Using statistical γ-ray spectra to measure astrophysical (n,γ) at NIF

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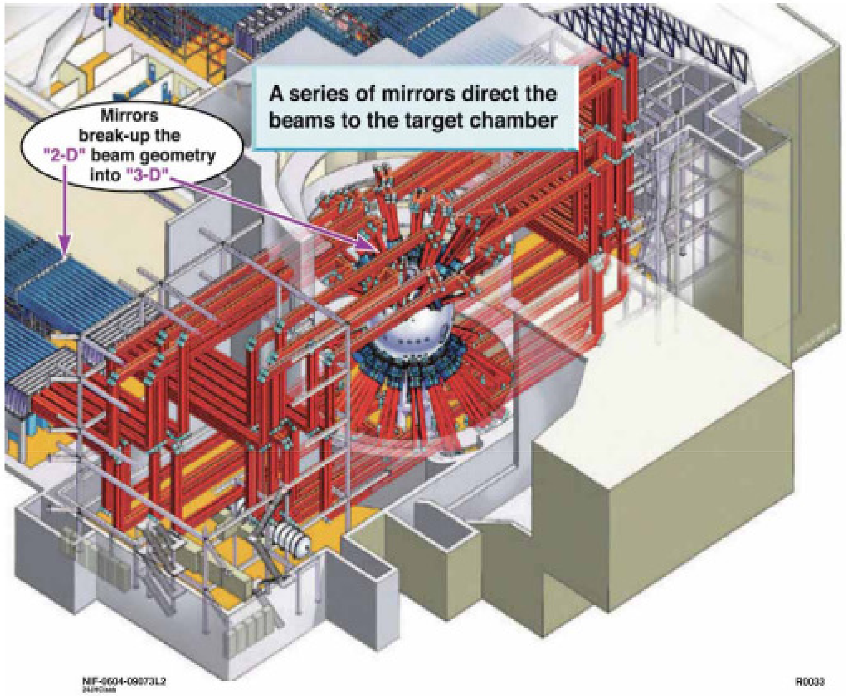
NIF-National Ignition Facility



NIF Laser System: 192 laser beams produce 1.8 MJ, IR-UV→ 3ω=352nm, 2+ ns, 5x10^{14} Watt in 1mm^2 spot)

Diagnostics (≈$90 M in FY11)

•**X-ray diagnostics**: ≈20 spectral, imaging and time-resolved diagnostics are planned/operational (developed over 25 years at NOVA, Omega etc.)

