Nuclear Science Experiments for National Security and Fundamental Science on NIF

High Energy Density Science Center Seminar Series

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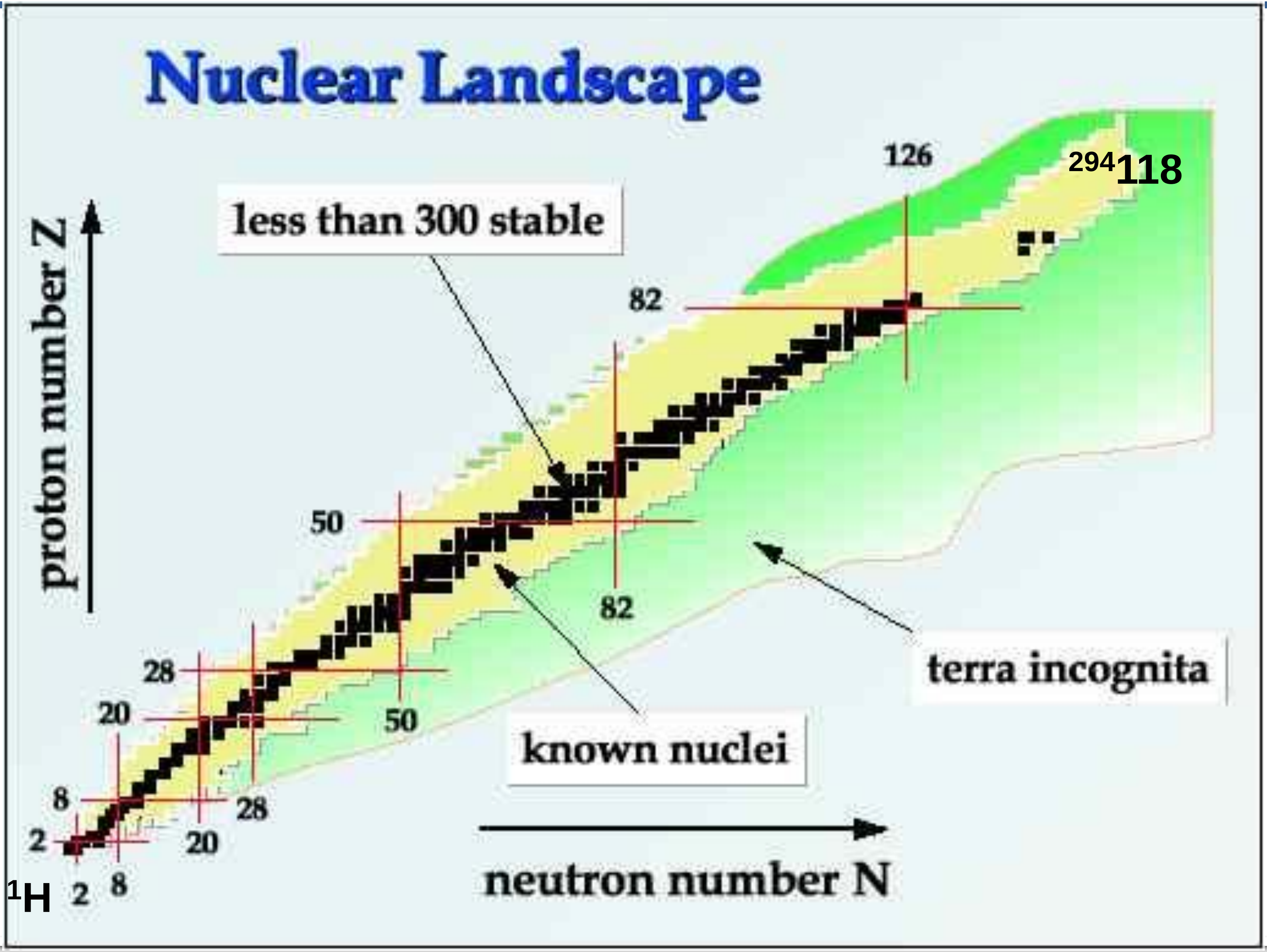
Neutron reactions can be performed at NIF for a variety of nation security programs



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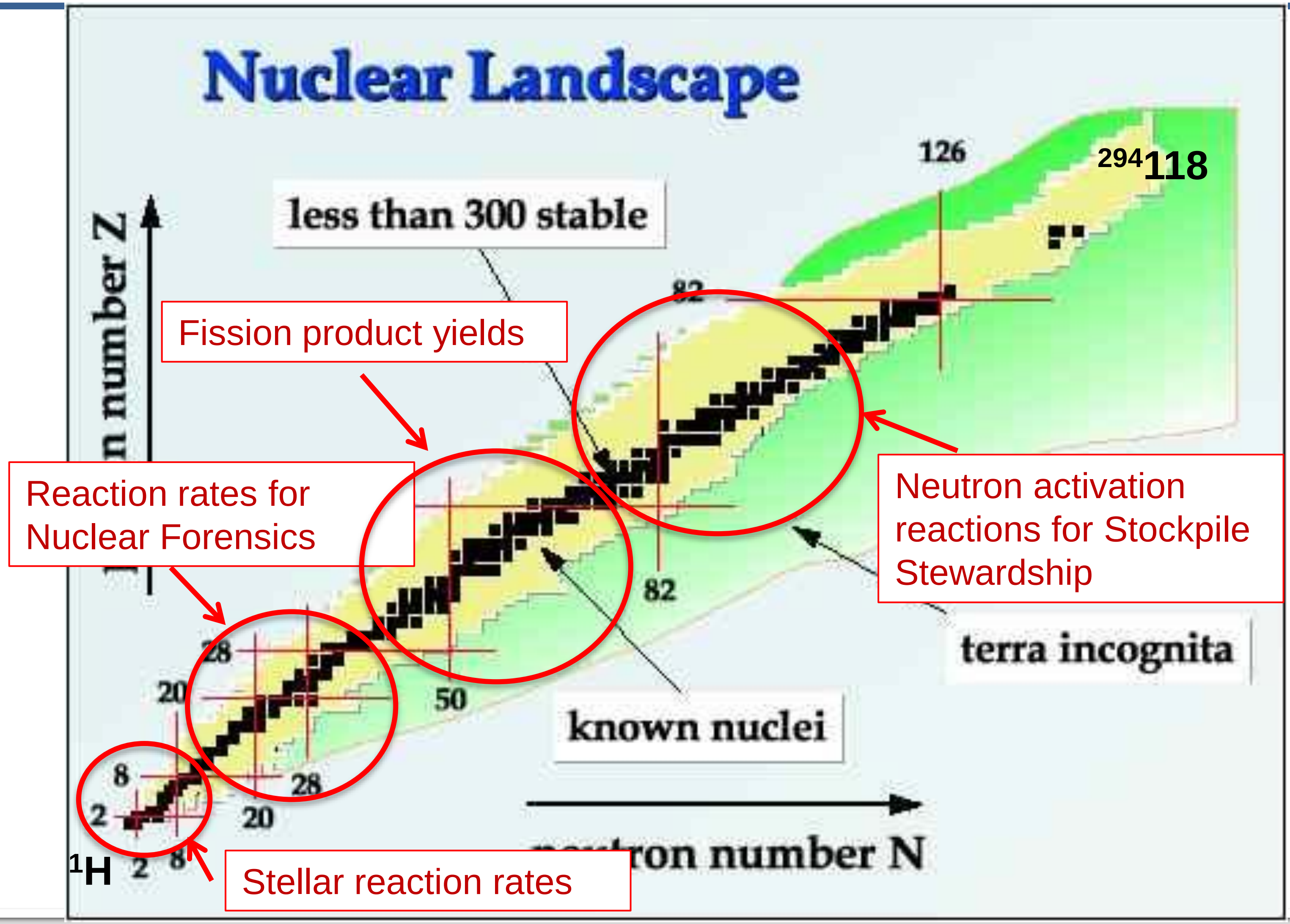
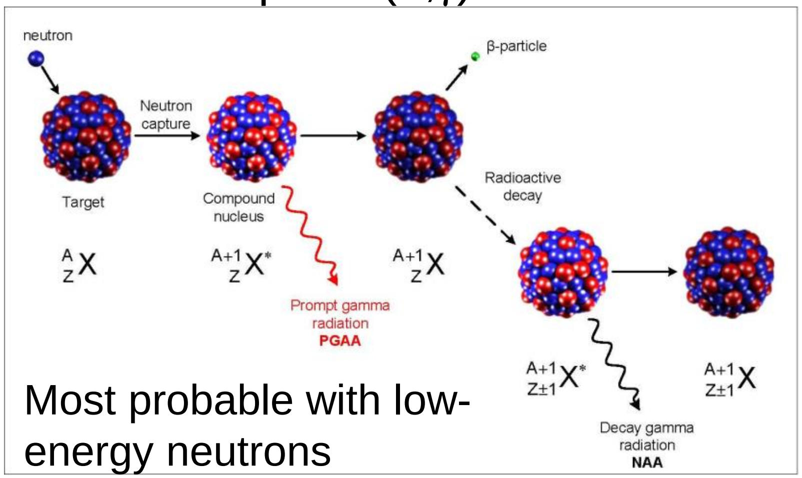


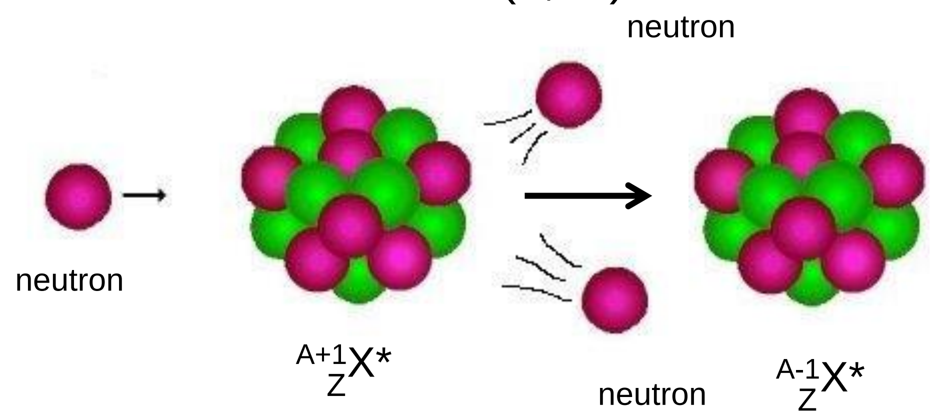
There are three neutron reactions of interest to various programs

Neutron capture (n,γ)



Most probable with low-energy neutrons

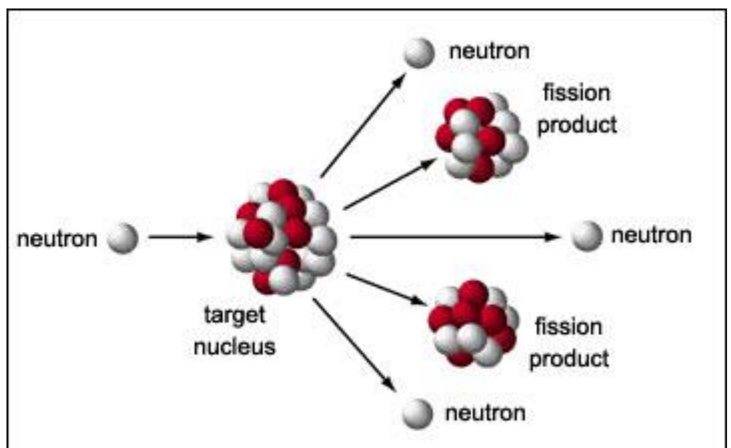
Neutron activation (n,2n)



Energetically forbidden with low-energy neutrons; very likely with 14-MeV neutrons

