Nuclear Physics Opportunities at OMEGA and the NIF

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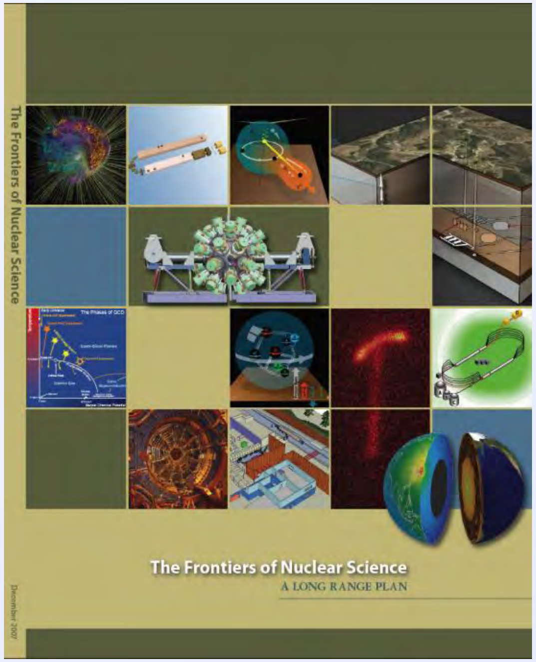
Burning HED plasmas provide unique opportunities for addressing important nuclear science questions

DOE and NSF nuclear science:

- **What are the nuclear reactions that drive stars and stellar explosions?**
- **What is the nature of the nuclear force that binds protons and neutrons into stable nuclei and rare isotopes?**
- **What is the origin of elements in the cosmos?**



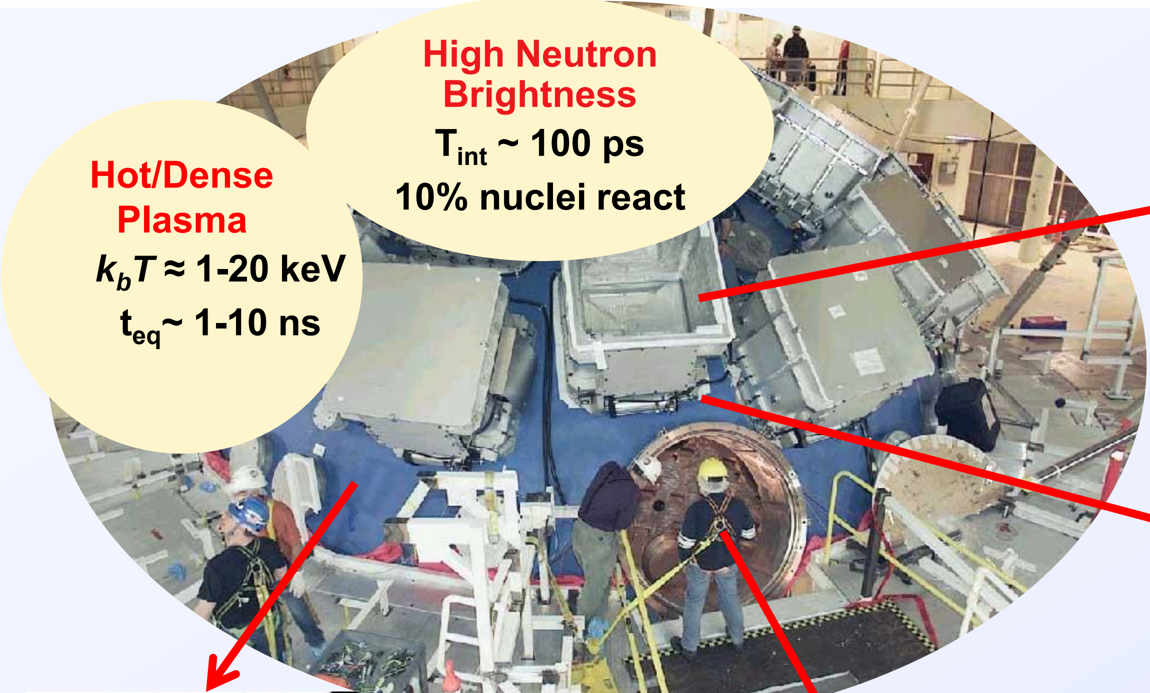
The Frontiers of Nuclear Science
A LONG RANGE PLAN

The Frontiers of Nuclear Science

December 2007

Community/DOE is open to proposals for nuclear physics at ICF facilities

Implosions at NIF have unique characteristics that can extend our understanding of nuclear reactions in plasma environments



Hot/Dense Plasma

$k_bT \approx$ 1-20 keV

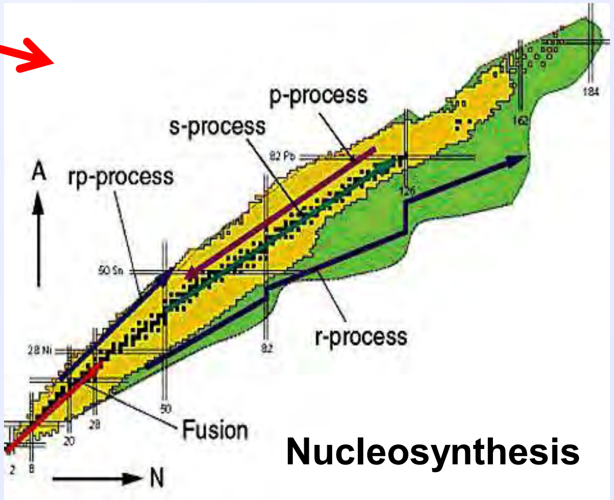
t_{eq}~ 1-10 ns

High Neutron Brightness

T_{int} ~ 100 ps

10% nuclei react

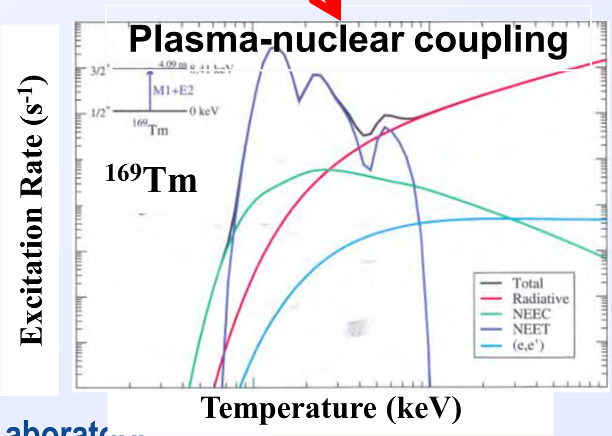
Stellar fusion



Nucleosynthesis

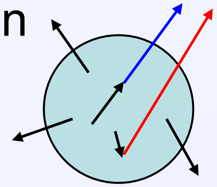
Neutronic coupling/ excited states

Plasma-nuclear coupling

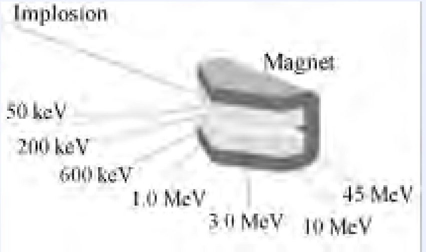


J. Frenje et al. have made the first relative nuclear cross section measurement at OMEGA

- Plasma serves as both neutron source and target
  - Neutrons up-scatter d and t ions

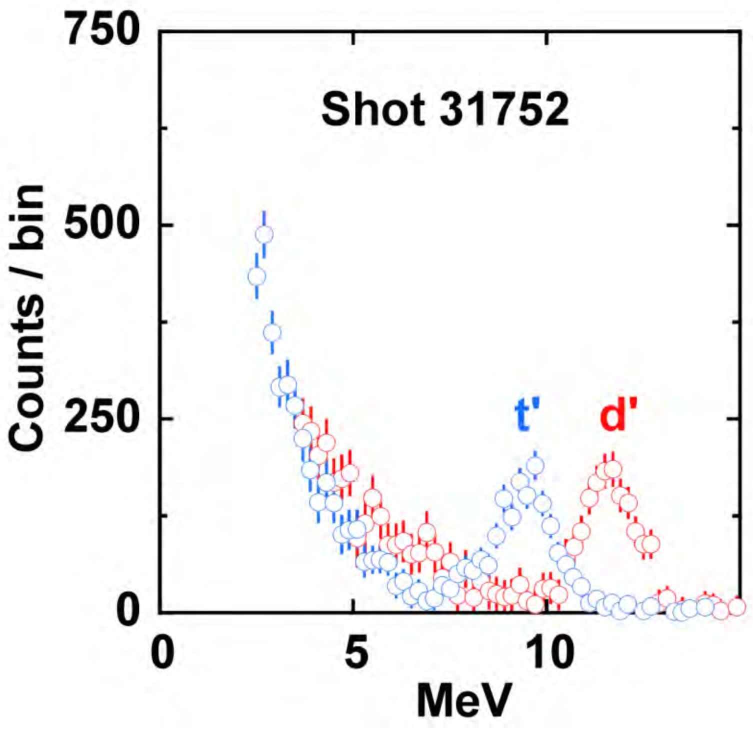


- Energy spectra were measured with a Charged-Particle Spectrometer



- Energy loss not significant
  - 3 mg/cm^2 plasma ≈ 300 μg/cm^2 cold
- Relatively clean
  - Proton “gunk” and multiple scattering is discriminated by track characteristics
  - Small contribution from T(n, d 2n) subtracted based on theory calcs.