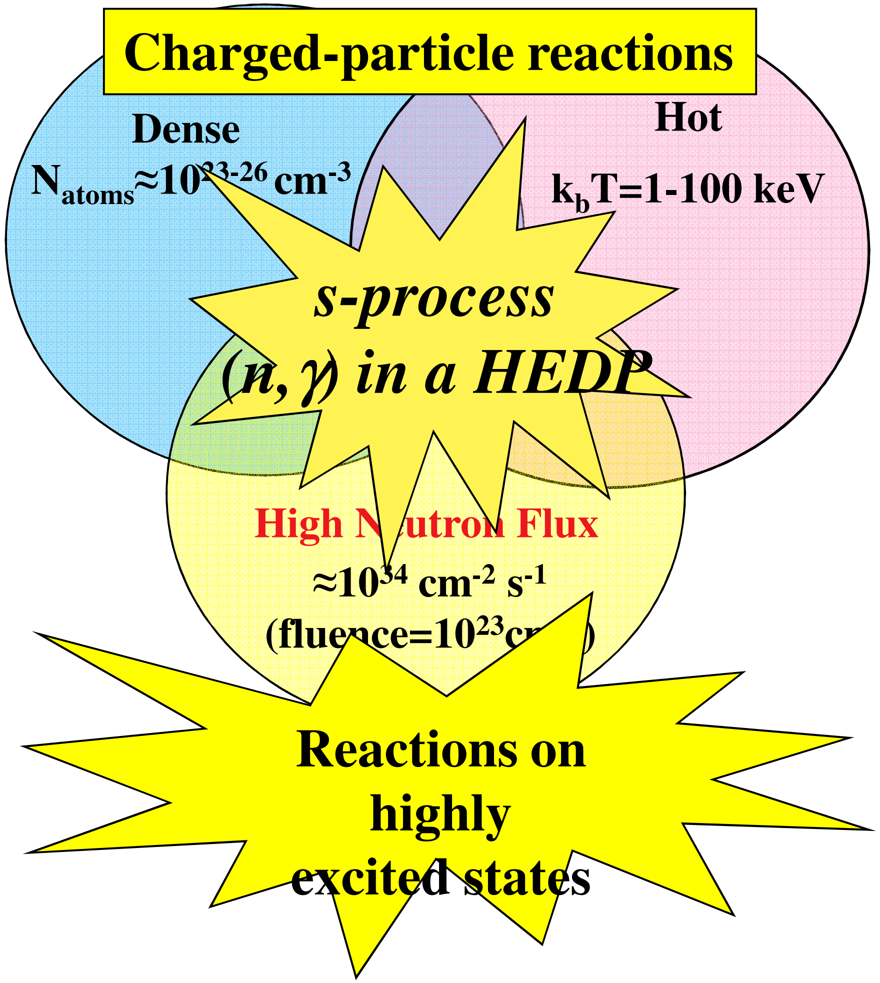
Very mature field

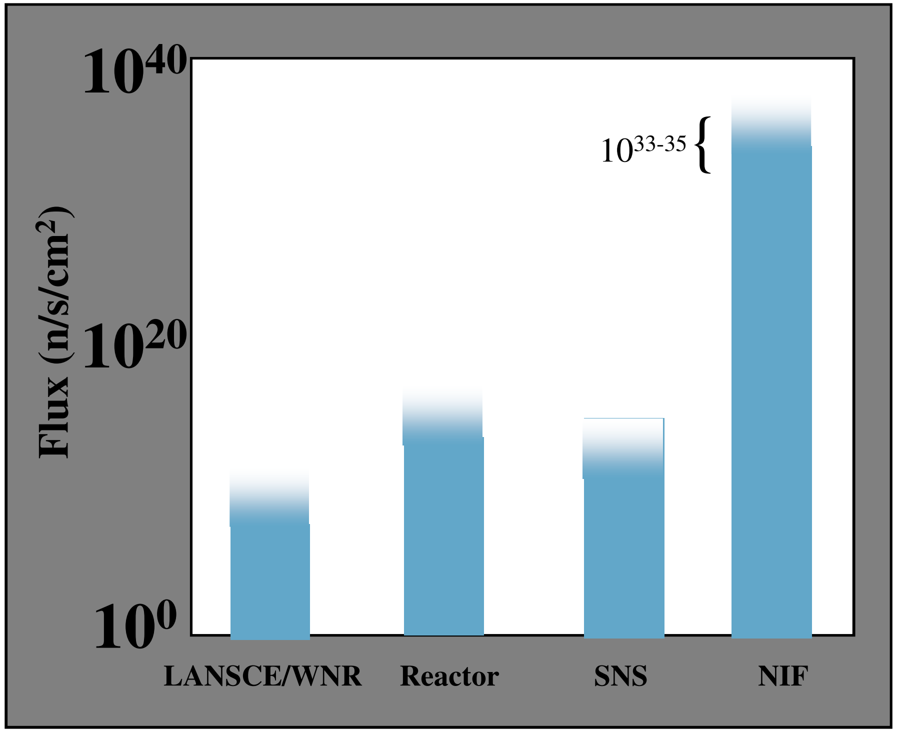
•**Nuclear Diagnostics**: 10 types of diagnostics are planned/operational
- nToF, Neutron imaging, Activation, Charged-particle spectrometry, Radchem, *Gamma Reaction History*

First proposal call has gone out (reviews in progress)