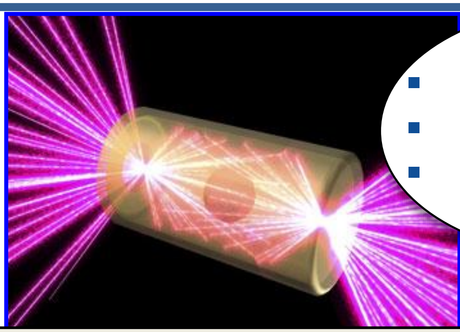
Neutron induced fission (n,f)

Depends on the nucleus; may be probable with low- or high-energy neutrons

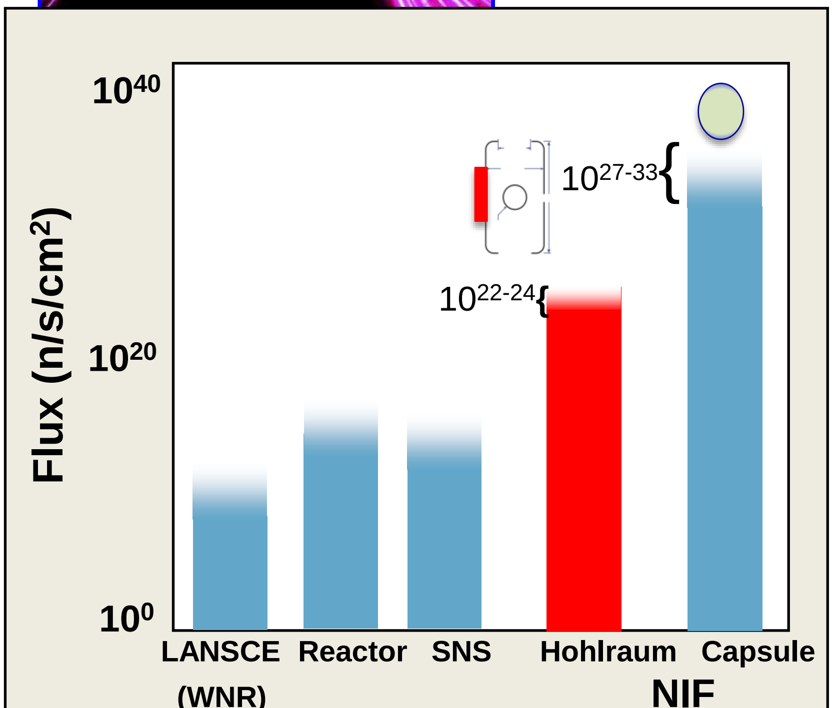


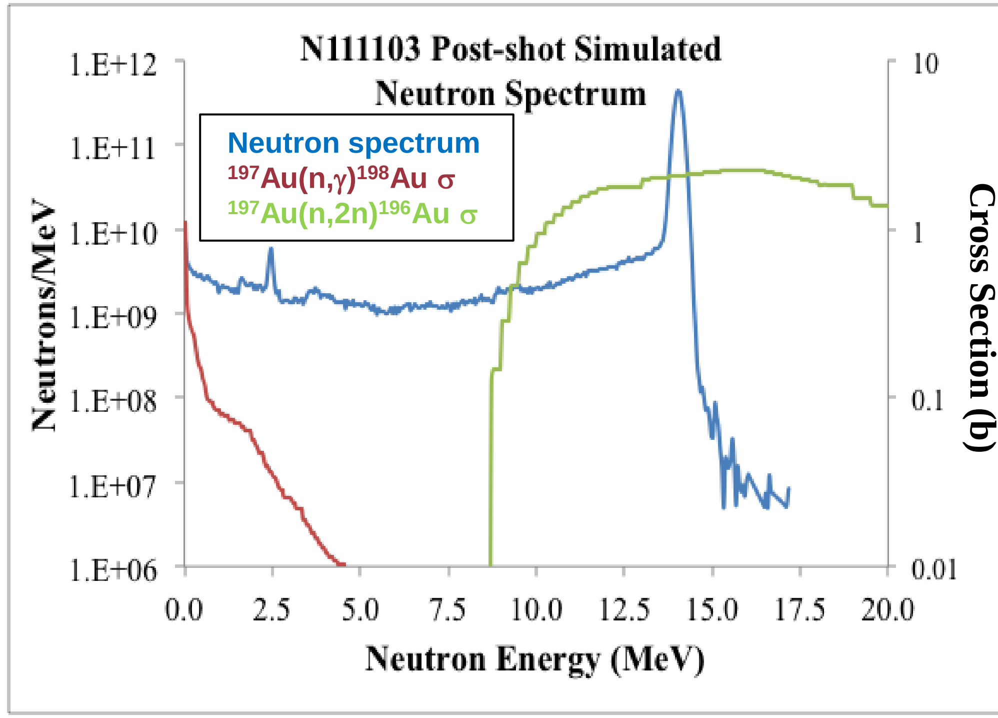
Reaction products are radioactive and can be detected through the use of γ-rays

The NIF capsule sees a unique neutron environment



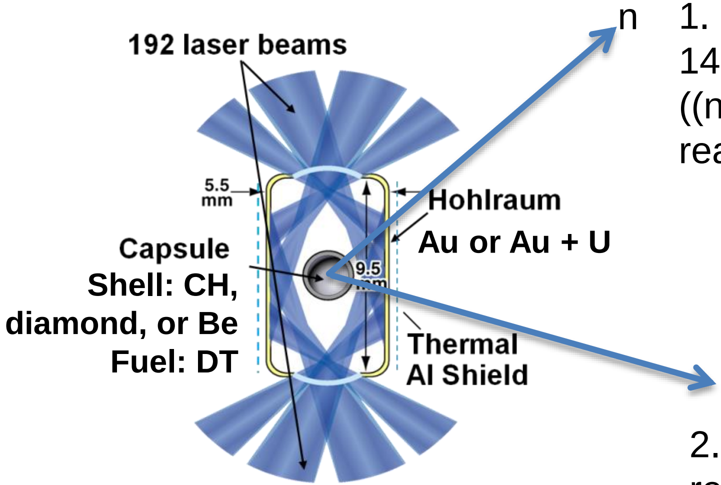
- Hot dense plasma
- High neutron flux
- Varied neutron energies





- Large neutron flux requires less target material (~10^{15} atoms)
- Short burn time means that short-lived nuclear states are accessible for reactions

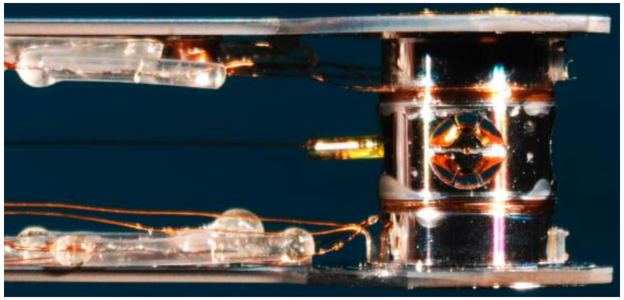
Neutrons from DT fusion are used for capsule diagnostics and nuclear data measurements



1. DT fusion creates 14.1 MeV neutrons ((n,2n) and fission reactions)

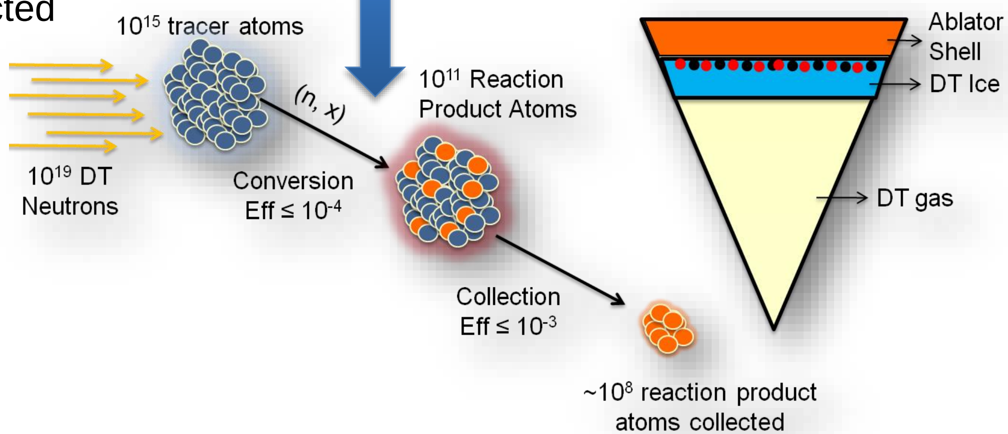
2. Neutrons scatter off remaining DT and ablator ((n,γ) reactions)

