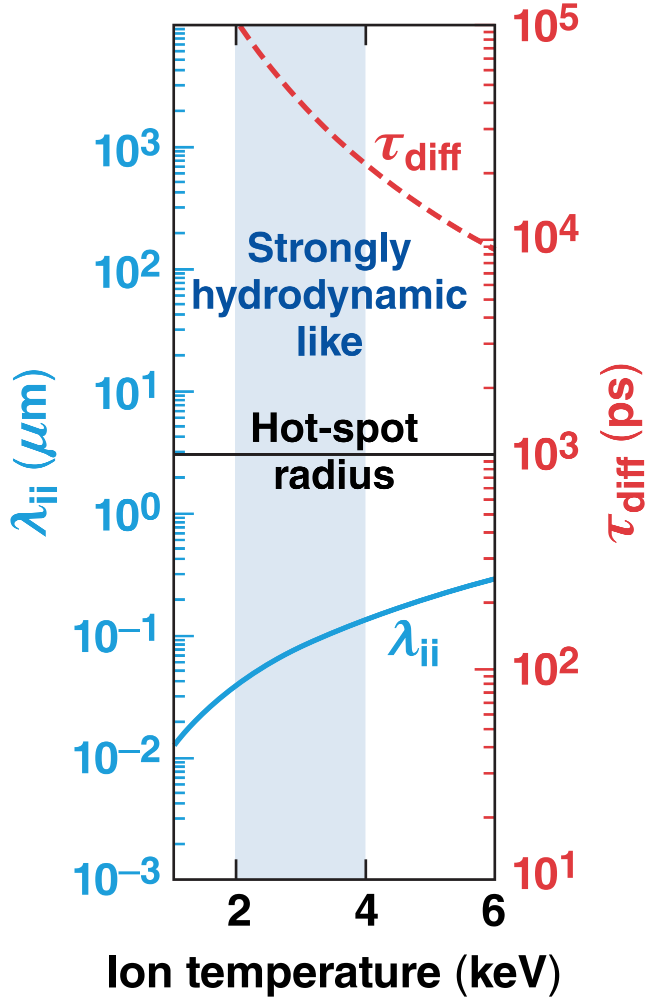
Exploding Pusher



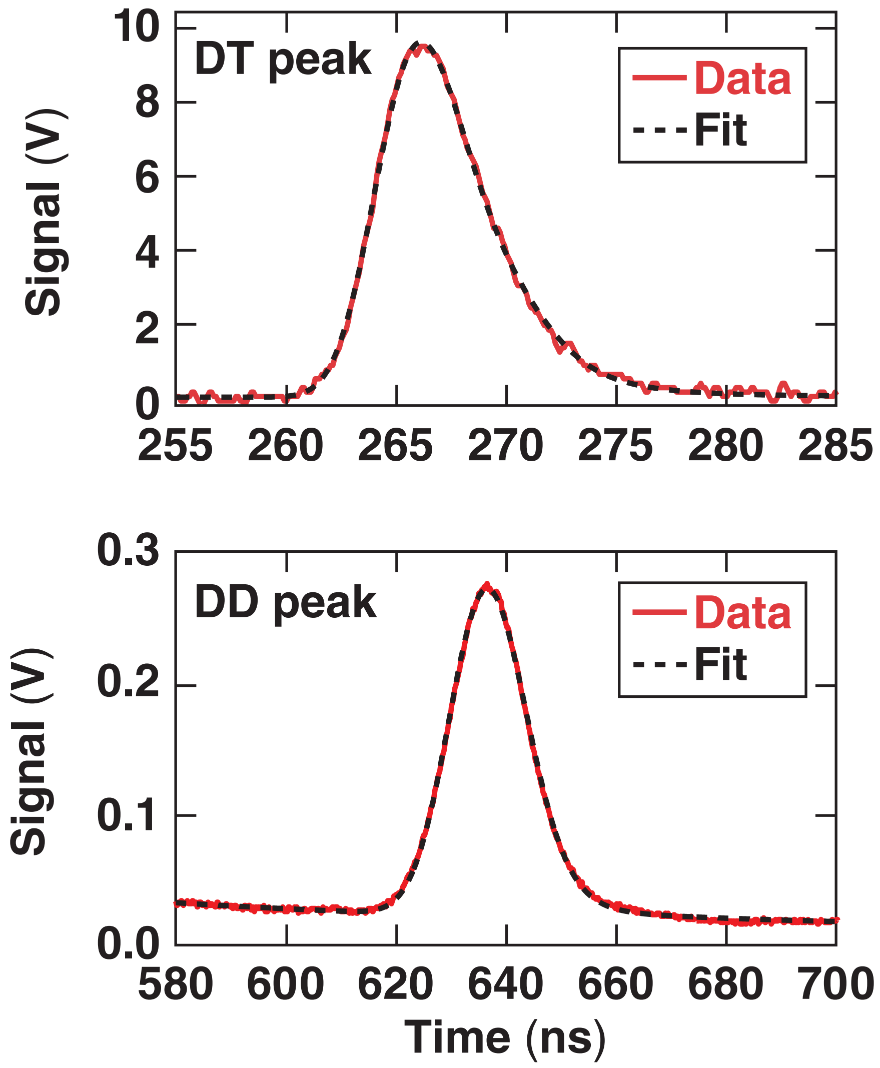


Cryogenic





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%,† respecively
- The Y_{DT}/Y_{DD} ratio uncertainty is given by

$$\frac{\Delta Y_{DT}}{Y_{DD}} = \sqrt{\frac{\Delta Y_{DT}\,Y_{DT}}{Y_{DT}} + \frac{\Delta Y_{DD}\,Y_{DD}}{Y_{DD}}} \sim 10\%$$