("Ride along" experiments often allowed)

NIF open new avenues of research in nuclear physics

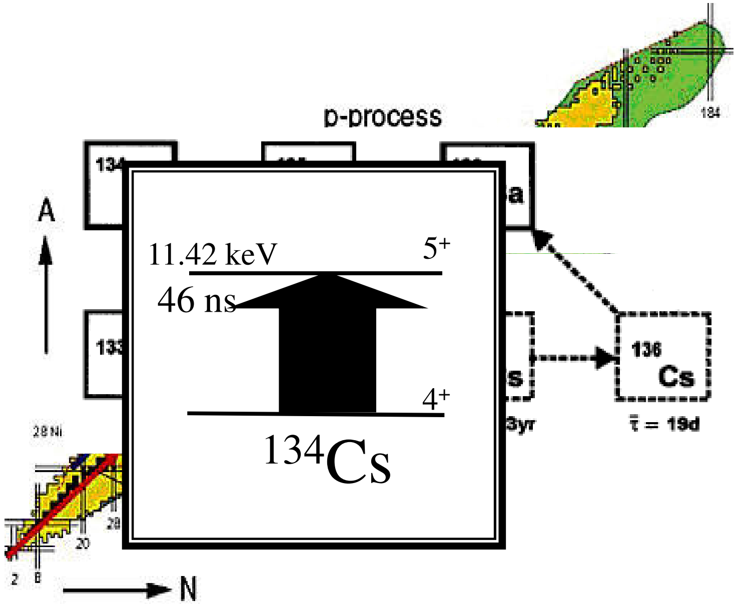




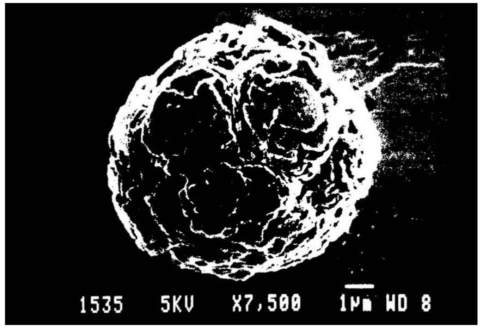
Common theme: Reactions on excited states

Nearly half of the elements are made via neutron capture *in a stellar plasma*

AGB stars ➔
disperse elements



Pre-solar grains



Required information: (n,γ) cross sections
on a thermal population of excited nuclear states
These experiments require an ICF environment

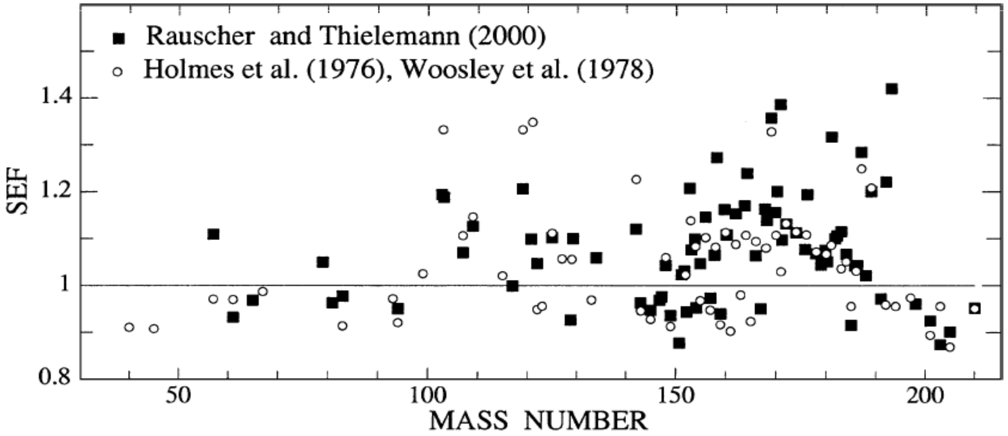
Busso, Gallino and Wasserburg, Annu. Rev. Astron. Astrophys. 1999. 37:239–309