3. Hohlraum material is activated and debris is collected

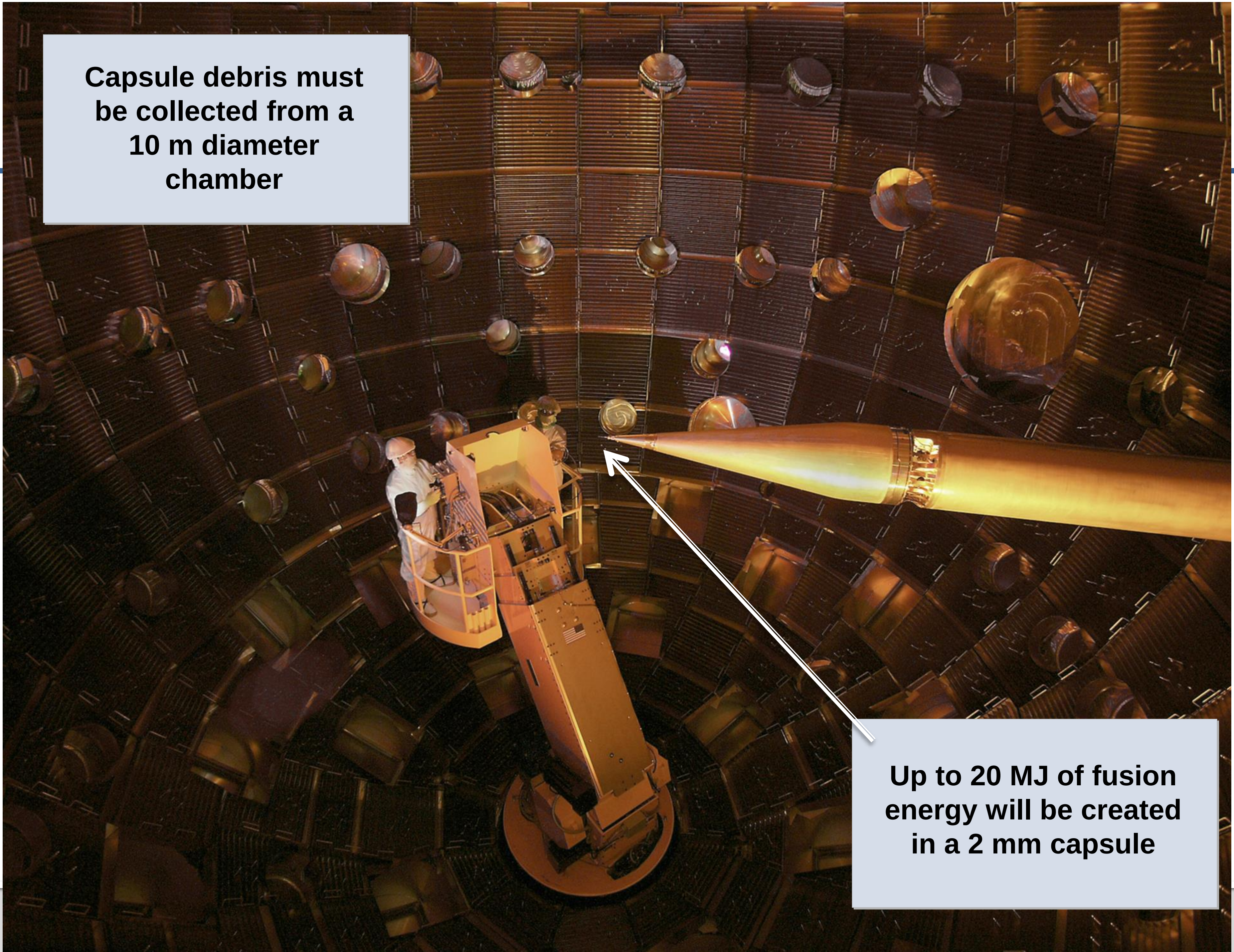


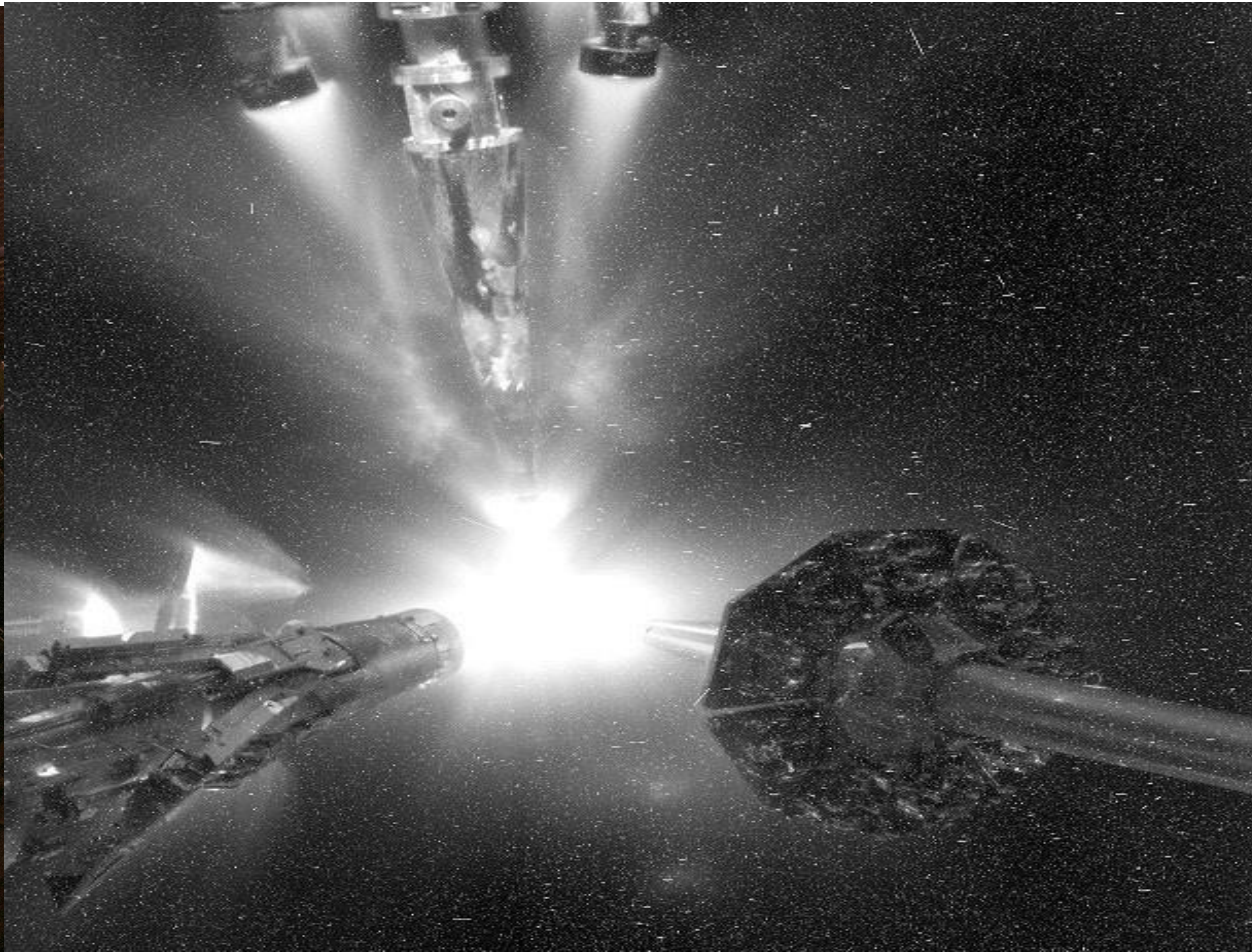
- Fuel areal density (ρR)
- Neutron capture (n,γ) cross sections (E_n<1MeV)
- Studies of fission
- Production of isotopes for various applications

4. Tracer material added to the capsule is activated and collected



- Fuel areal density (ρR)
- 1^{st} and 2^{nd} order (n,2n) reaction cross sections
- Excited state cross sections
- Fuel-ablator mix (charged particle reactions)


Capsule debris must be collected from a 10 m diameter chamber
Up to 20 MJ of fusion energy will be created in a 2 mm capsule



Radiochemistry diagnostics at NIF

Solid debris collection

Vast Area Detector for Experimental Radiochemistry (VADER), ~1%

Solid debris collection

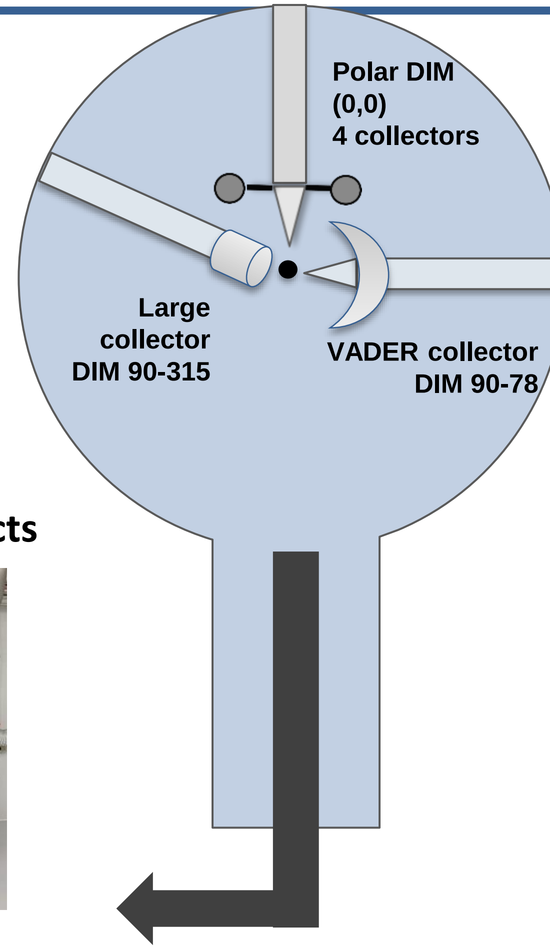
Large area solid radiochemistry collector, 1-5%

Solid debris collection

Solid radiochemistry collectors (4), ~0.1%

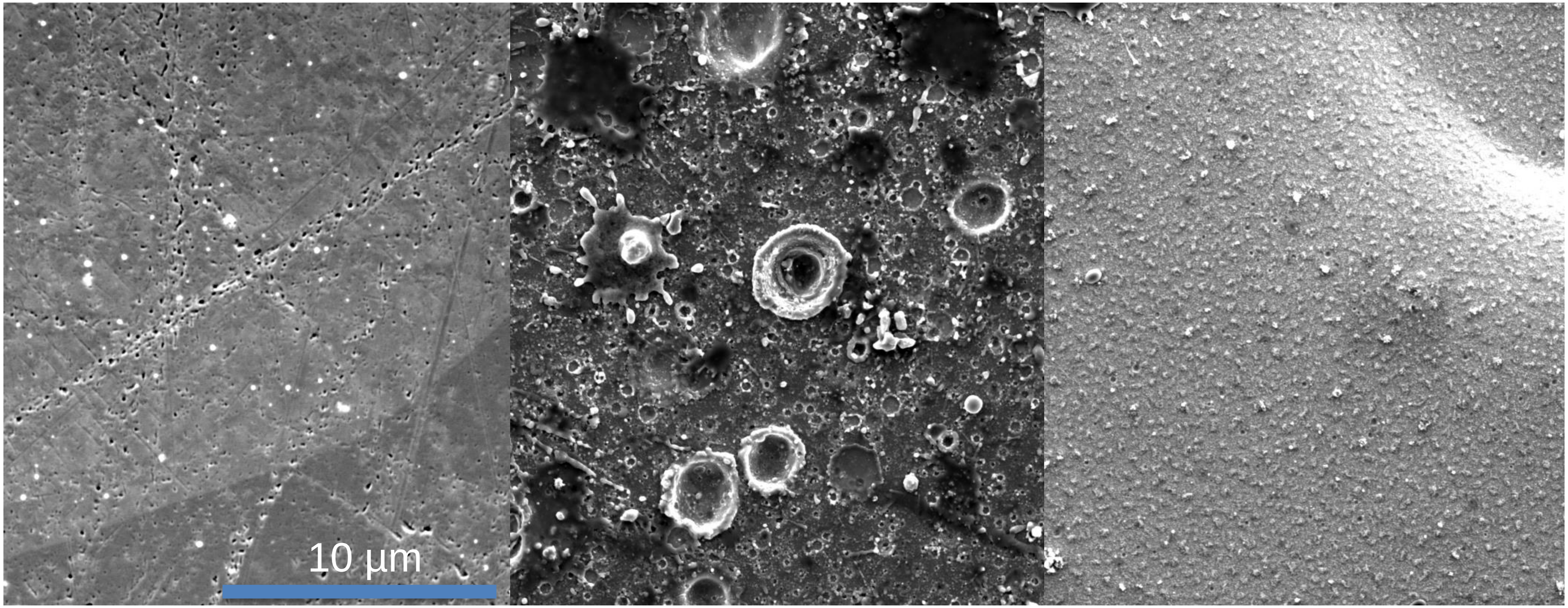
Collection of noble gas products

Radiochemical Analysis of Gaseous Species (RAGS)



Neutron yield, neutron imaging, bang time, x-ray imaging, ion temperature are provided as standard NIF diagnostics

Surface Comparison of Pre-shot, Post-Shot Polar and Equator Nb Plates.

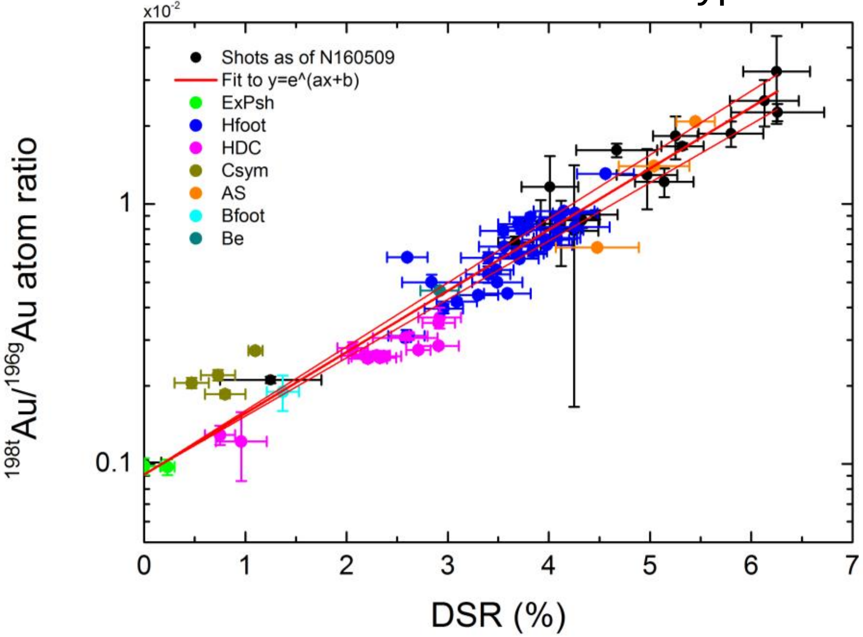


Pre-shot | Post-shot (0-0, Polar) Little debris collection | Post-shot (90-78, Equator) Debris collection ≈ solid angle

- Polar samples have a high density of craters and large splats.
- Equatorial samples have fewer craters and large debris particles. There is a high density of very small (< 1µm) features on the disks.