- The uncertainty in the ion temperature is driven by the instrument response fuction 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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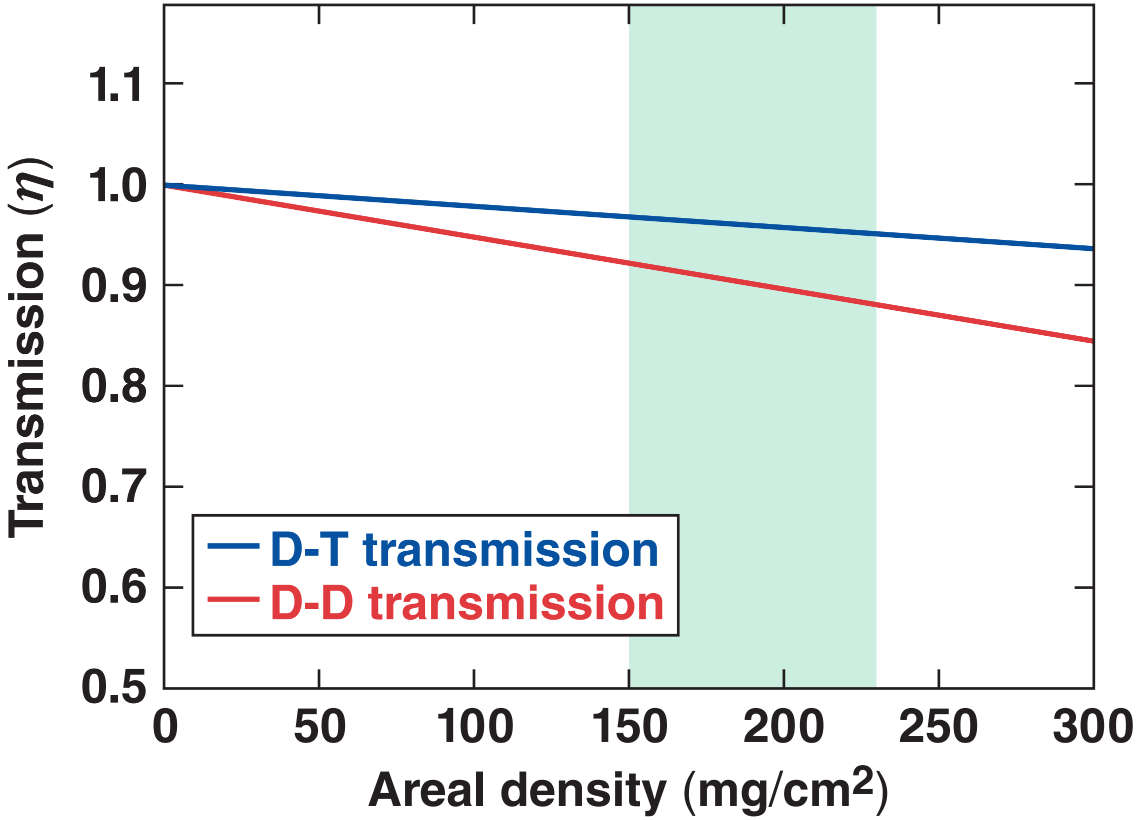
*L. Ballabio, J. Källne, and G. Gorini, Nucl. Fusion 38, 1723 (1998).