Many important* s-process branch point nuclei have HEDP-populated low-lying excited states

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

$$SEF(kT) = \frac{\sigma_{HEDP}}{\sigma_{GS}} = \frac{\sum_{i=0}^{\infty}(2J_i+1)\sigma(E_x = E_i)e^{-E_i/kT}}{\sigma_{GS}\sum_{i=0}^{\infty}(2J_i+1)e^{-E_i/kT}}$$

*Bao & Kappeler At. Dat. Nucl. Dat. Tables **76,** 70–154 (2000)



Branch Point	Gnd State J^π	1st Exc. State E_x (keV)	1st Exc. State J^π
^{79}Se	**7/2+**	**95.77**	**1/2-**
^{85}Kr	9/2+	304.871	1/2-
^{147}Pm	**7/2+**	**91.1**	**5/2+**
^{151}Sm	**5/2−**	**4.821**	**3/2-**
^{163}Ho	**7/2−**	**100.03**	**9/2-**
^{170}Tm	**1-**	**38.7139**	**2-**
^{171}Tm	**1/2+**	**5.0361**	**3/2+**
^{179}Ta	**7/2+**	**30.7**	**9/2+**
^{204}Tl	2-	414.1	4-
^{205}Pb	5/2-	703.3	7/2-
^{185}W	**3/2-**	**23.547**	**1/2-**

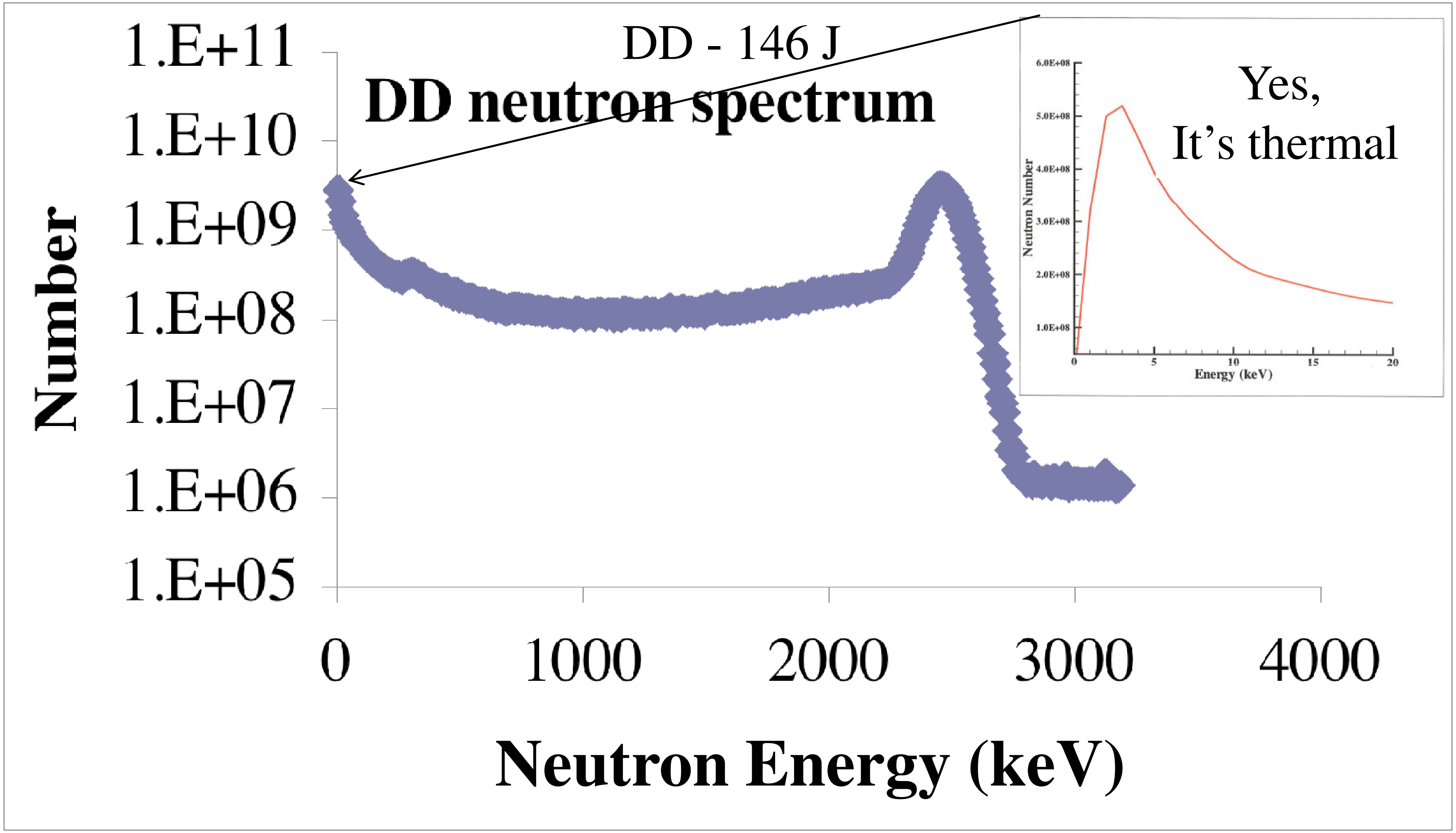
NIF (or LMJ) are the *only* places where (n,γ) might be measured on ground+excited states