The first nuclear science results came from development of debris collection

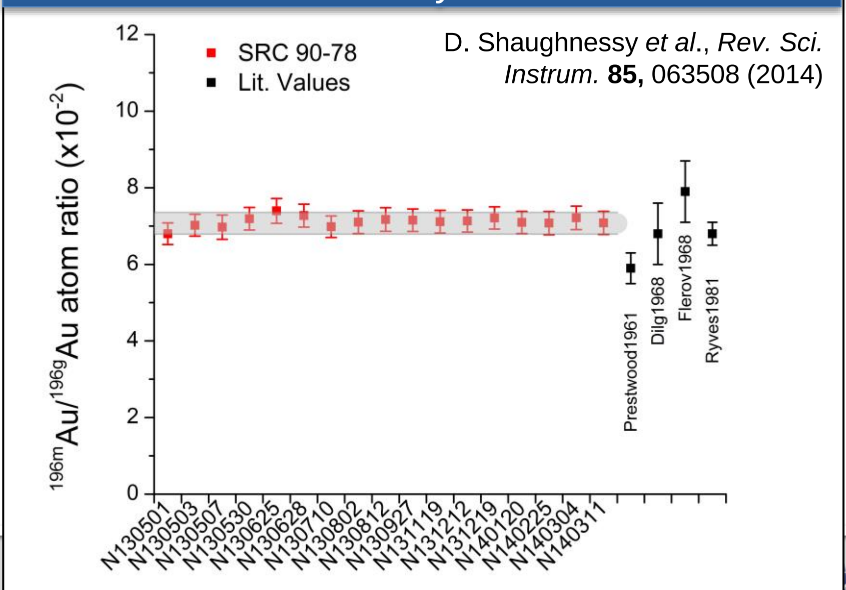
SRC data based on shot type



- SRC data from activated gold hohlraum debris
- A set of calibration shots (more spherical implosions) were used to create a predictive fit to SRC data
- SRC is line of site independent (spatially averaged)

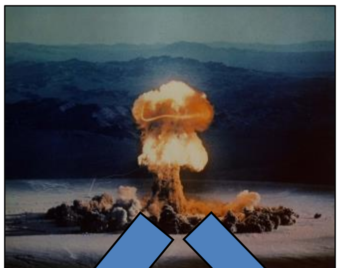
- Improved nuclear data measurements were made on gold isotopes
- $^{196m}Au/^{196g}Au$ isomer ratio produced from $^{197}Au(n,2n)$ reaction
- ^{196m}Au half-life, γ-ray energies, intensities, and decay branch (K.J. Moody *et al*., J. Phys. G Nucl. Part Phys. 47, 045116 (2020))

Improved isomer ratio measurement from Solid Radiochemistry debris data



A nuclear forensic campaign was started to provide improved nuclear data

- Nuclear forensic models require realistic exercise samples for method validation



Event

Activated soil components

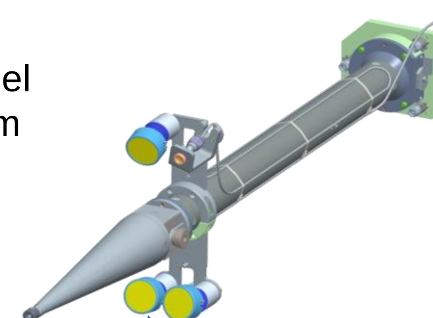
Activated structural materials

Debris samples contain all components

- Materials can be placed at several locations in NIF to generate activated species at different neutron energies
- Improved nuclear reaction data are also obtained from these experiments

Structural materials (e.g., steel components) on the hohlraum

Materials in the capsule see the largest neutron flux

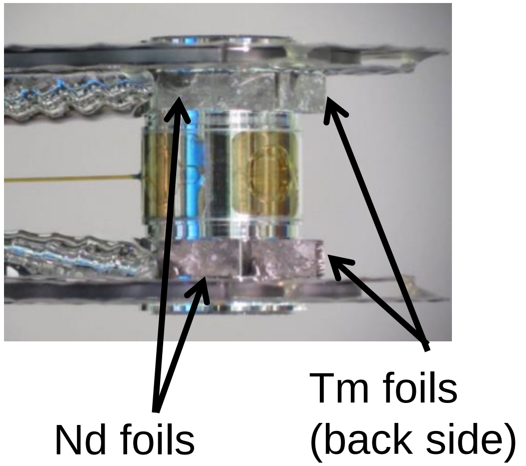


Radiochemistry collectors at 50 cm also house irradiated materials

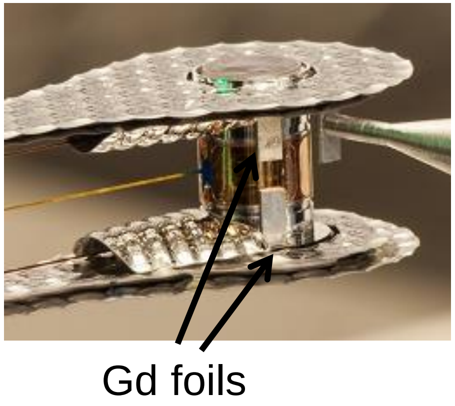
Two shots were fielded in FY15 to develop a platform for cross section measurements

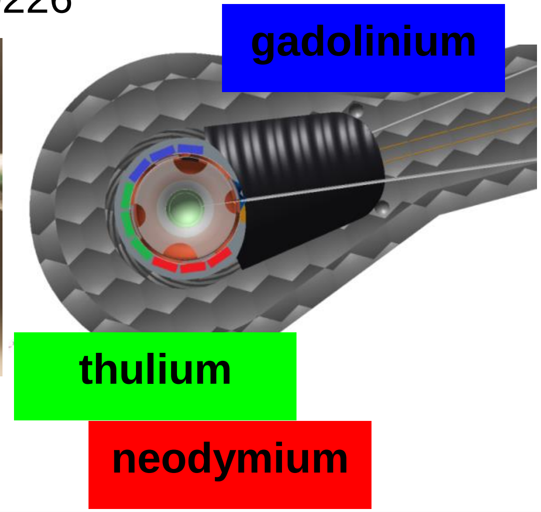
- Indirect-drive exploding pusher (IDEP) shots were used as a pure source of 14-MeV neutrons without downscatter to measure (n,2n) activation products
- N141130 and N150226 consisted of 120-m plastic capsules with DT gas-fill (~900 kJ, Y_n=5e14) in 575 near-vacuum hohlraums
- Rare earth foils were attached to the outside of the TMP (0.5 mm thick) to evaluated distribution of solid debris in the chamber