n-D and n-T Elastic Scattering



One of 3 shots

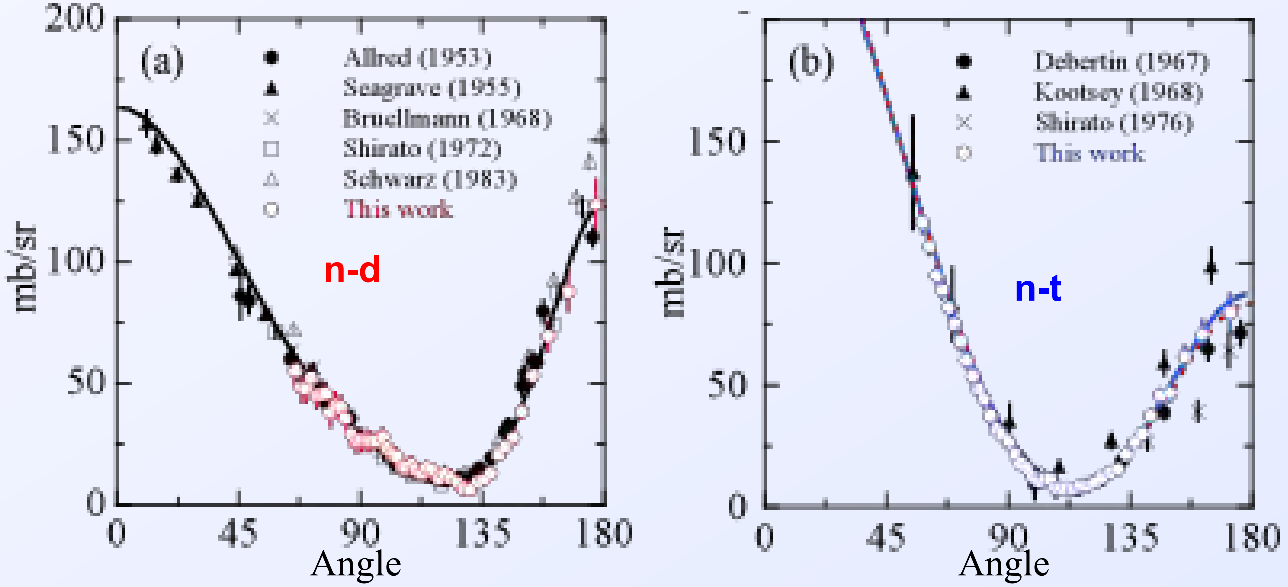
J. Frenje et al. have made the first relative nuclear cross section measurement at OMEGA

n-d scattering data normalized to Epelbaum et al. Fadeev calculations to determine absolute scale.

Resulting n-t data is of very high quality and compares very well with both ab-initio and R-matrix calculations.

Ab-initio results obtained by scaling p-3He data with calculated n-T/p-3He ratio.

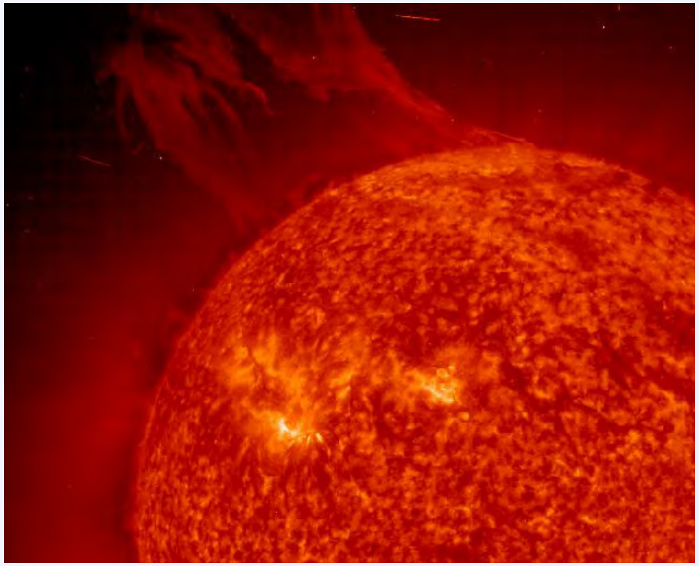
Comparison with ab initio calculations

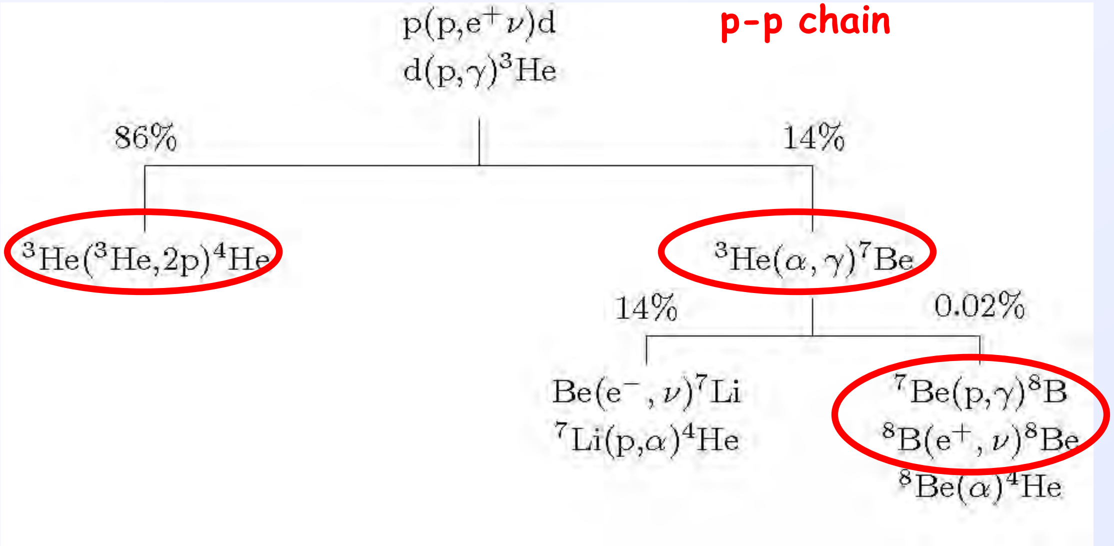


1. E. Epelbaum et al., Phys. Rev. C 66, 064001 (2002).
2. P. Navrátil et al., LLNL-TR-423504 (2010).
3. G.A. Hale et al., Phys. Rev. C 42, 438 (1990).

Suggests isobaric measurements in ICF capsules can be used to constrain calculations of pp chain cross sections in the sun: T+T for ^{3}He+^{3}He, T+α for ^{3}He+α

MIT, LLNL, Rochester, Indiana U. collaboration is pursuing measurements of ^{3}He+^{3}He and T+T at Omega & NIF





p-p chain

$p(p,e^+\nu)d$

$d(p,\gamma)^3He$

86%

14%

$^3He(^3He,2p)^4He$

$^3He(\alpha,\gamma)^7Be$

14%

0.02%

$Be(e^-,\nu)^7Li$

$^7Li(p,\alpha)^4He$

$^7Be(p,\gamma)^8B$

$^8B(e^+,\nu)^8Be$

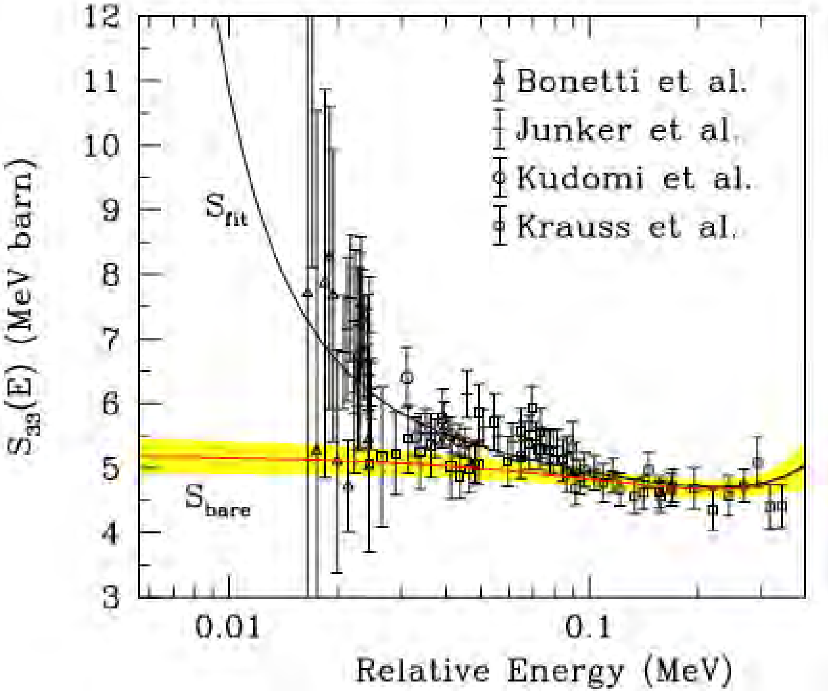
$^8Be(\alpha)^4He$

- ^{3}He+^{3}He rate sets the ratio of pp/^{7}Be neutrinos produced in the sun
  - Effects the balance of low- and high-energy neutrinos detected on earth
  - Determines sun's core temperature
- Helps develop a theoretical description of the nuclear 3-body continuum

