A Platform for Measuring Neutron Capture Cross Sections in a Plasma Environment

Imperial College London

CIFS

B. Appelbe[1], M. Gatu Johnson[2], J. Despotopulos[3], J. Escher[3], C. Yeamans[3], J. Benstead[6], A. Crilly[1], C. Forrest[5], W. Garbett[6], K. Kmak[3], S. Labb[3], W. J. Ong[3], D. Pitman-Weymouth[6], B. Reichelt[2], C. Lederer-Woods[7], W. Taitano[4]

1) Imperial College London, UK 2) Massachusetts Institute of Technology, USA 3) Lawrence Livermore National Laboratory, USA 4) Los Alamos National Laboratory, USA 5) Laboratory for Laser Energetics, University of Rochester, USA 6) AWE, UK 7) University of Edinburgh, UK

Overview

A new experimental platform is being developed at the National Ignition Facility (NIF) for measuring the neutron capture cross sections of isotopes contained in a plasma with similar conditions to stellar environments.

1. The NIF

The NIF laser at Lawrence Livermore National Laboratory can deliver 2 MJ of energy in ~10 ns to targets that are 1 mm–1 cm in scale. It consists of 192 individual laser beams.

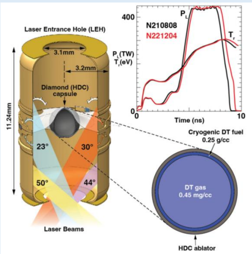
Right: Laser beams entering the target chamber (a spherical vacuum chamber 10 m diameter). Below: A typical NIF target (a hohlraum, ~1 cm length).

lasers.llnl.gov

2. Plasma environments created at NIF

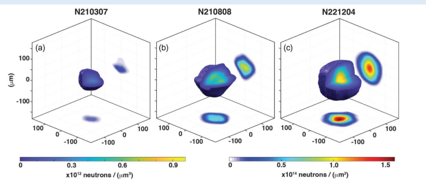
Laser energy is used to drive the implosion of a ~1 mm spherical capsule of deuterium-tritium (DT) fuel. Two drive configurations can be used: Indirect-drive in which laser beams are directed onto the inner surface of a hohlraum creating x-rays that compress the DT capsule (right), or direct-drive in which lasers beams are directed onto the capsule surface.

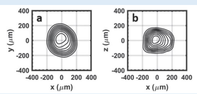
The implosion compresses the fuel, reducing its radius by a factor of ~20, resulting in a plasma with ~100 μm diameter, temperature of 5-10 keV, particle density ~10^{31} m^{-3}. This plasma is surrounded by a thin shell of colder (~500 eV), denser (~10^{32} m^{-3}) DT fuel. This plasma state survives for ~100 ps before violently disassembling due to its high pressure.

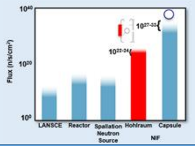


Abu-Shawareb *et al* 2024 *Phys. Rev. Lett* **132** 065102

3. NIF as a neutron source







D(t,n)α and D(d,n)He^3 reactions in the hot plasma produce neutrons at 14.05 MeV and 2.45 MeV, respectively. Indirect-drive experiments at NIF have produced ~10^{18} neutrons in ~100 ps with a ~100 μm diameter source size.

Top left: reconstruction of the neutron source from neutron images for indirect-drive experiments. Top right: neutron images for direct-drive experiments producing ~10^{16} D(t,n)α neutrons.

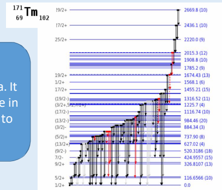
Estimates of neutron fluxes available at different facilities.

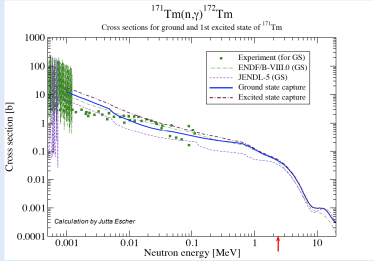
Abu-Shawareb *et al* 2024 *Phys. Rev. Lett* **132** 065102 C.B. Yeamans *et al* 2021 *Nucl. Fusion* **61** 046031

4. Tm^{171}(n,γ)Tm^{172}

An experiment is being designed to measure the Tm^{171}(n,γ)Tm^{172} cross section at 2.45 MeV on NIF by doping 10^{16} Tm^{171} isotopes into the capsule using the direct-drive configuration and using deuterium-only fuel.