N141130

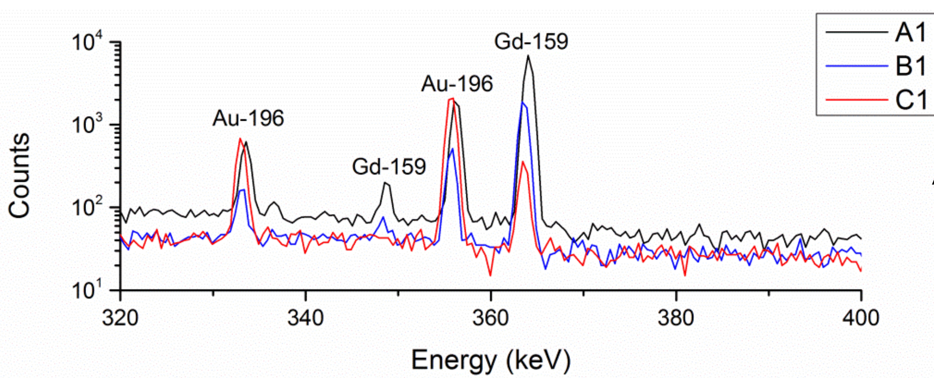


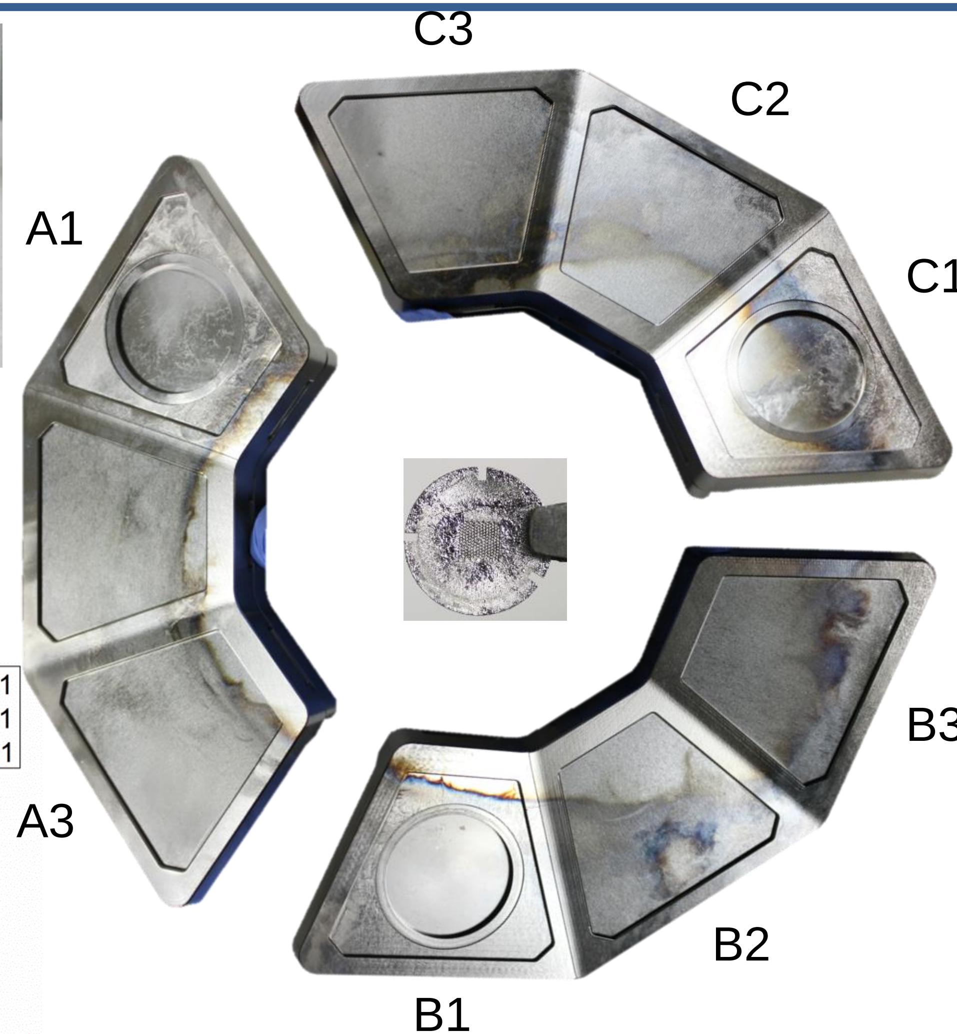
N150226





Hohlraum debris is highly directional

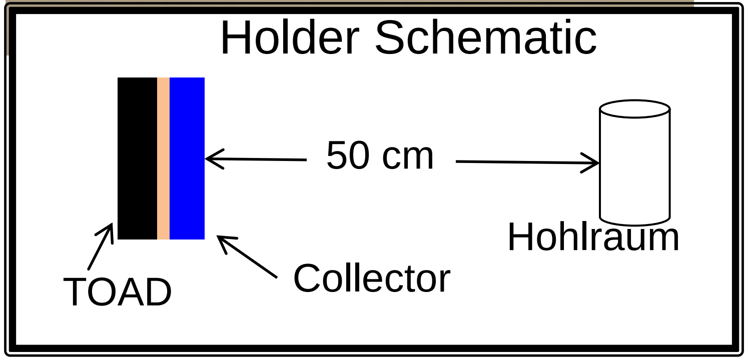




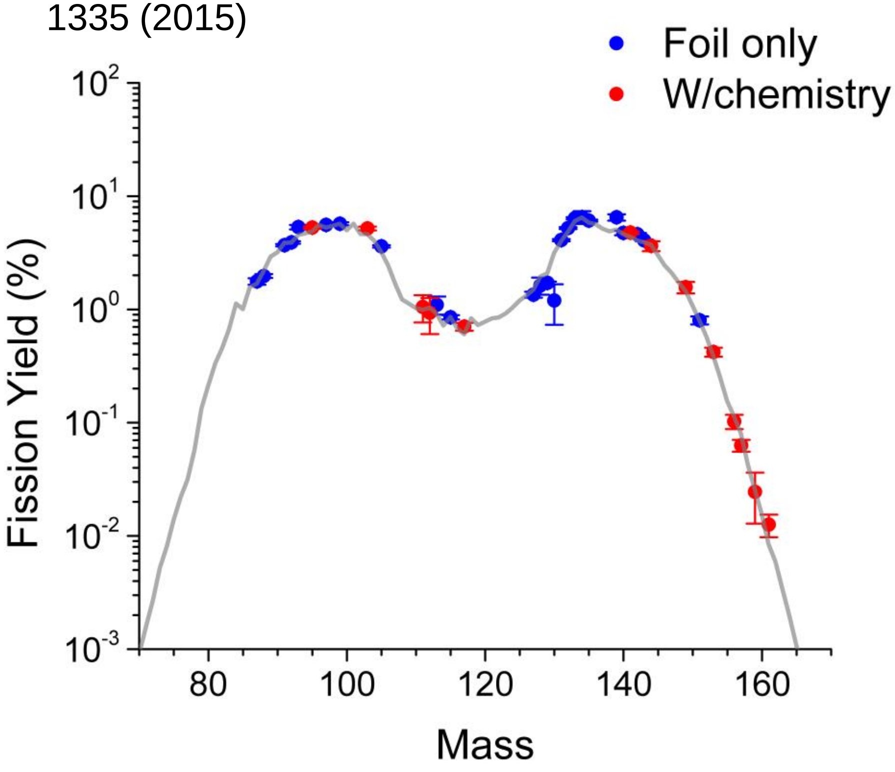
VADER collected > 6% of the gadolinium material – Increased hohlraum mass improves debris transport

TOAD sample holder can field larger (1 g) samples for irradiation studies

Small amounts of material (1 mm thick, 2.5 cm diameter) are sealed inside



N. Gharibyan et al., J. Radioanal. Nucl. Chem., 303, 1335 (2015)

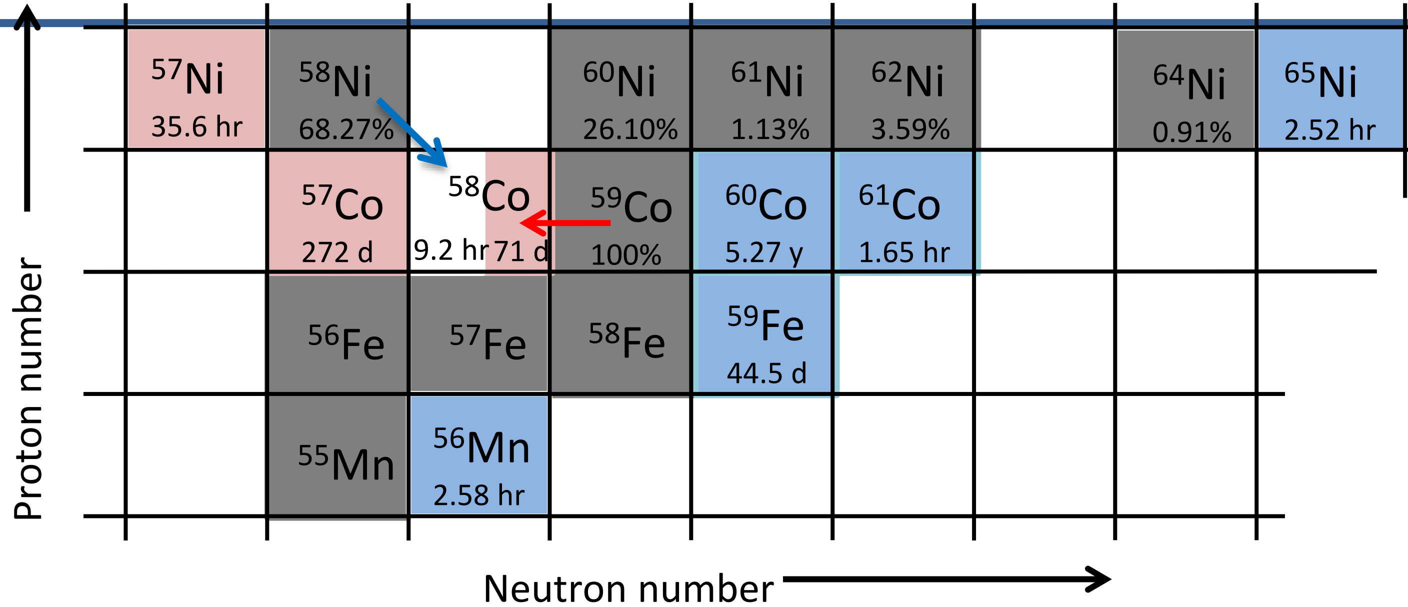


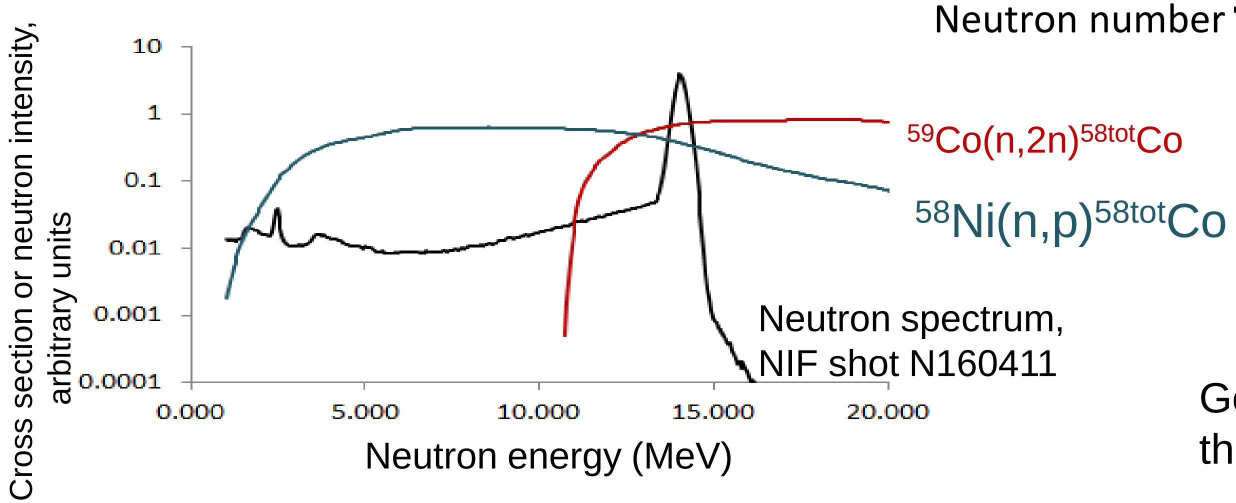
We observe Np-239, U-237, and ~10^8 fissions (Yn ~10^{15}) in DU TOAD samples

First measurement of stainless steel reaction network – Neutron induced reactions on Ni and Co foils (TOAD)

$^{59}Co(n,2n)^{58m+g}Co$

$^{58}Ni(n,p)^{58m+g}Co$

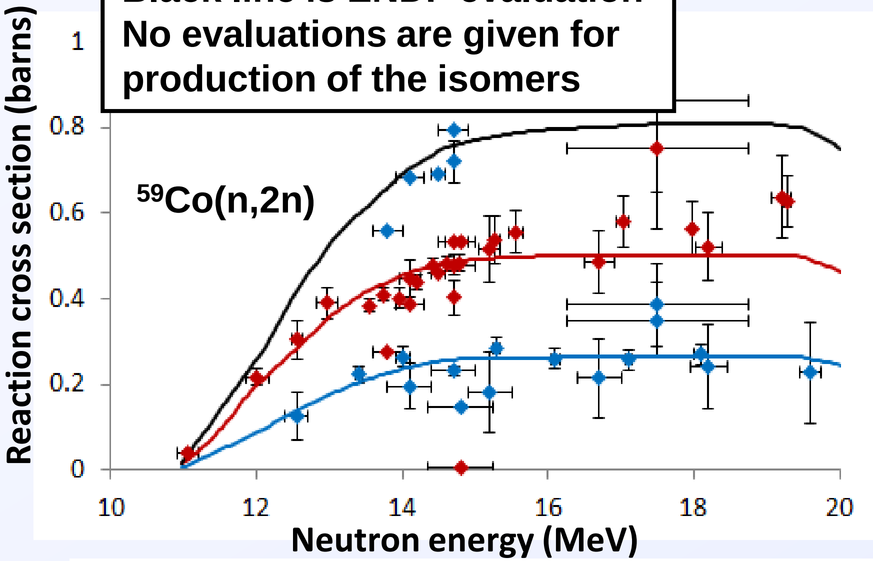




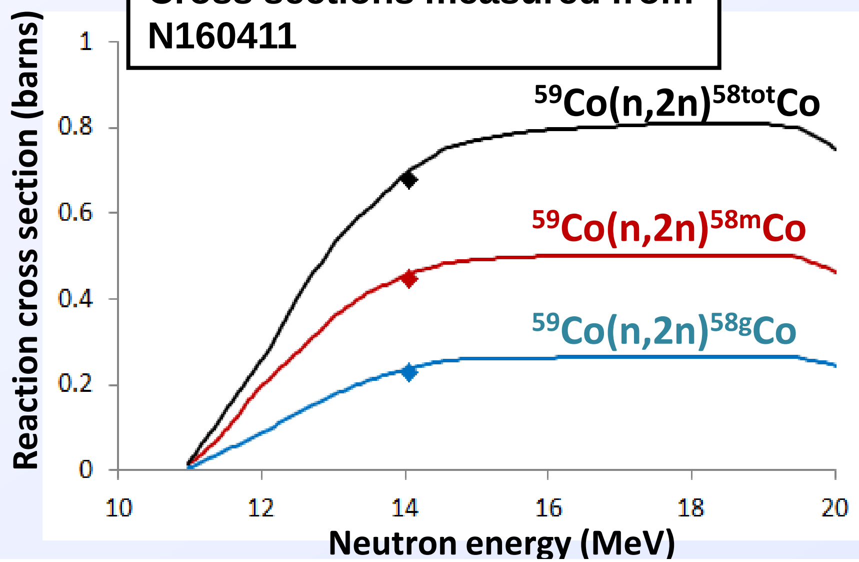
Goal: Measure cross sections to the isomer and ground states