**O. Landoas *et al.*, Rev. Sci. Instrum. 82, 073501 (2011).

†C. Waugh, M.S. thesis, Massachusetts Institute of Technology, 2014.

‡C. J. Forrest *et al.*, Rev. Sci. Instrum. 87, 11D814 (2016).

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× more attenuation as compared to the D-T neutron**
- **With the areal densities achieved on OMEGA (<300 mg/cm^2), 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**

$$\Delta\eta_{Y_{DT}/Y_{DD}} = \sqrt{\frac{\Delta\eta_{Y_{DT}}\eta_{Y_{DT}}}{\eta_{Y_{DT}}} + \frac{\Delta\eta_{Y_{DD}}\eta_{Y_{DD}}}{\eta_{Y_{DD}}}} \sim 1\%$$

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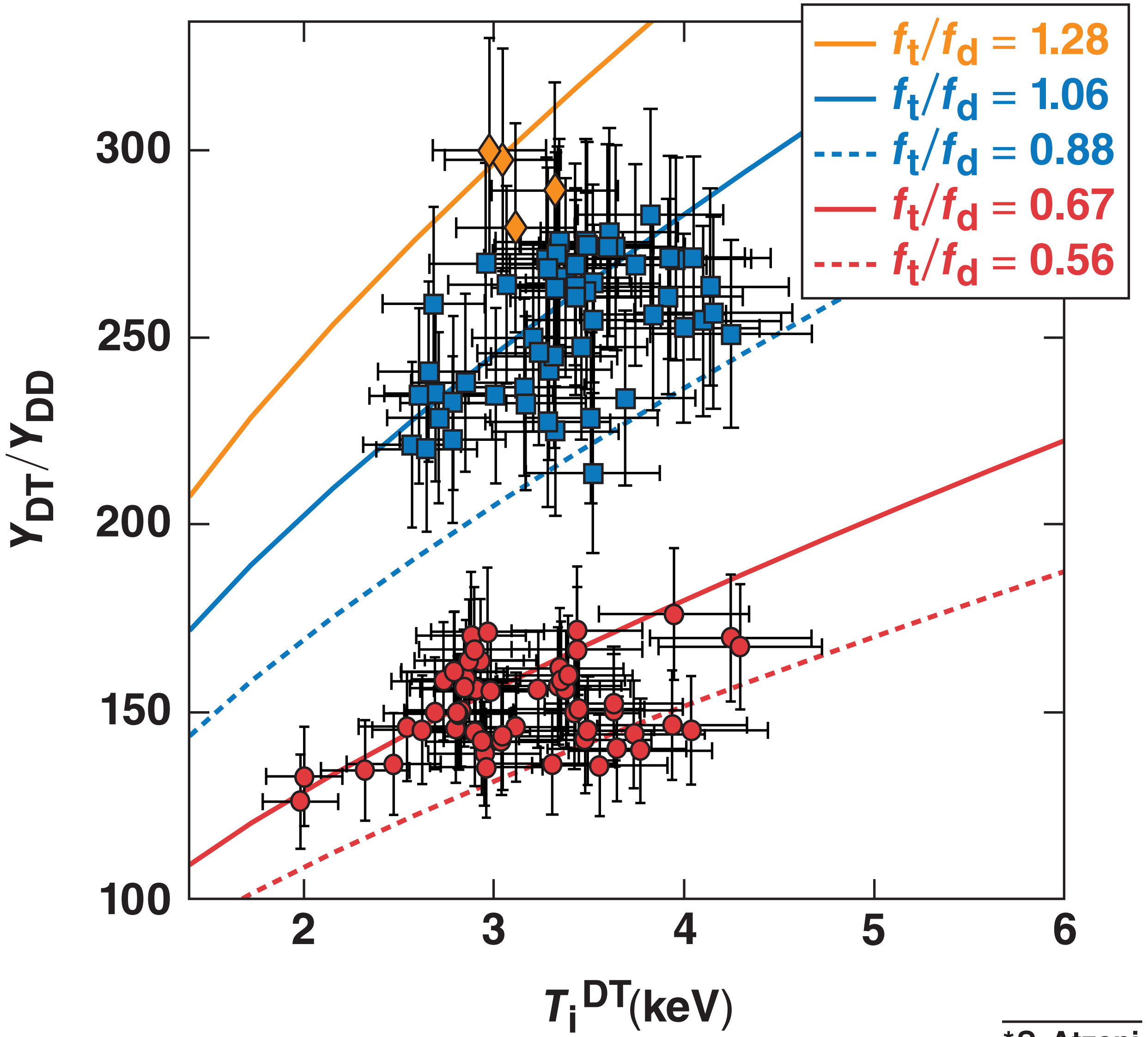
The calculated Y_{DT}/Y_{DD} ratios show good agreement with the nuclear measurements



- **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.