Measurements of $^3He(^3He,2p)^4He$ and other fusion reactions near solar conditions can be uniquely carried out at ICF facilities

See Johan's talk tomorrow

Accelerator measurements of $^3He+^3He$ cross section, $\sigma(E) \cong \frac{e^{-\sqrt{E_C/E}}}{E} S(E)$, and quadratic fit, with uncertainties



Parameter	Value	Uncert.
$S_{33}(0)$	5.21 MeV-b	5%
$S'_{33}(0)$	-4.90 b	65%
$S''_{33}(0)$	22.4 b-MeV^{-1}	76%

Most uncertainty comes from screening

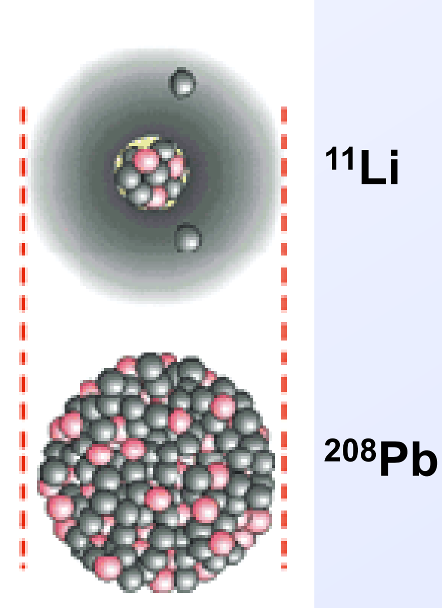
- Electron screening and radioactive backgrounds are significant systematic uncertainties in accelerator experiments
- Weakly-coupled plasmas produced in ICF implosions electron screening has no impact and data rates are very high

ICF facilities provide a unique opportunity to study an important problem in nuclear physics: 3-body states

- Exotic nuclei (borromean halos, dripline nuclei)
  - ^{6}He (= $\alpha + n + n$)
  - ^{6}Be (= $\alpha + p + p$)
  - ^{11}Li (= ^{9}Li + $n + n$)
  - ^{14}Be (= ^{12}Be + $n + n$)
  - …

T+T not available at accelerator facilities

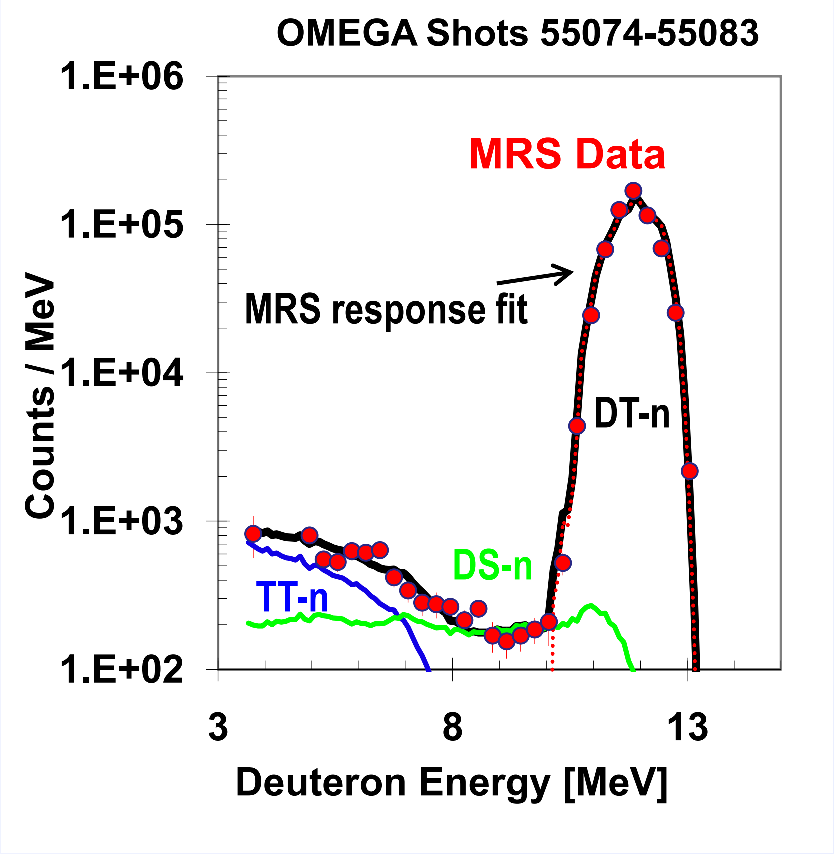
- Three-body breakup reactions
  - $T + T \rightarrow \alpha + n + n$ (*n* emission in HT(D) plasma)
  - $^3He + {}^3He \rightarrow \alpha + p + p$ (*p-p* chain)
  - $\alpha + \alpha + n \rightarrow {}^9Be + \gamma$ (with $^9Be(\alpha,\gamma)^{12}C$, ^{12}C production)
  - any reaction above three-body breakup threshold
- Virtual breakup below three-body breakup threshold
  - *e.g.*: $p + {}^7Be$ (~ $\alpha + {}^3He$) $\rightarrow {}^8B + \gamma$ (standard model of solar neutrinos)
  - whenever target (projectile) is weakly bound



Borromean halo nuclei are two particles and a nucleus weakly bound together

Understanding these nuclei and reactions require us to treat 3-body continuum states

D. Casey has analyzed T-T neutron spectra in DT implosions – The results are very encouraging

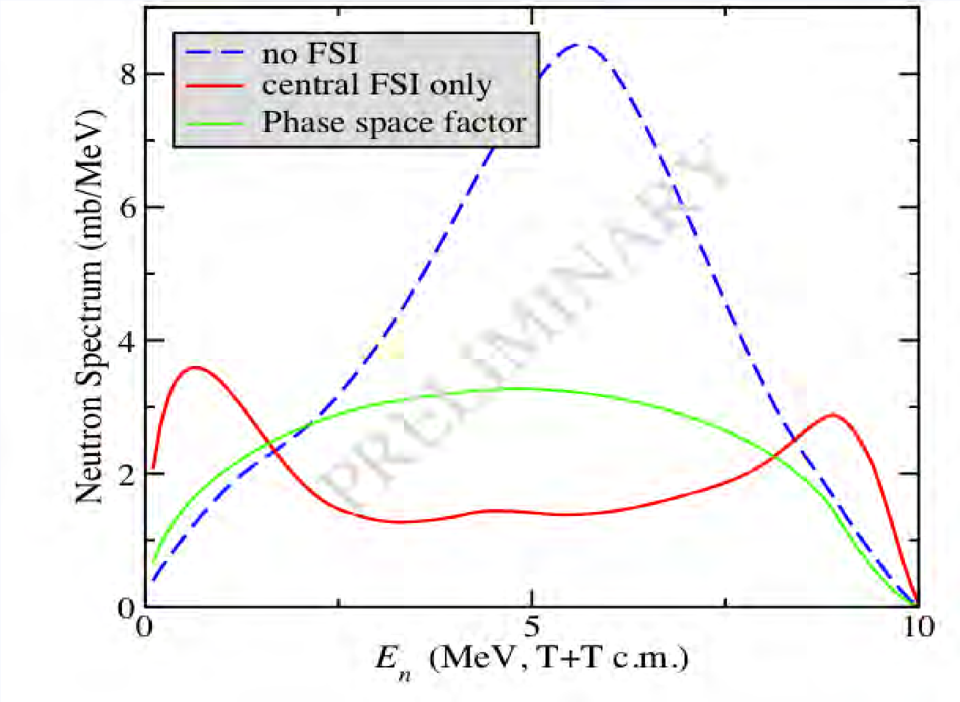


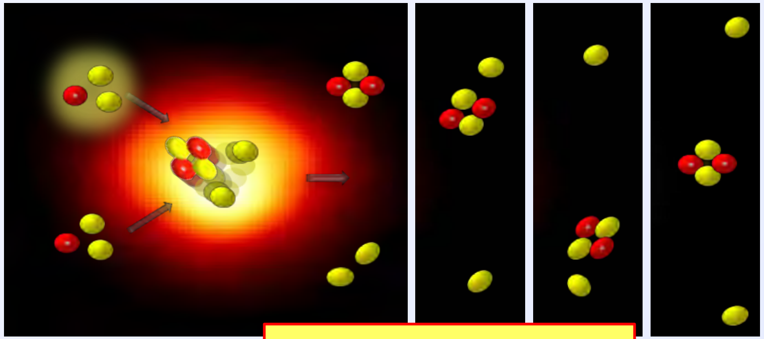
Collaboration is proposing to improve on this work