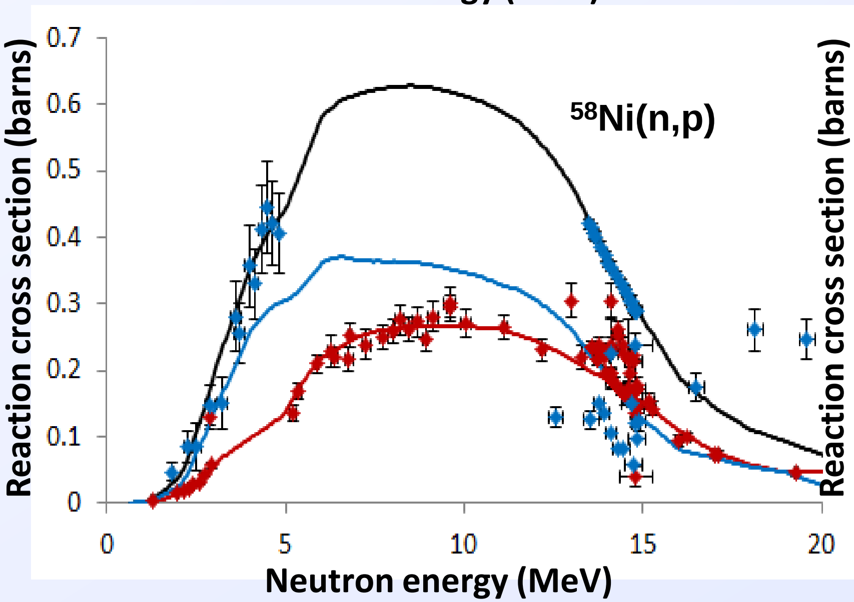
Measurement of production of radionuclides from Ni

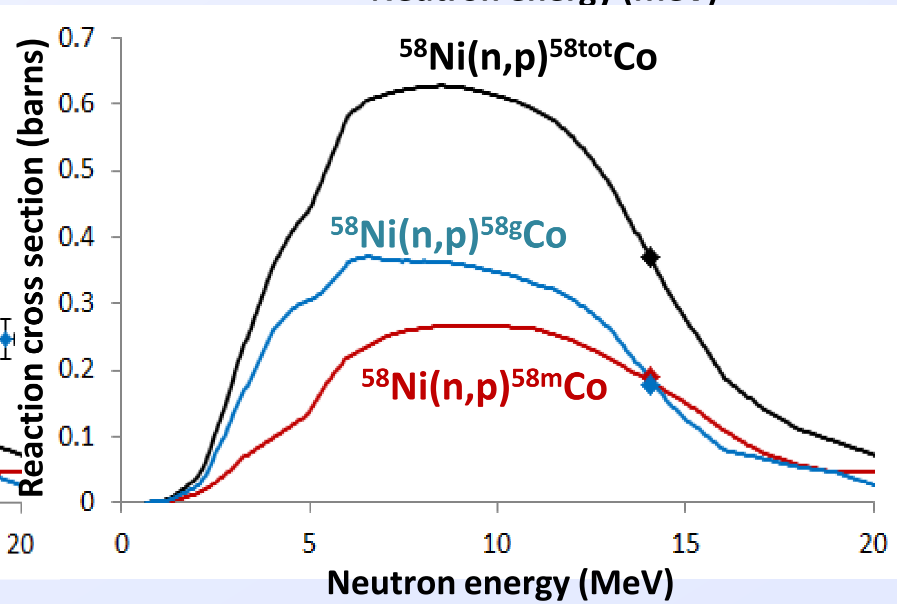
Black line is ENDF evaluation
No evaluations are given for production of the isomers



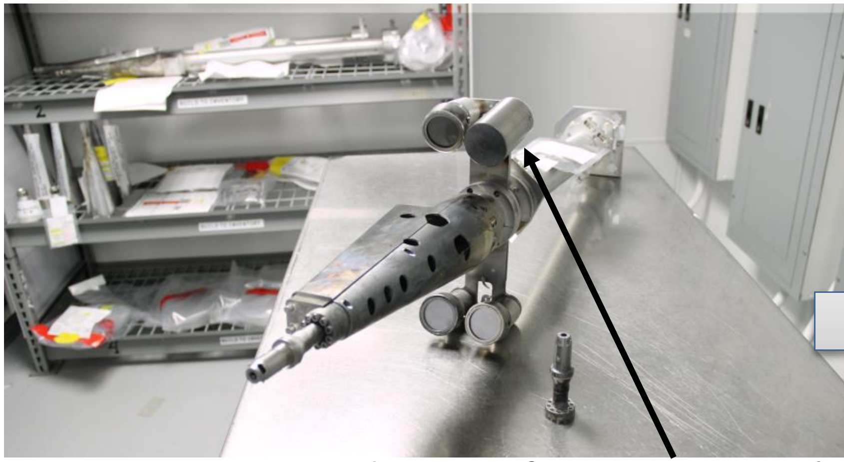
Cross sections measured from N160411



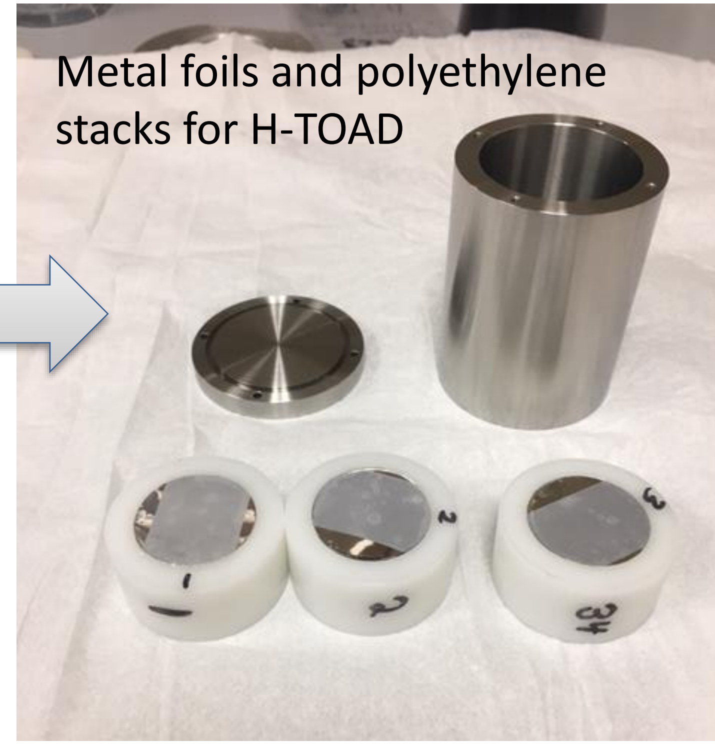


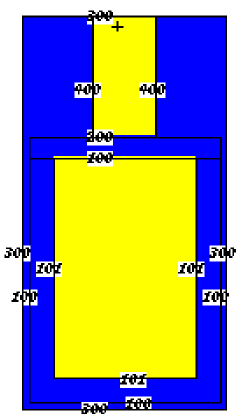


Collaboration with U.C. Berkeley Nuclear Engineering on neutron spectral modification



H-TOAD mounted 50 cm from NIF capsule





- MCNP models of the DIM and H-TOAD have been created in the full NIF MCNP model
- Early models match experimental data reasonably well

Goal: Tailor a NIF neutron spectrum for irradiation of materials for Nuclear Forensics applications

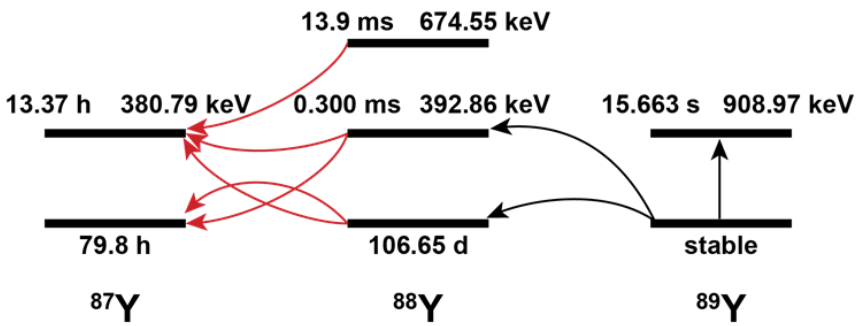
Radiochemical measurements of first-order (n,2n) reactions

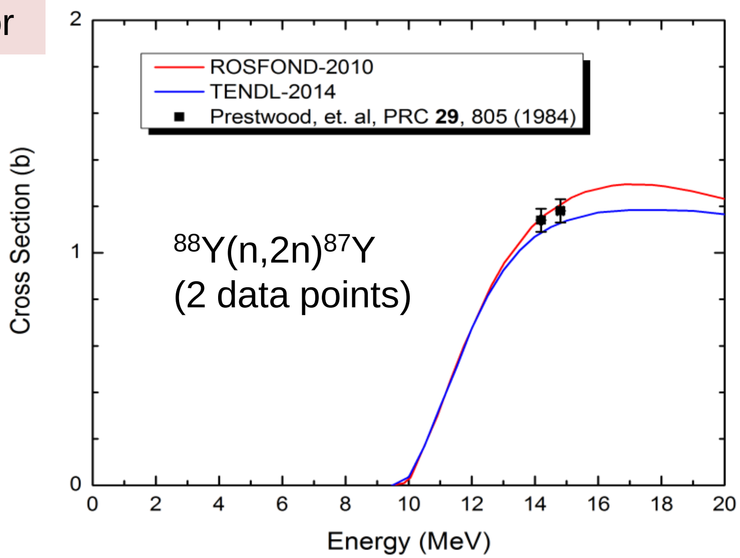
- Large neutron flux requires less target material (~10^{15} atoms) to make a measurement
  - Material must be <10 μm from the DT fuel
  - Measurements on radioactive species are doable
  - Comparable accelerator measurements require 100 times more target material

- Short burn time (~10 ps) means that short-lived excited nuclear states are accessible for subsequent reactions (second-order), but higher neutron yields are required

^{88}Y and ^{87}Y were measured

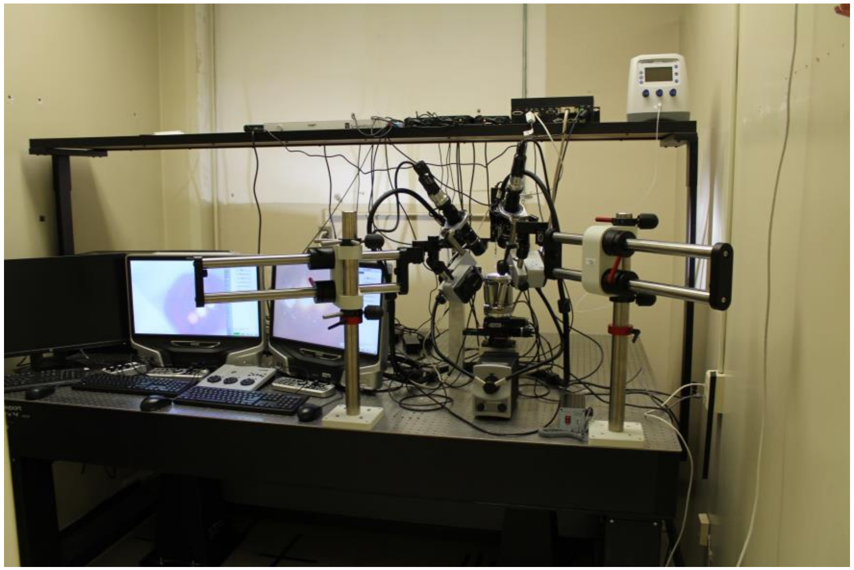
^{89}Y was loaded as a radiochemical detector