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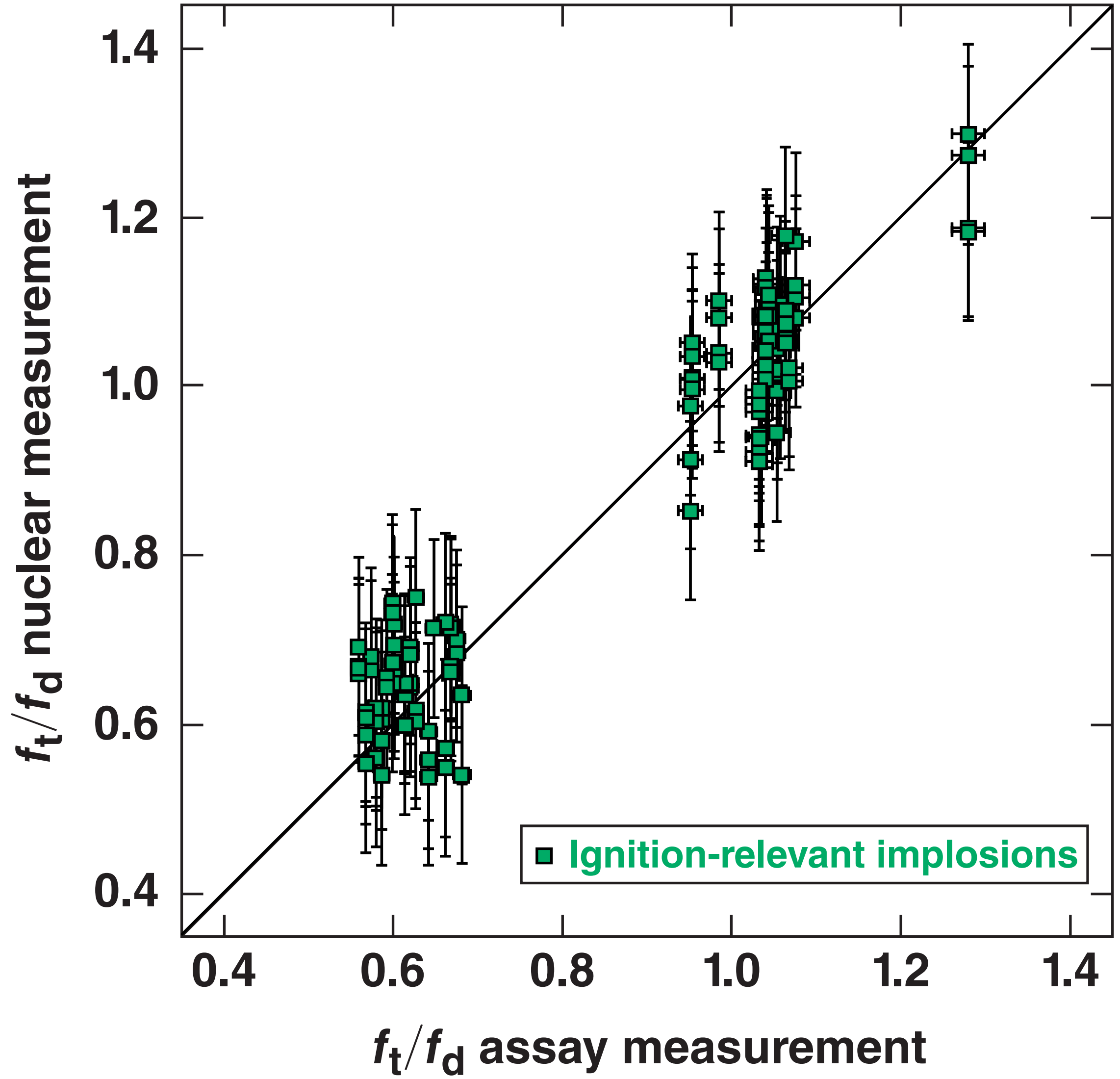
*S. Atzeni and J. Meyer-ter-Vehn, *The Physics of Inertial Fusion: Beam Plasma Interaction, Hydrodynamics, Hot Dense Matter, International Series of Monographs on Physics* (Clarendon Press, Oxford, 2004).