How do you measure an astrophysical (n,γ) cross section at NIF?

1. Create the correct environment (neutrons, T, ρ)
   - Fuel load and moderation environment
2. Get the material into the capsule
   - Ion-implantation
3. Measure target areal density
   - Energy resolved X-ray imaging
4. Measure the number of reactions and the neutron spectrum
   - Prompt γ-ray detection using Gas Cerenkov Detectors

All of this is from a diagnostician's standpoint

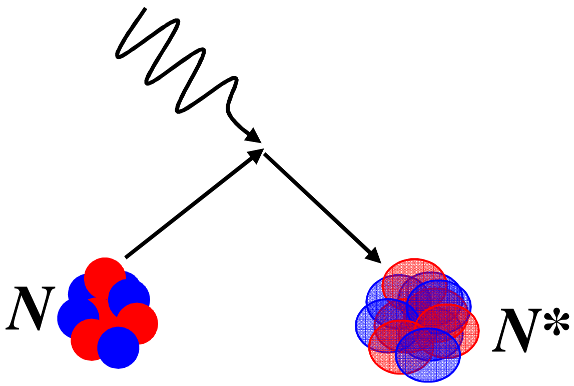
Step 1: Varying the fuel loaded creates wide range of neutron spectra



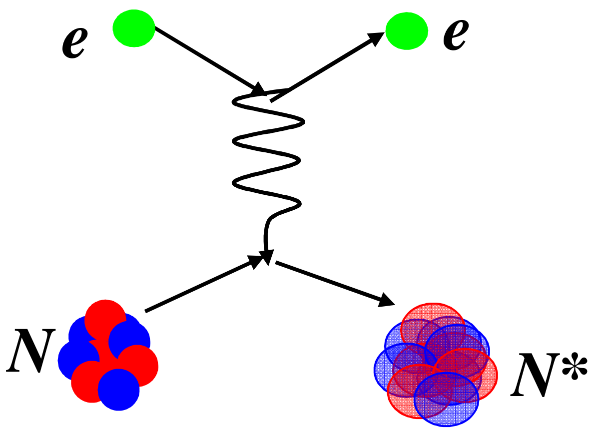
(Modeling courtesy of C. Cerjan)