- Pure ~99% tritium fill
  - Removes main source of background
  - Increases yield
- High resolution mode for MRS
  - Thinner conversion foil
- Detect alphas
  - Spectral shape also depends on final state interactions
- High temperatures

Flexible tritium fill capability is a clear need
Low-energy, spectral neutron detector would be very useful

With an accurate measure of particle spectra produced in T(T,2n)^{4}He we might be able to interpret the 3-body final state effects

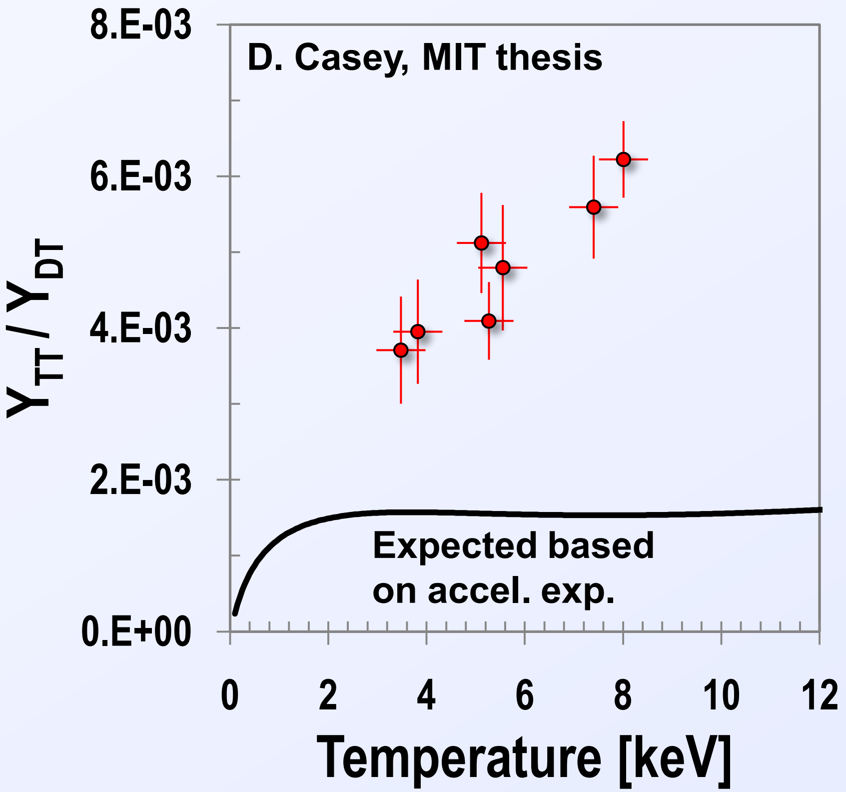




All are part of ^{6}He(^{6}Be) continuum

- **Phase space considerations not enough**
  - Initial structure of ^{3}H(^{3}He) influences final configurations
- **Fragments are subject to three- and two-body final-state interactions**
  - Two-body final-state interactions can persist at larger distances
  - All these contributions interfere and affect the shape of the energy spectra
- **There is no real distinction between two- and three-body breakup effects**
  - Two-body breakup mechanisms are really a manifestation of the three-body continuum

The scaling of T-T yields poses an intriguing puzzle

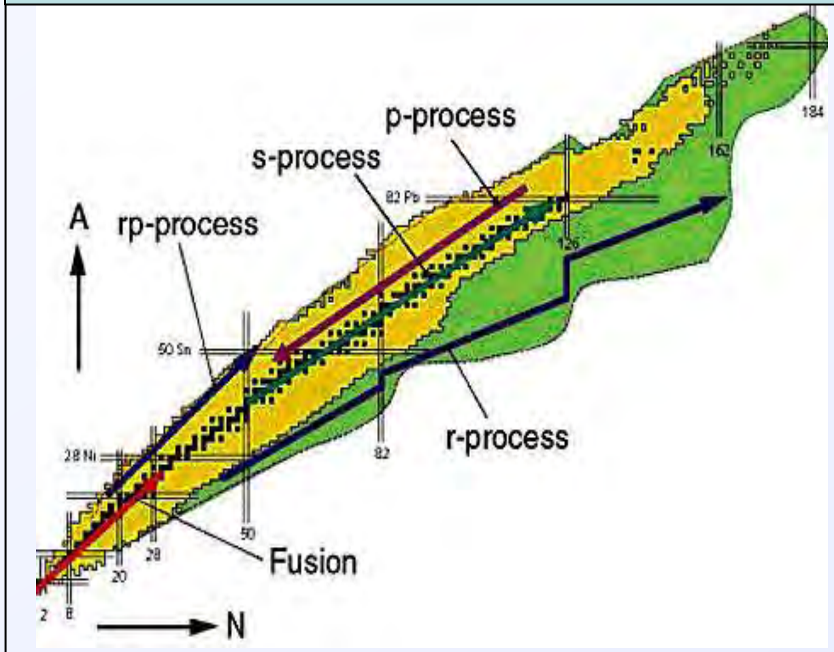


See Dan's Poster this afternoon in Session II

- Is the T-T cross section wrong?
- Are the T and D ions segregating?
- Are the T and D ions uncoupled and at different temperatures?

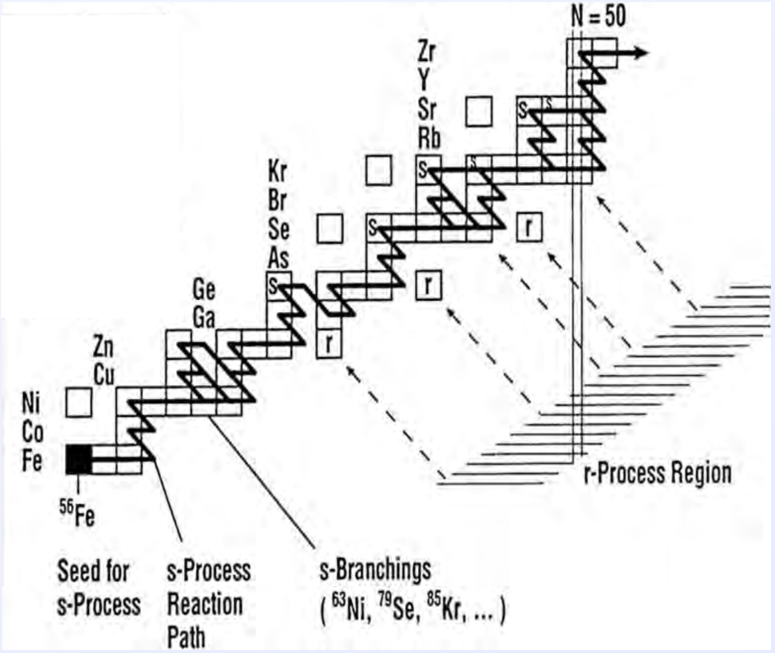
NIF as a “red giant”
Measuring nucleosynthesis at s-process branch points