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**

$$\Delta f_{\frac{t}{d}} = \sqrt{\left(\Delta Y_{DT}/Y_{DD}\right)^2 + \left(\Delta\eta_{Y_{DT}/Y_{DD}}\right)^2 + \left\langle \sigma v_{DT}\right\rangle^2} \sim 10\%$$

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

$$\Delta f_{\frac{t}{d}} = 1.5\%$$

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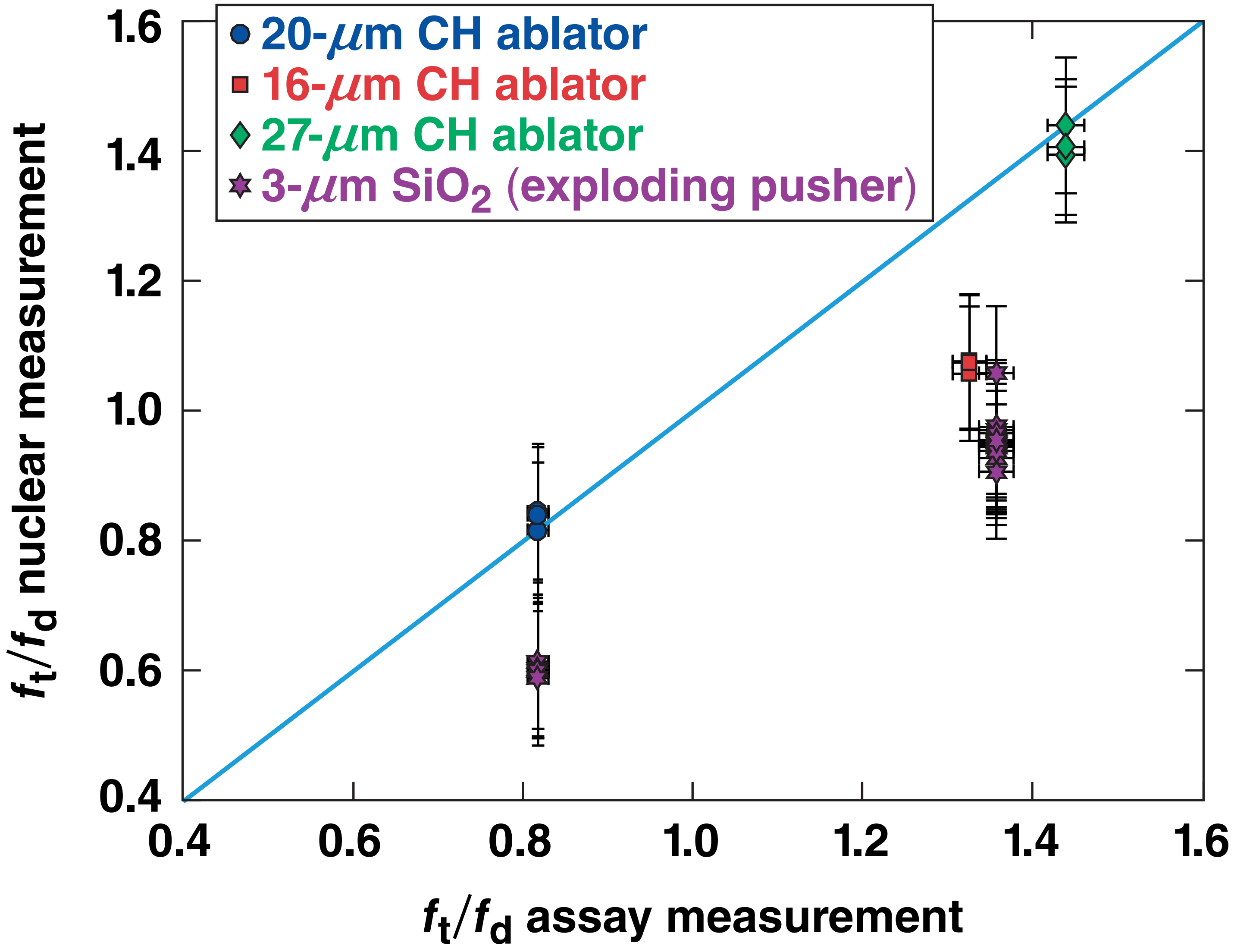
*W. T. Shmayda *et al.*, Fusion Eng. Des. 109–111, Part A, 128 (2016).

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



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Summary/Conclusions

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