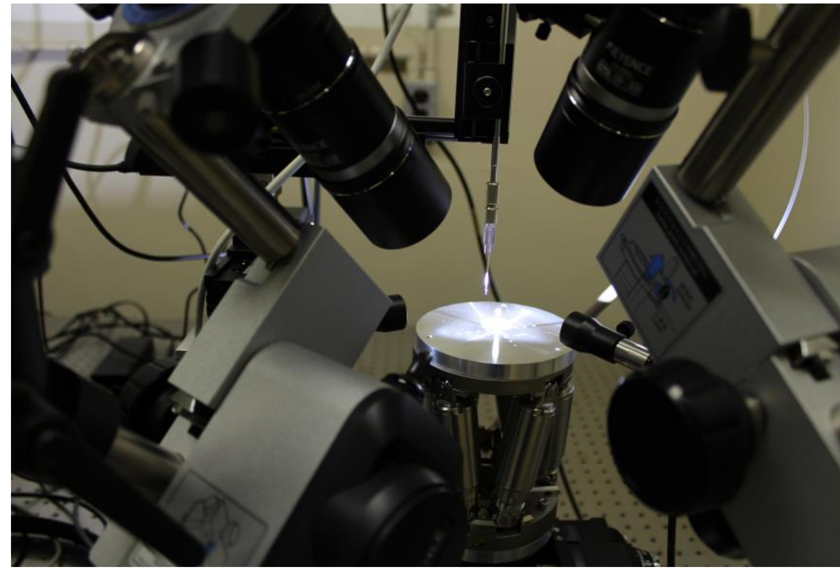




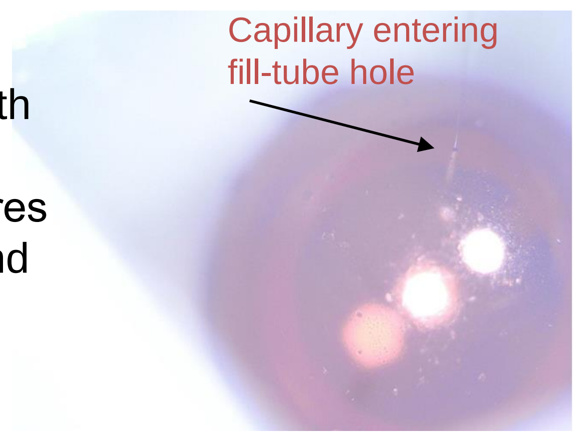
- ^{88}Y could be produced at a cyclotron and loaded into a NIF capsule
- Future harvested isotopes from FRIB could also be loaded and measured

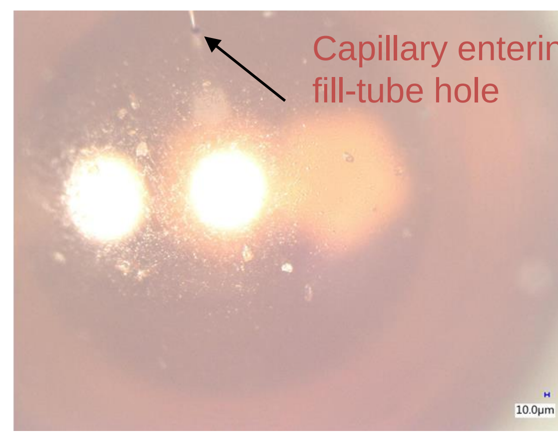
Apparatus for NIF Doping: Automated Robotic Injection System for Targets (ANDARIST)





- System allows for precision alignment of microcapillary with fill-tube hole for injection
- Each material “cocktail” requires R&D to optimize the matrix and mass loadings





First doped capsules contained ^{238}U and ^{7,10}Be (^{7}Be $t_{1/2}$=53 d)

Reference reactions are used to determine unknown cross sections

- The product of the reaction of an "instantaneous" pulse of neutrons with a detector element (n^0) is given by:

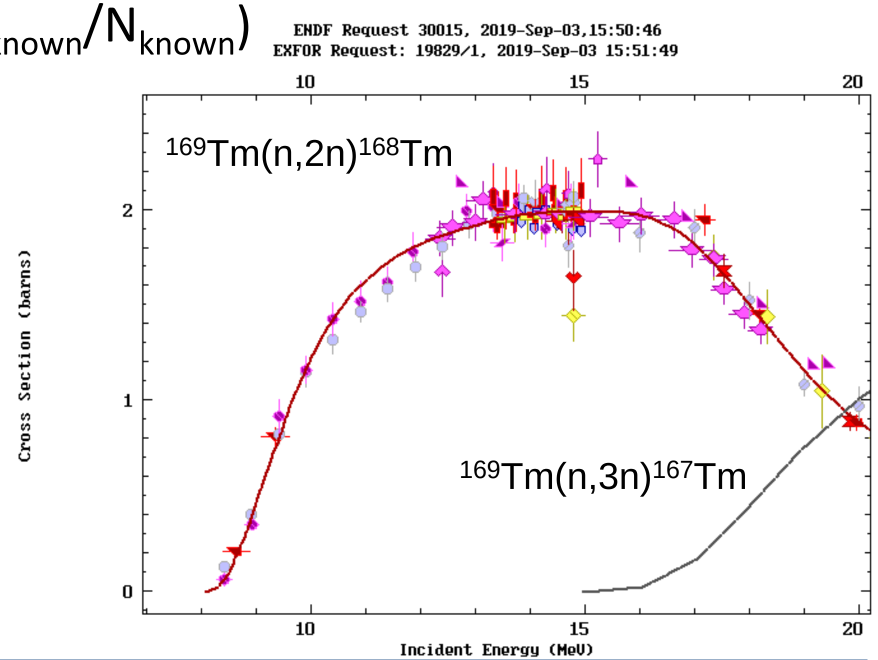
  $$N = n^0\phi\sigma$$

- If two target nuclides are co-loaded together, one with a known cross section (σ), the flux (ϕ) cancels:

  $$\sigma_{unknown} = \sigma_{known}\,(n^0_{known}/n^0_{unknown})(N_{unknown}/N_{known})$$

- Uncertainty is related to errors in the known cross section, loaded target assay, counting statistics, and some correction factors (e.g., differing reaction thresholds)

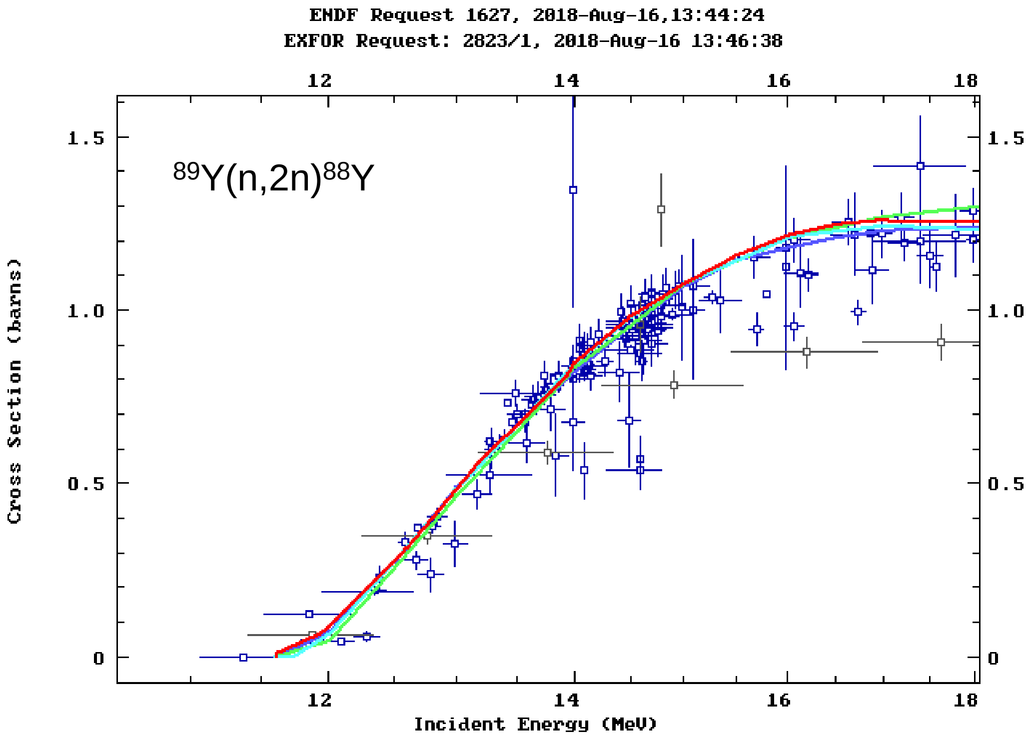
- ^{169}Tm(n,2n) is the "known" reaction for ^{88}Y(n,2n)



Uncertainty on measured first-order (n,2n) at NIF will be ~5% depending on nuclide

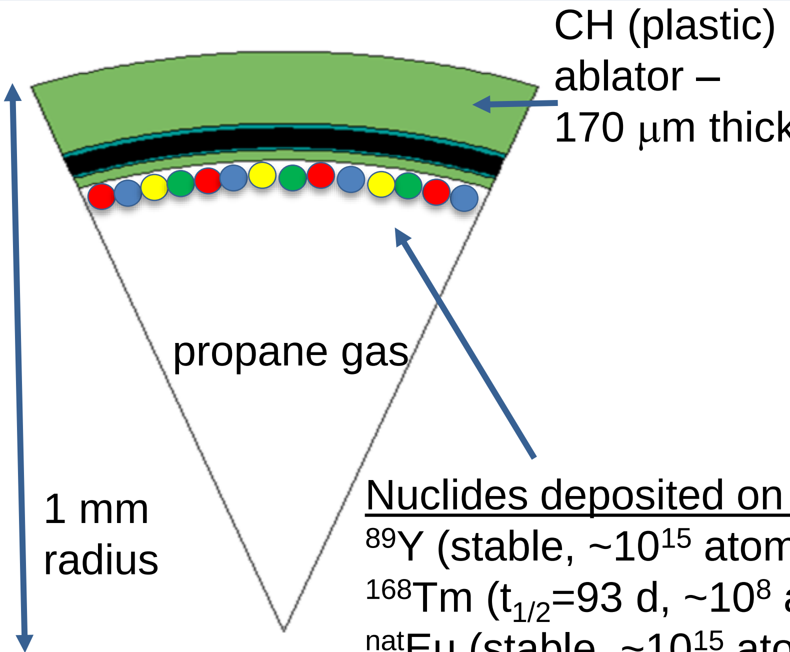
First measurements on the known $^{89}Y(n,2n)^{88}Y$ reaction for method validation

- Use the $^{89}Y(n,2n)$ reaction for method validation
- Compare to known data to establish uncertainties related to ICF-based cross-section measurements
- Must load ^{89}Y, ^{169}Tm and collection efficiency tracers into the NIF capsule
- First shot scheduled for November

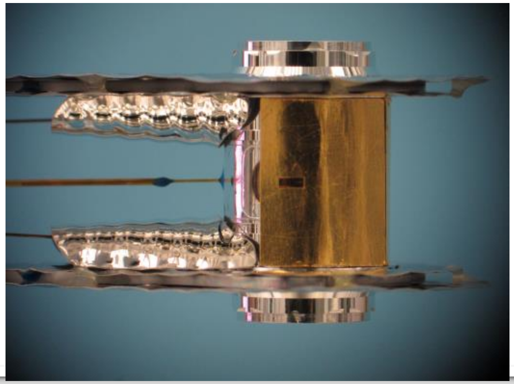


Two NIF shots were executed to evaluate fractionation of dopants in capsules

- Two shots (January, 2020) were fielded to establish fractionation effects between dopants (N200114-001, -002)
- Capsule 1: ^{89}Y, ^{168}Tm, and ^{nat}Eu deposited on the inner surface; capsule 2: ^{168}Tm and ^{nat}Eu
  - Shot 2 measures chamber background between shots
- Mass spec. in process to measure ^{89}Y and ^{nat}Eu; γ-spec. used to measure ^{168}Tm collection
- Similar capsule will be shot with DT in November