S-process abundances depend on the stellar environment



Temperature
Density
Pressure
Convection mixing

Branch points, where β-decay and n-capture compete, a measure of neutron density



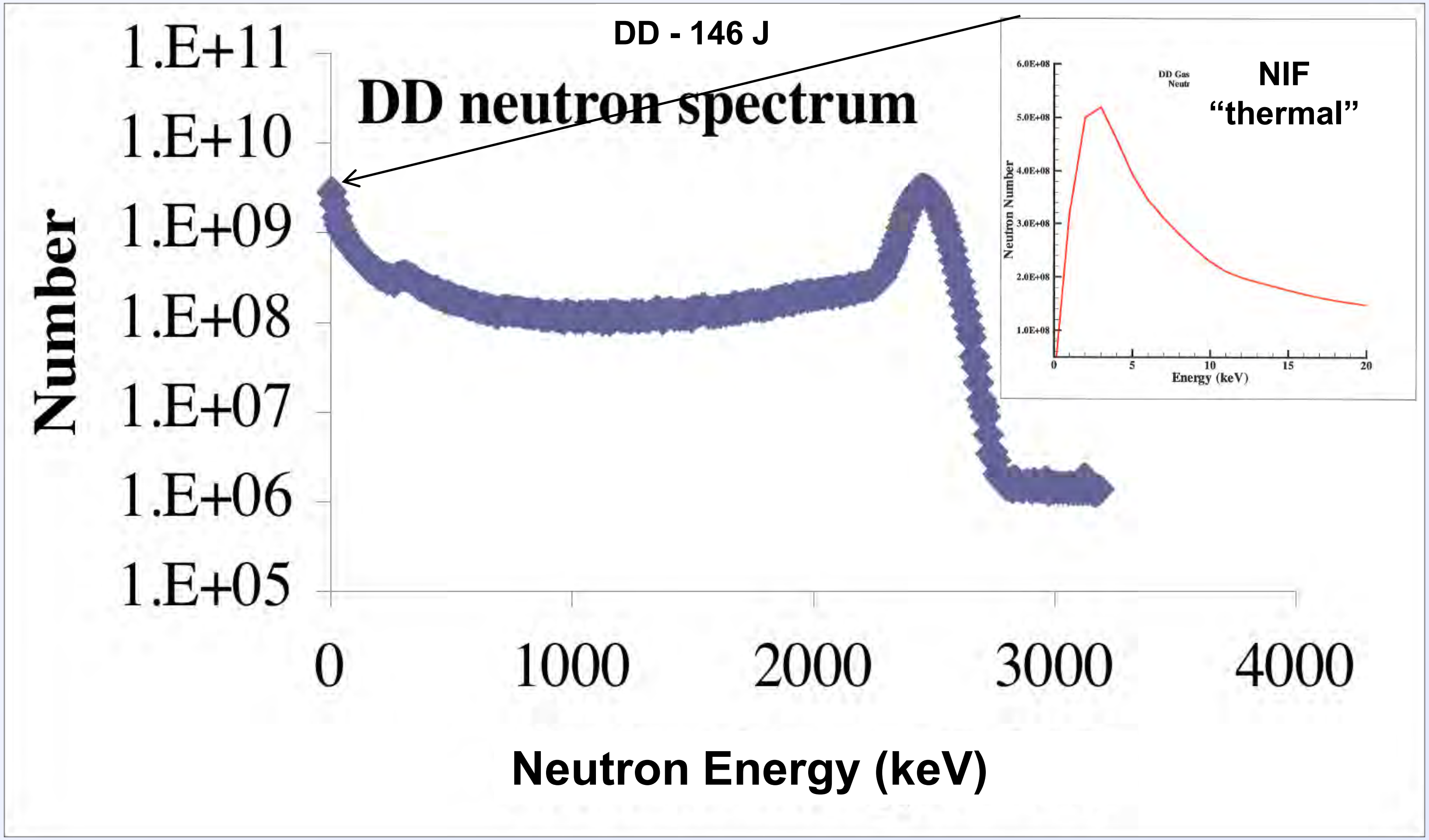
Short-lived s-process branch point nuclei include:

^{79}Se, ^{85}Kr, ^{147}Pm, ^{151}Sm, ^{163}Ho, ^{170}Tm, ^{171}Tm, ^{179}Ta, ^{204}Tl, ^{205}Pb

Branch point nuclei are typically short-lived making cross section measurements difficult or impossible; targets are radioactive and difficult to fabricate

OMEGA research into cryogenic DD capsules could enable high neutron flux and “stellar” conditions for n-capture measurements

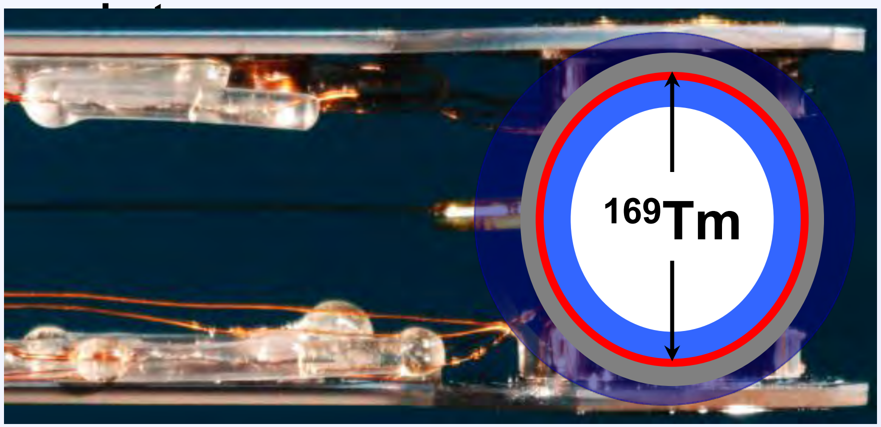
Simulation courtesy of C. Cerjan



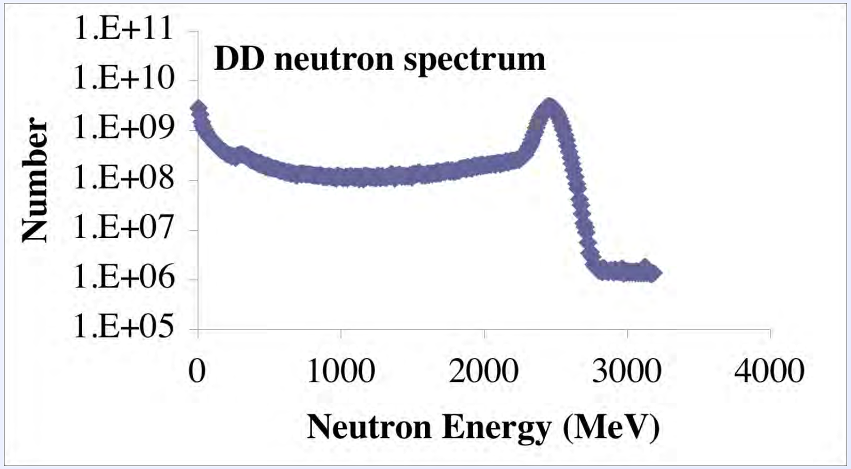
Simulations predict low energy, high-flux neutron spectrum from DD capsules

Slow neutrons convert to gamma-rays in (n,γ) reactions: neutron spectra, capture rates and products need to be measured

1) Load as few as 10^{15} atoms into the inner ablator of a DD or DT capsule pre-

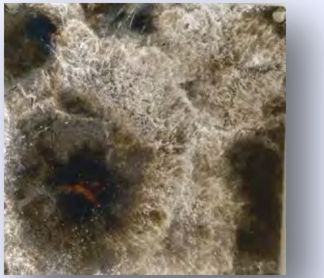


2) Subject to “tailored” neutron spectrum/plasma conditions



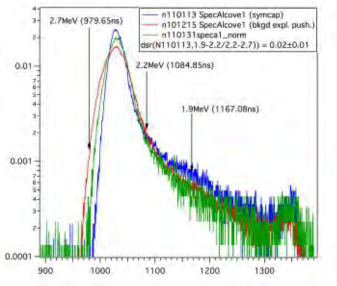
3) Measure reaction products using prompt γ□s & solid collection radchem

Gamma Reaction History

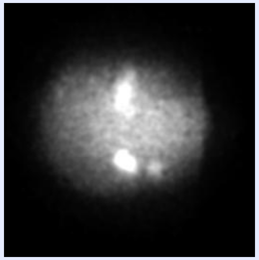


Radchem debris

4) Measure $\phi_{neutron}$, T_{ion}, ρR_{Tm} using nToF, hohlraum capture γ□s & X-ray imagers