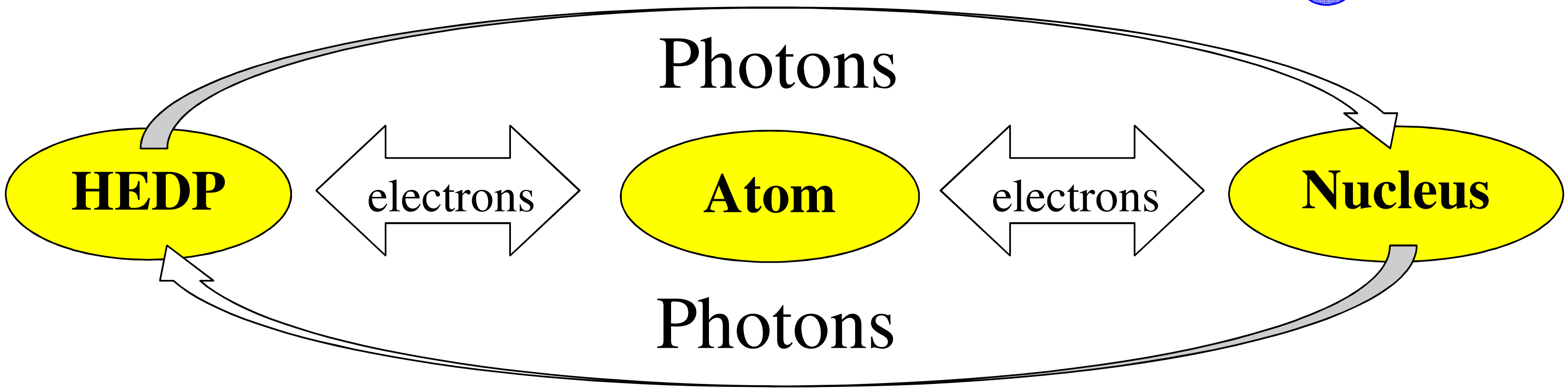
Step 1: Nuclear-plasma interactions in the HEDP can cause thermal population of low-lying nuclear states

Photo-absorption