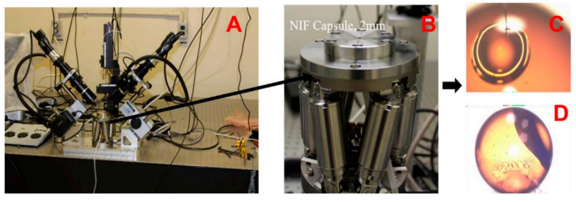
Tm^{171} isotopes will be contained in the hot plasma. It is estimated that 40% will be in excited nuclear states due to thermal processes.





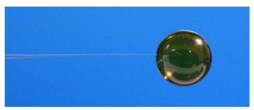
nds.iaea.org

5. Isotope doping



Top: The ANDARIST system (based on in vitro fertilization technology) is used to add rare earth isotopes to capsules. (A) ANDARIST, (B) miniature hexapod holding capsule, (C) capsule being injected with dopants in solution, (D) filled capsule.

Right: The 4mm diameter capsule that will be used for measuring the Tm^{171} neutron capture cross section.

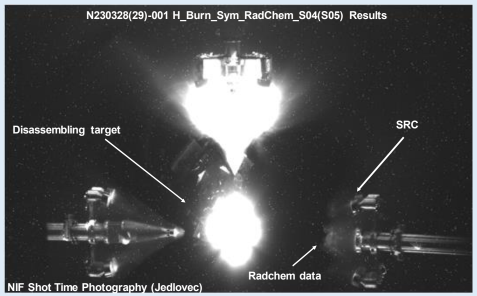


Despotopulos *et al* 2022 *Front. Phys.* 10:944400 C.B. Yeamans *et al* 2021 *Nucl. Fusion* **61** 046031

6. Reaction product detection

Solid Radiochemistry Collection plates (SRCs) are located ~50 cm from the capsule. As the hot plasma disassembles, Tm^{172} reaction products are transported to the SRCs. It is estimated that ~10^5 Tm^{172} isotopes will be collected by the SRCs.

Right: Visible light image of NIF experiment with SRCs. Below: Diagnostic arm with 5 cm SRC collection plates.

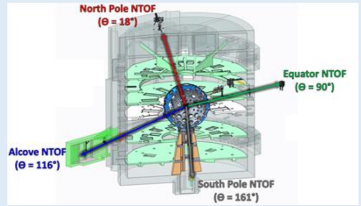


Despotopulos *et al* 2024 *Rev. Sci. Instrum.* **95**, 021102

7. Plasma diagnostics

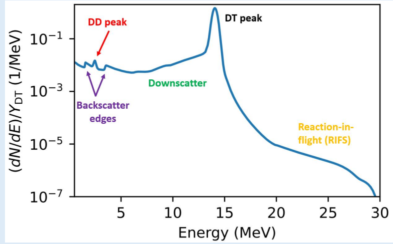
Neutron time-of-flight detectors (nTOFs) provide measurements of neutron energy spectra from 1-30 MeV. These can be used to infer the neutron yield, and the temperature and areal density of the plasma.

Right: Locations of nTOFs around NIF target chamber. Below right: An example neutron spectrum emitted in an indirect-drive DT fuel experiment.



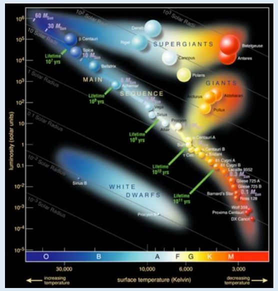
Diagnostics for x-rays, γ-rays and fast (>1 MeV) ions emitted by the plasma provide additional information on hot plasma size, electron temperature and density, and spatial and temporal variation of the plasma.

Plasma diagnostics provide measurements that can be used to calculate populations of excited states and estimate processes such as nuclear excitation by electron capture and nuclear excitation by electronic transition.



8. Future directions

The capsule doping technology is capable of doping a wide range of isotopes into capsules. Future experiments will aim to measure capture cross sections of nuclei in excited states by varying plasma conditions (temperature and density) to vary the populations of excited states. Future experiments will also aim to more closely recreate the conditions of stellar nucleosynthesis by moderating neutrons to lower energies.



Hertzsprung-Russell diagram

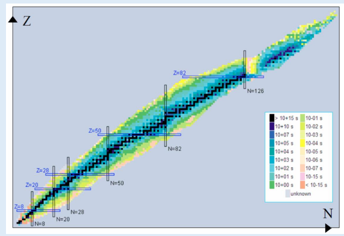


Chart of nuclides

chandra.harvard.edu nndc.bnl.gov

Conclusions

An experiment is being designed for NIF to measure the Tm^{171}(n,γ)Tm^{172} cross section. Future experiments aim to measure capture cross sections of nuclei in excited states.

Email: bappelbe@ic.ac.uk

CNR*24 8th - 12th July 2024