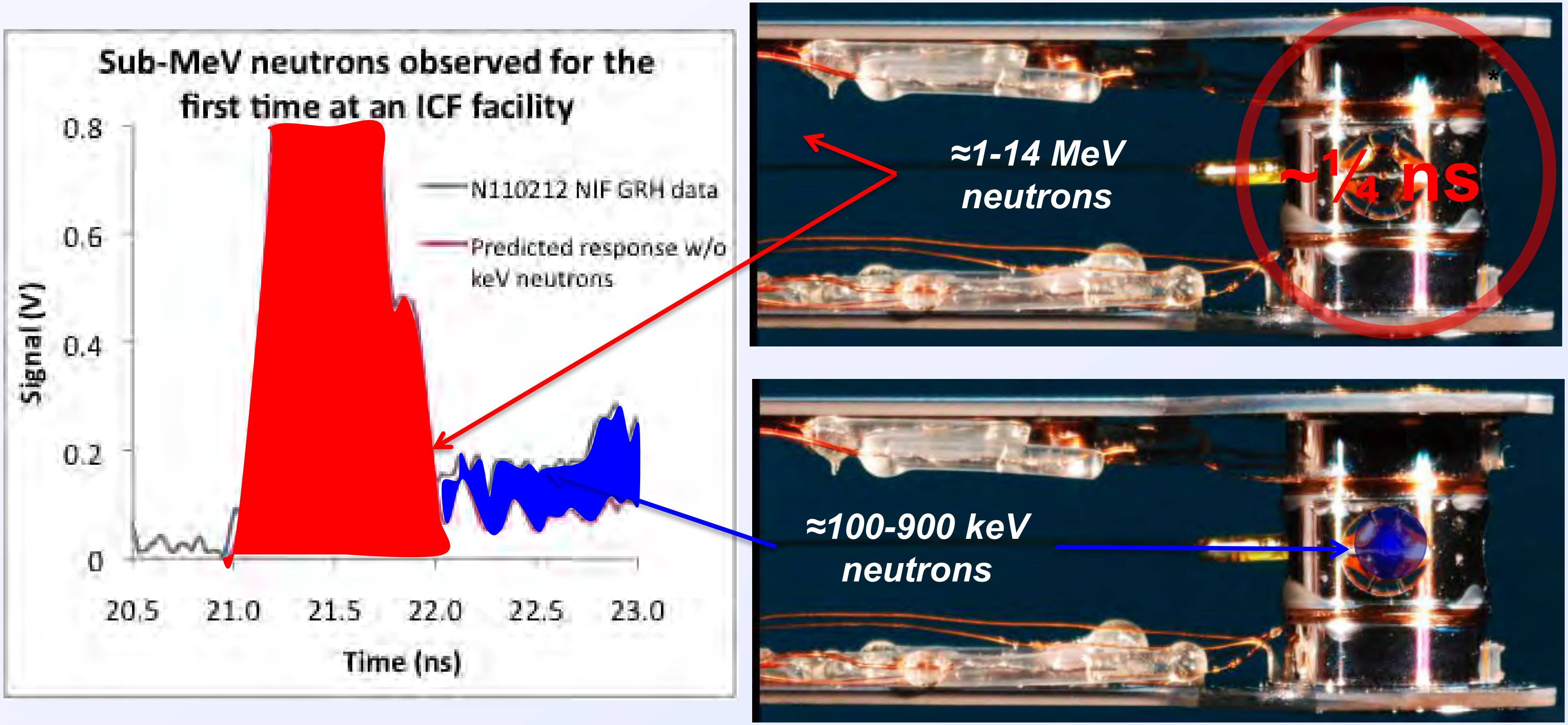
DD nToF data



X-ray Image

Prompt capture γ-rays from gold hohlraum late in time would be indicative of neutrons with E_n < 1 MeV

Effort being spearheaded by Lee Bernstein



≈1-14 MeV neutrons

~¼ ns

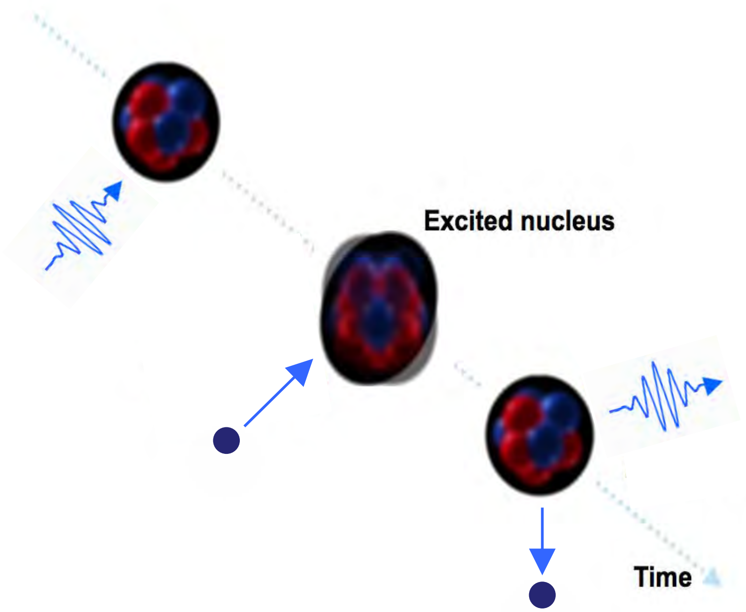
*

≈100-900 keV neutrons

Initial results seem to be promising

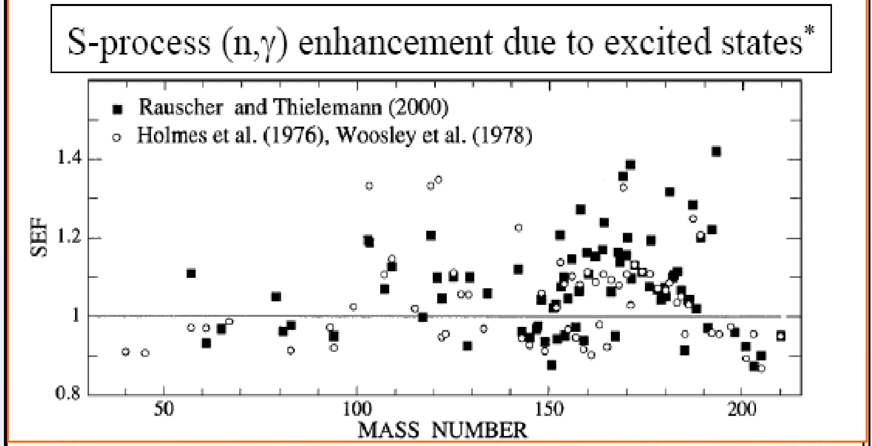
Nuclei in a burning plasma need not be in their ground state

Atomic and nuclear interactions lead to a distribution of nuclear states



- **Neutron and charged-particle scattering**
- **Atomic-nuclear coupling**
- **Plasma environment enhances coupling**

Relevant plasma environments occur in astrophysics and ICF


S-process (n,γ) enhancement due to excited states*

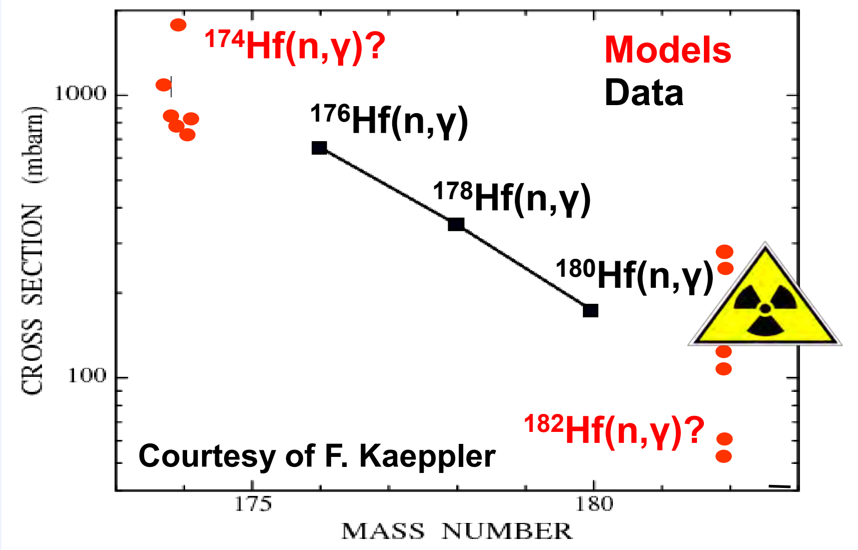
S-process (n,γ) is affected by excited states
Known as "stellar enhancement"

- **Nucleosynthesis**
- **Neutron capture**
- **Fission**

Burning plasma environments excite nuclei through several mechanisms, which leads to a change in the effective cross section

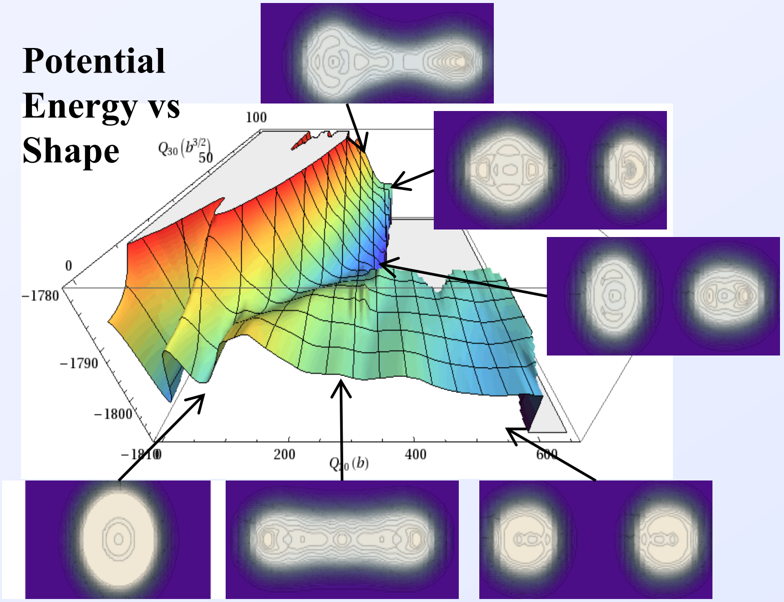
Nuclear cross sections can be very sensitive to small changes