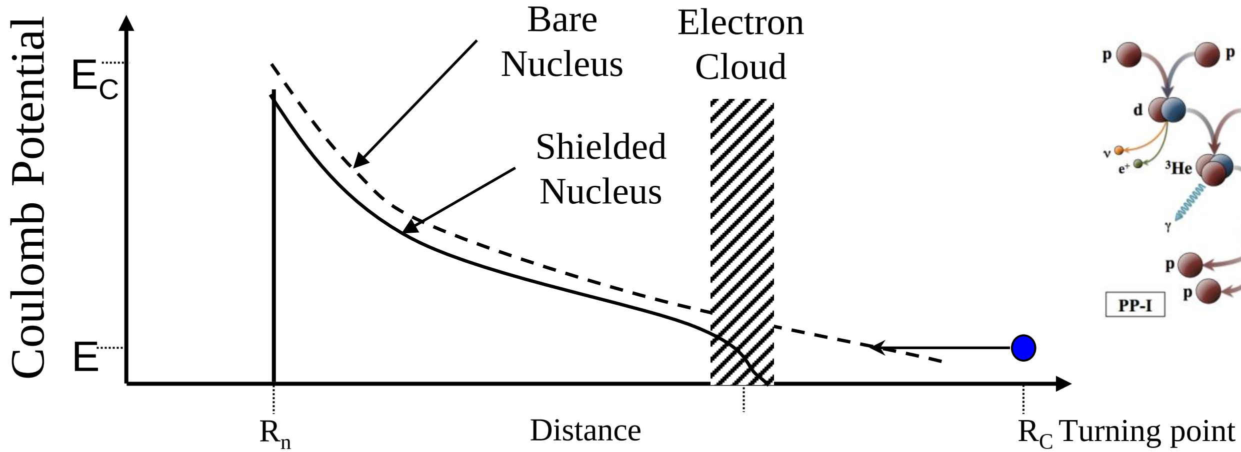


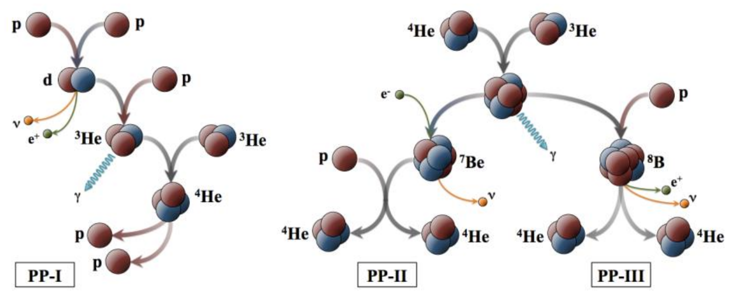
Nuclides deposited on inner surface:
^{89}Y (stable, ~10^{15} atoms)
^{168}Tm ($t_{1/2}$=93 d, ~10^{8} atoms)
^{nat}Eu (stable, ~10^{15} atoms)

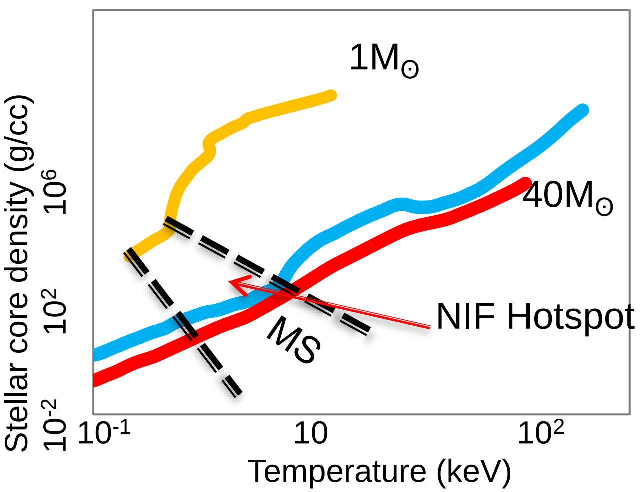


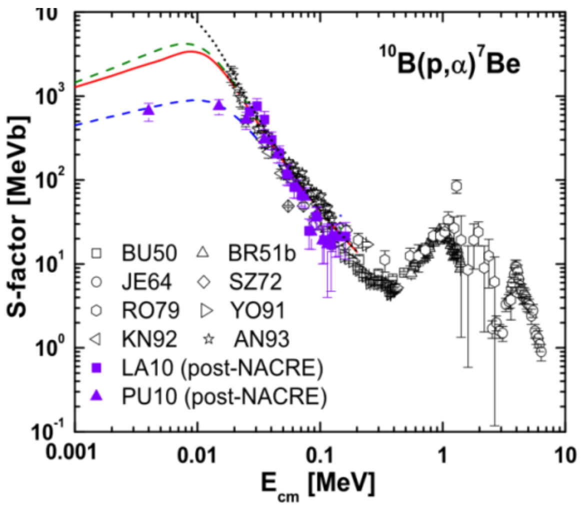
Final target assembly with extra gold to enhance debris collection

Charged-particle reactions in a plasma are a measure of stellar rates









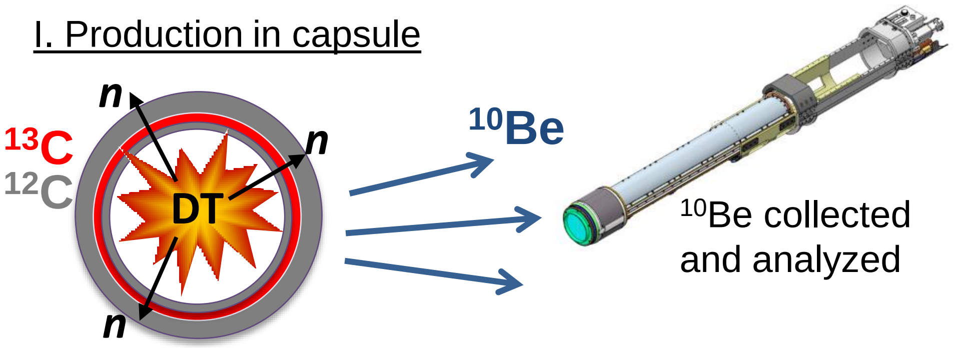
- Add ^{10}B to an indirect-drive exploding-pusher
- Based on DT yield ~10^{11}, expect ~$8x10^5$ $^{10}B(p,\alpha)^7Be$ reaction products
- Initial results from Be capsule shots show collection of capsule material on the equator

Hotspots in NIF implosions replicate stellar cores and are not complicated by bound screening

The $^{13}C(n,\alpha)^{10}Be$ reaction establishes platforms for measuring cross sections

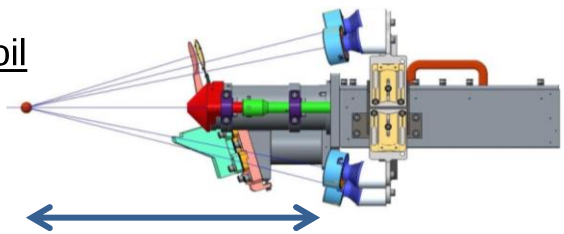
- Low-*Z* debris collection
- Interpretation of reaction rate data
- Solve major discrepancy between data and evaluations (based on calculations) with two measurements:

I. Production in capsule

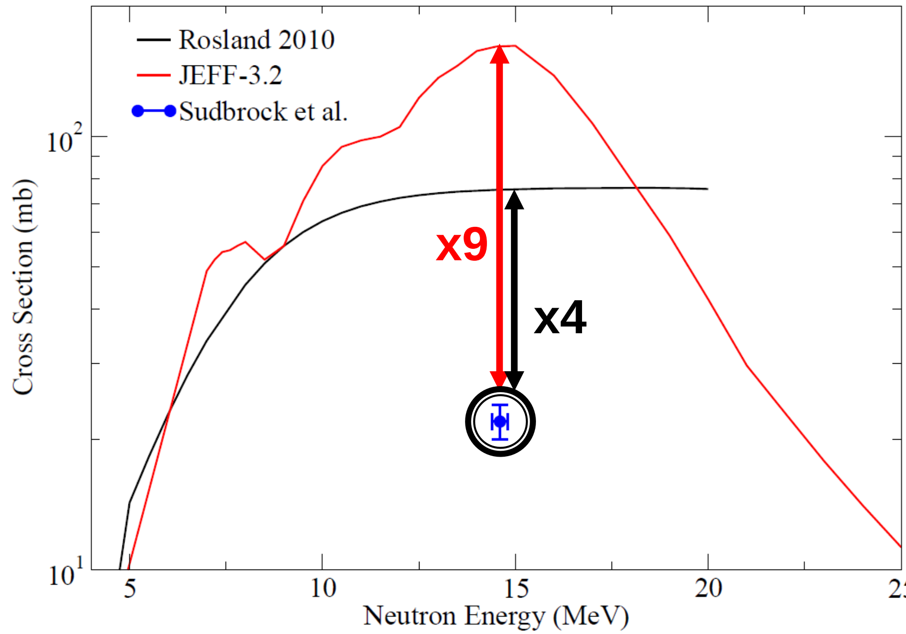


II. Production in graphite foil

Carbon foil fielded behind radiochemistry collector on DIM



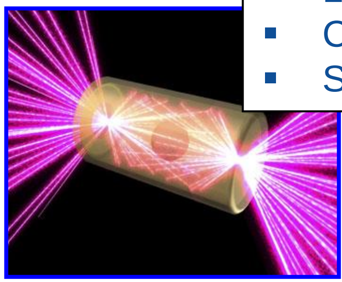
50 cm to collector



$^{13}C(n,\alpha)^{10}Be$ reaction data and calculated evaluations

Results are currently being prepared for a publication

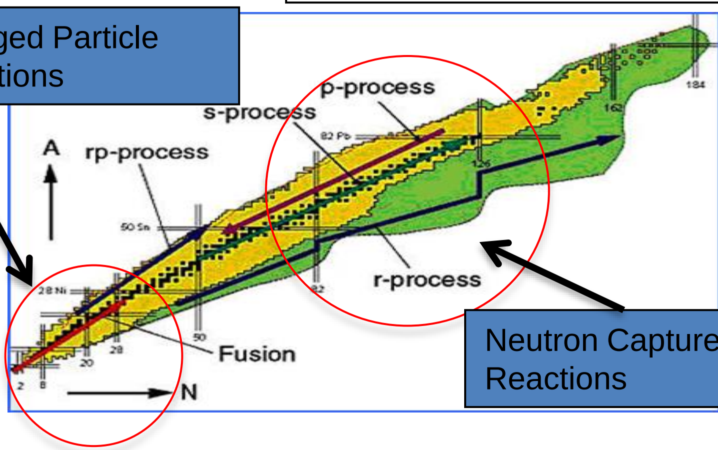
Nuclear reactions measured in a plasma are important to several laboratory mission areas



- High energy density plasma
- Large neutron yield (~10^{16})
- Compressed volume (<10^{-6} cm^3)
- Short burn time (~100 ps)

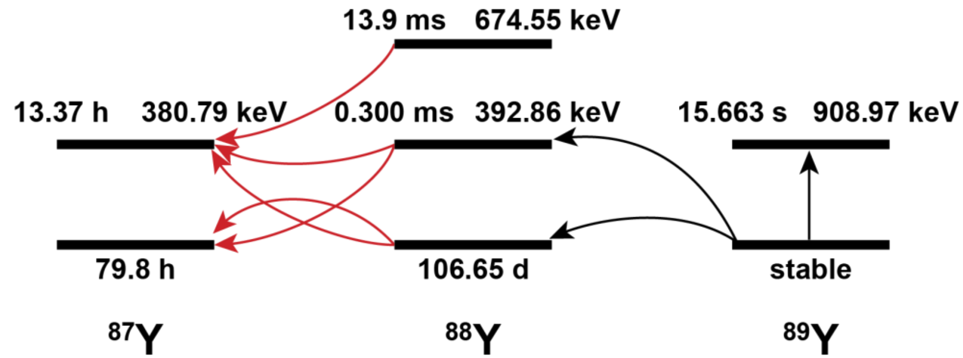
Stellar reaction rates in a plasma

Charged Particle Reactions



Neutron Capture Reactions

Neutron reactions on excited nuclear states for interpretation of UGT data



Reaction networks for post-detonation nuclear forensics analysis

The unique NIF neutron source probes reactions not possible at accelerators

Lawrence Livermore National Laboratory