Time Reverse: γ-ray decay



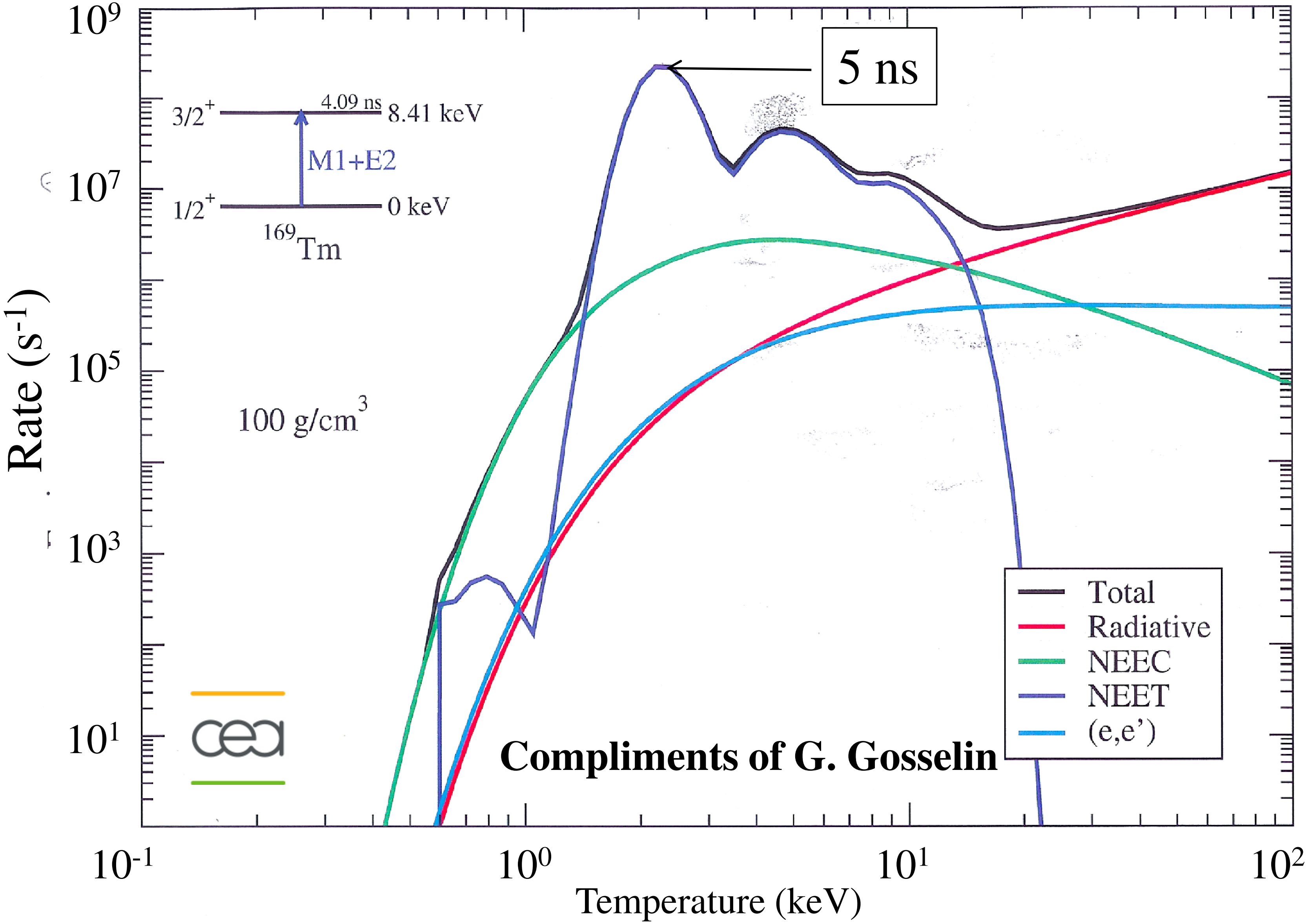
Atomic-nuclear (electron) interactions
NEEC, NEET, IES*
Time Reverse: IC-decay