Experimental data is key when heading into unknown territory



- Neutron capture
- Fission

High performance computing is driving a renaissance in nuclear theory

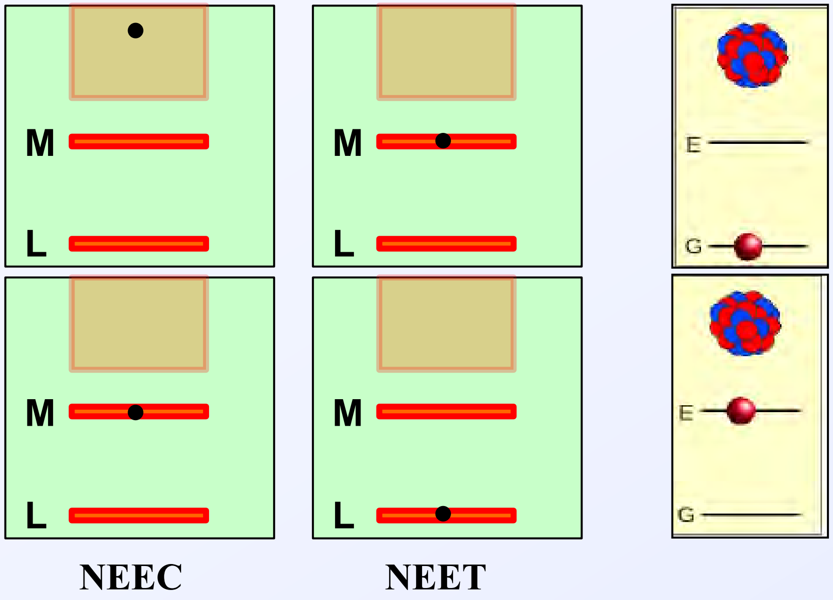


- Fission -- The “impossible” problem
- Funded by DOE/SC/NP and ASC/PEM

Need both theory and experiments to tie down phenomenological nuclear models which are used because of limited resources

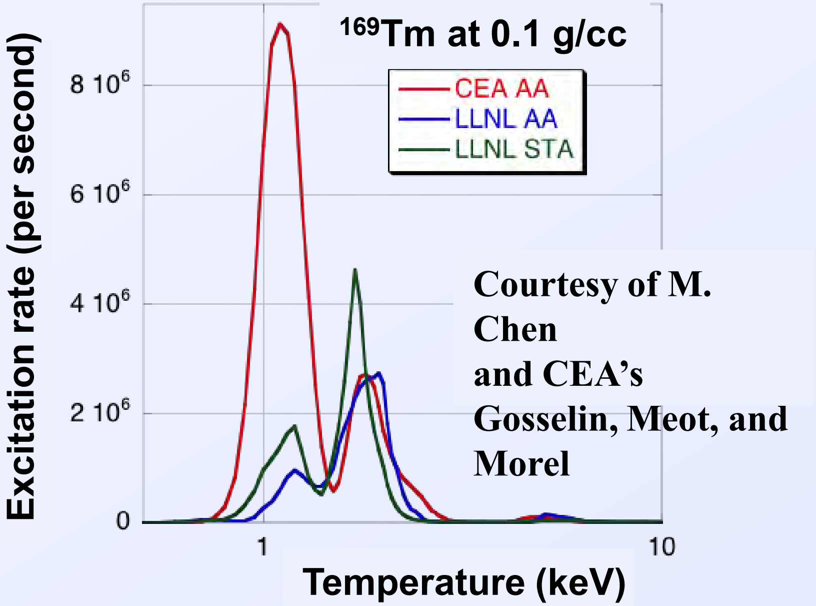
In a burning plasma, plasma-nuclear interactions lead to the population of nuclear excited states

Various electronic configuration transitions can couple to the nucleus



- Higher-order terms not yet considered
- Probes higher energies more than Rosseland opacity calculations

Initial calculations indicate that resonant bound-bound dominates



Courtesy of M. Chen and CEA's Gosselin, Meot, and Morel

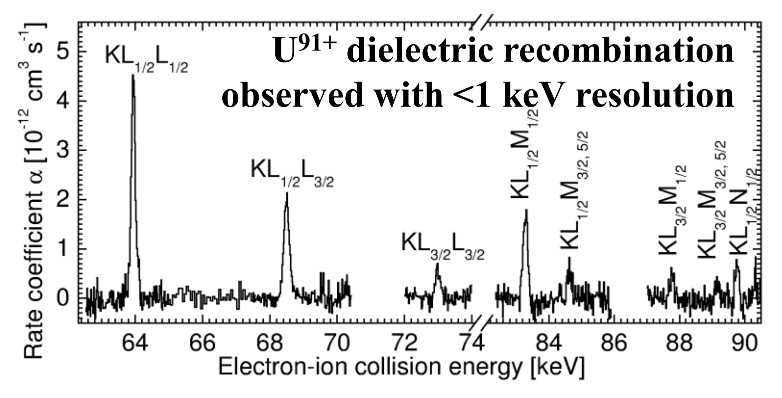
- Uncertainties are large
- Plasma rates have not been experimentally observed

Nuclear distributions evolve in time and might not be in thermodynamic equilibrium

There are exciting nuclear-atomic science opportunities at Omega and the NIF that complement other international capabilities

Storage ring: Precision measurements of nuclear-atomic interactions

Idea is to observe NEEC after cold U beam passes through electron beam



D. Bernhardt et al. Phys. Rev. A83 020701(R) (2011); C. Kozhuharov is GSI leader

- Collaboration with GSI, German Univ,, CEA

NIF offers the potential for plasma-nuclear experiments

Idea is to populate first excited state and observe its decay after laser is turned off

Lasers can be used to create hot plasmas

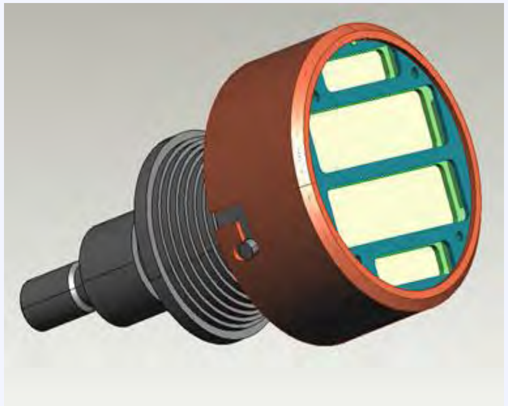
A. Kritcher, Lawrence fellow, is PI proposing to develop techniques at LLE

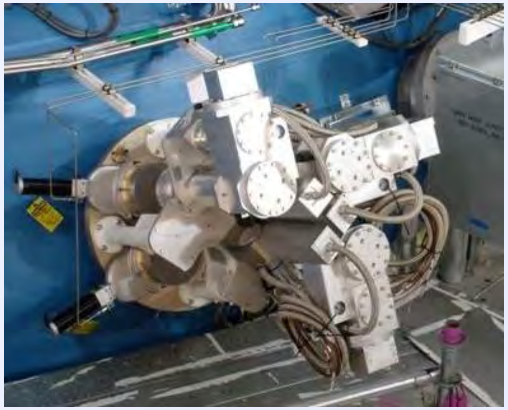
- Collaboration with CEA, LLE, GSI

Now is the time to validate and improve theory

LLNL is adding capabilities to model dynamic, multi-physics experiments which is key to leveraging unique capabilities of ICF facilities

OMEGA will clearly have a leadership role in the development of next-generation nuclear diagnostics for science experiments





- Charged-particle, neutron, and gamma detectors
  - Low-energy spectral information still needed
- Electron and photon decay can occur over many time scales
  - Delayed counting capabilities useful for cross section measurements
  - Radiochemical debris collection for longer counting times

Attend Maria Gatu's talk in breakout session

"Standard" nuclear physics capabilities necessary to maximize nuclear science

The OMEGA community is in the best position to prioritize and coordinate

There are compelling science questions at the interface of nuclear and plasma physics

- ICF has a role in fundamentally understanding fusion reactions
  - 3-body continuum, Electron screening, S-factors
- ICF has potential for studying neutron capture nucleosynthesis reactions
  - s process measurements on short-lived states?
- Can we come up with concepts to study nuclear-plasma interactions?
  - Nuclear level populations in burning plasma

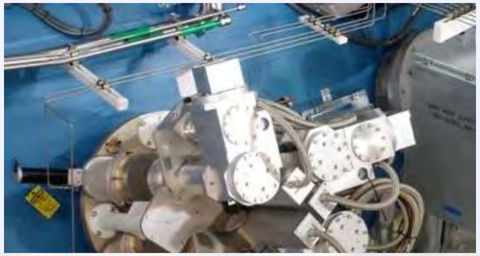
Success in these areas of nuclear physics has the potential to open new windows for understanding HED plasma physics.

Backup slides

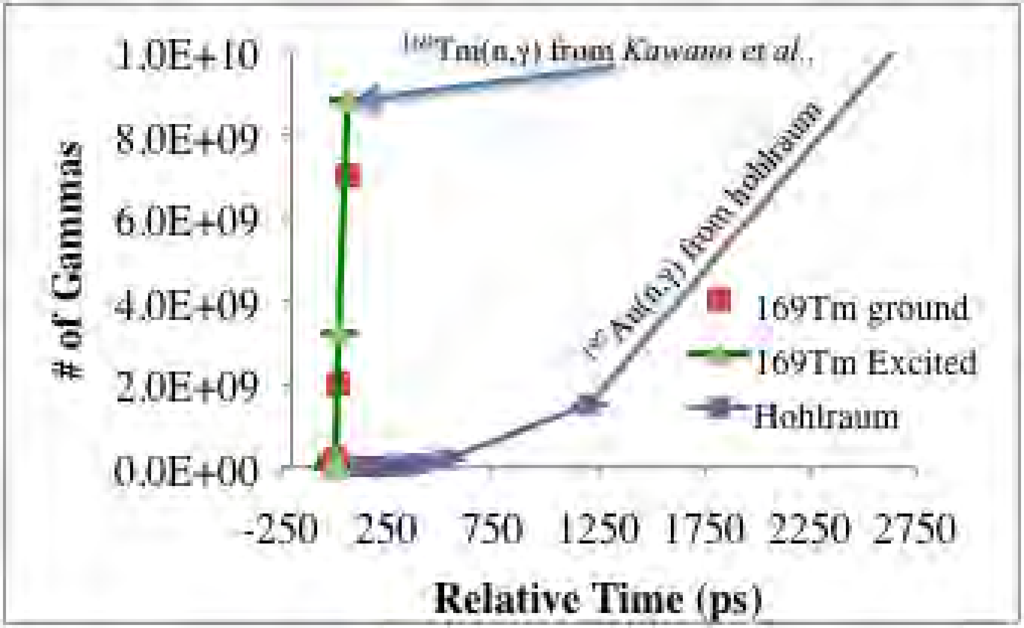
EXTRAS

Slow neutrons convert to gamma-rays in (n,γ) reactions: n spectra and capture rates measured using energy and time-resolution

^{169}Tm is loaded in or ar
And neutrons interact v



Cherenkov-based gamma-ray history diagnostic provides time-resolved, high-energy gamma-ray measurement

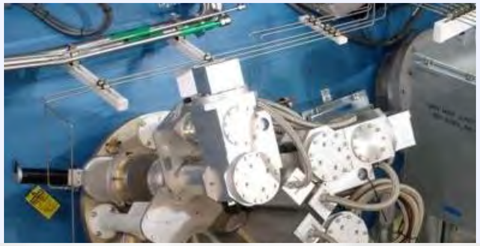


OCL Oslo Cyclotron Laboratory

Berkeley Lab

Universitas Carolina
Charles University in Prague

Slow neutrons convert to gamma-rays in (n,γ) reactions: n spectra and capture rates measured using energy and time-resolution



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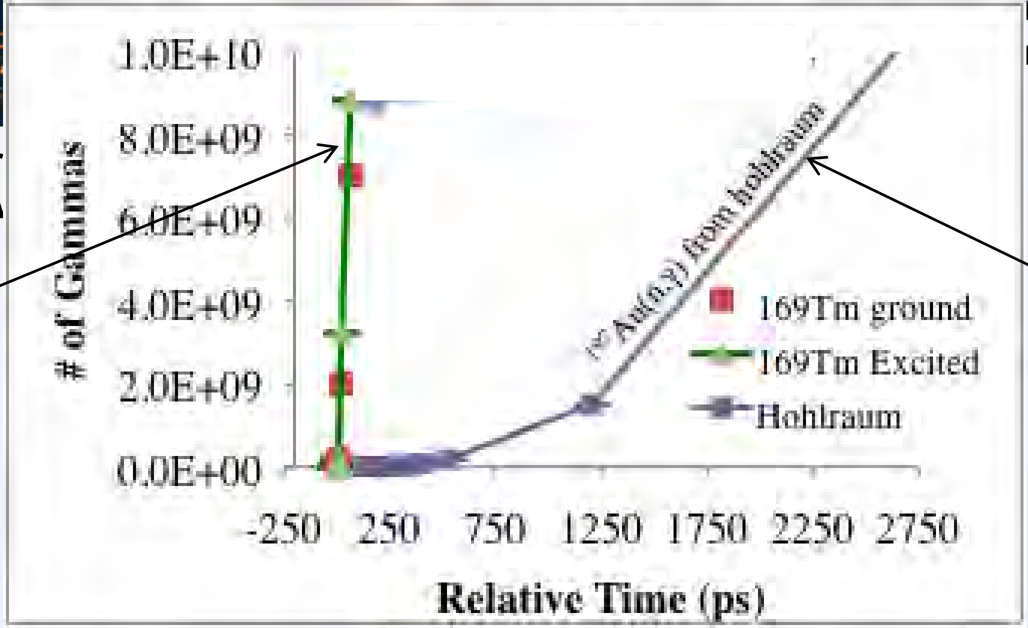


Prompt signal from capture on ^{169}Tm

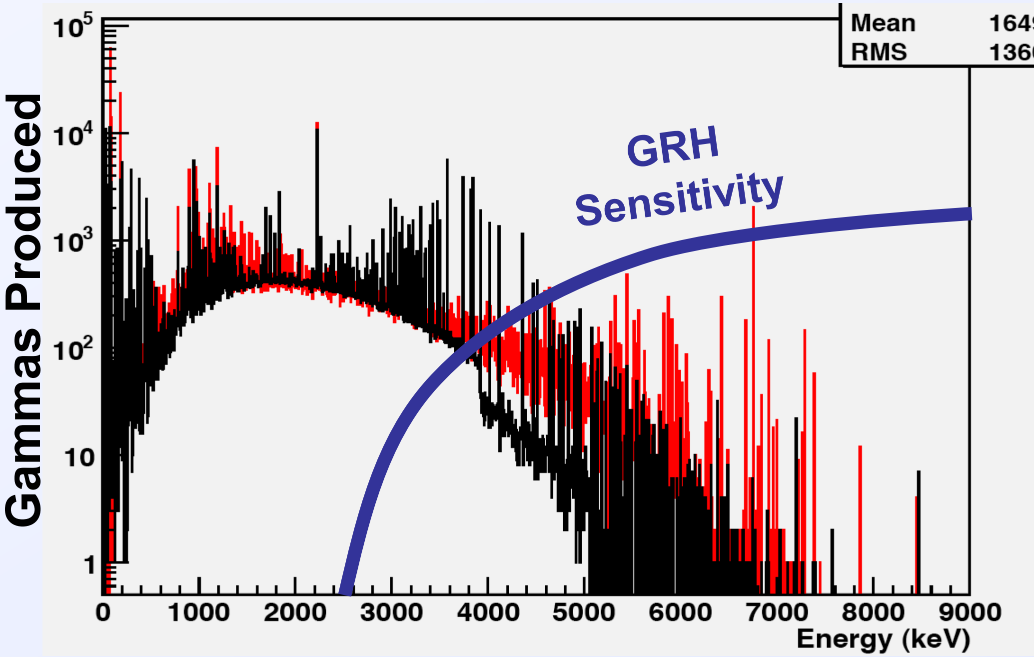
Delayed signal from capture on ^{197}Au hohlarum provids spectrm

OCL
Oslo Cyclotron Laboratory
Berkeley Lab
Universitas Carolina
Charles University in Prague

One of the main technical challenges is to relate the signal strength measured by GRH to the number of (n,γ) events

What we need: the efficiency for “seeing” a (n,γ) product with GRH

$$\frac{N_\gamma^{Tm}}{N_\gamma^{Au}} = \frac{\int \varepsilon_{Tm}^{\gamma}(\rho R)_{Tm}\,\sigma_{Tm}(E_n)\phi(E_n)\,dE_n}{\int \varepsilon_{Au}^{\gamma}(\rho R)_{Au}\,\sigma_{Au}(E_n)\phi(E_n)\,dE_n}$$



Other technical issues:

- Loading material into capsules
- Capsule design
- Non-uniformities
- Low efficiency of GRH

NIF may be the first facility to directly measure cross sections on very short-lived targets, not possible at accelerator facilities