Electron-mediated interactions are most important at *T*≈keV

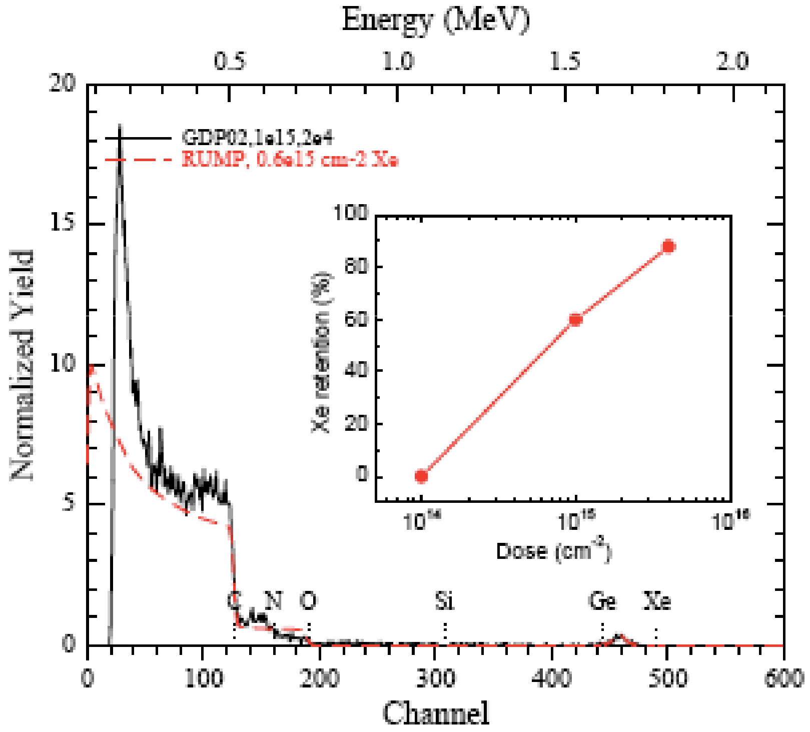
Thermalization time scales for ^{169}Tm

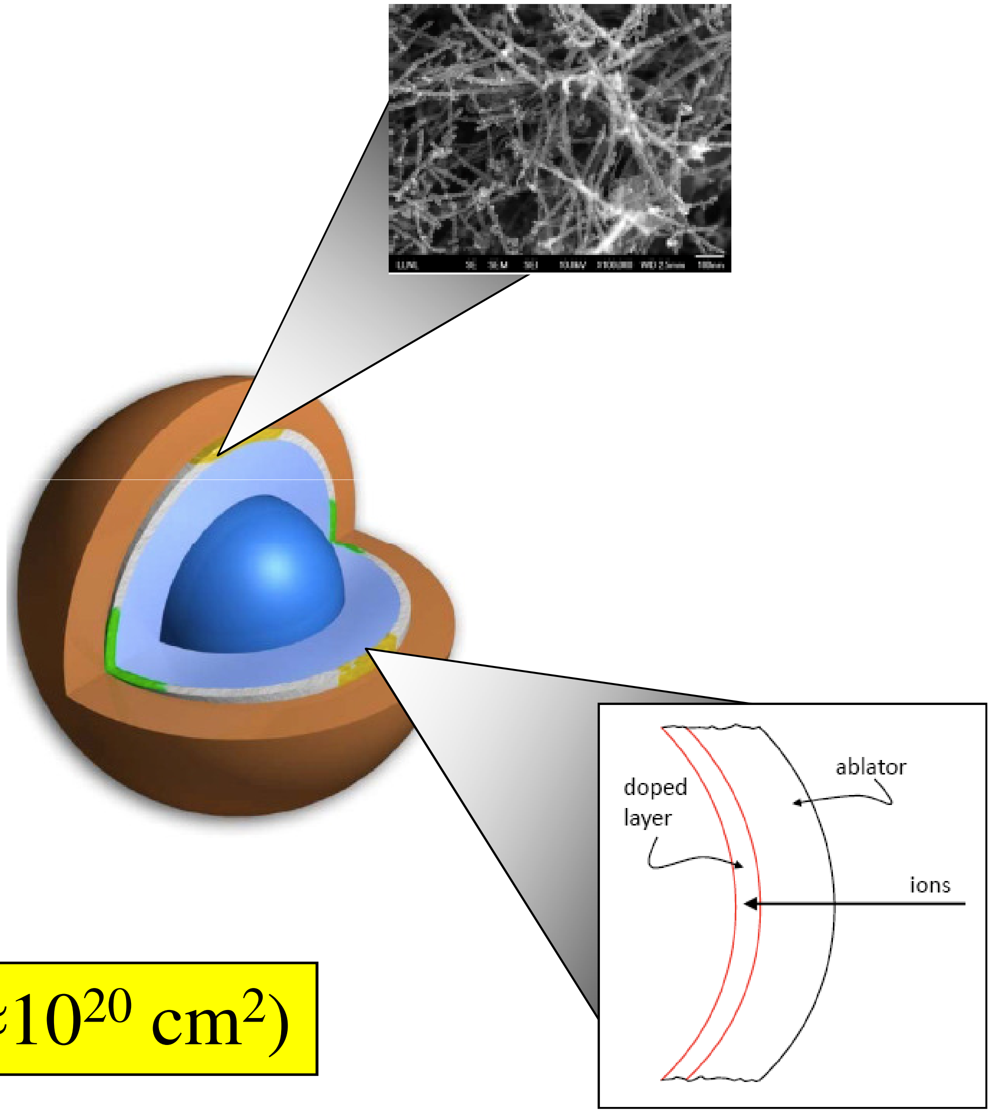


Compliments of G. Gosselin

Step 2: D-loaded capsules can be made using a Carbon nanofoam "scaffold" into which ions are implanted*

Ion implantation of Xenon

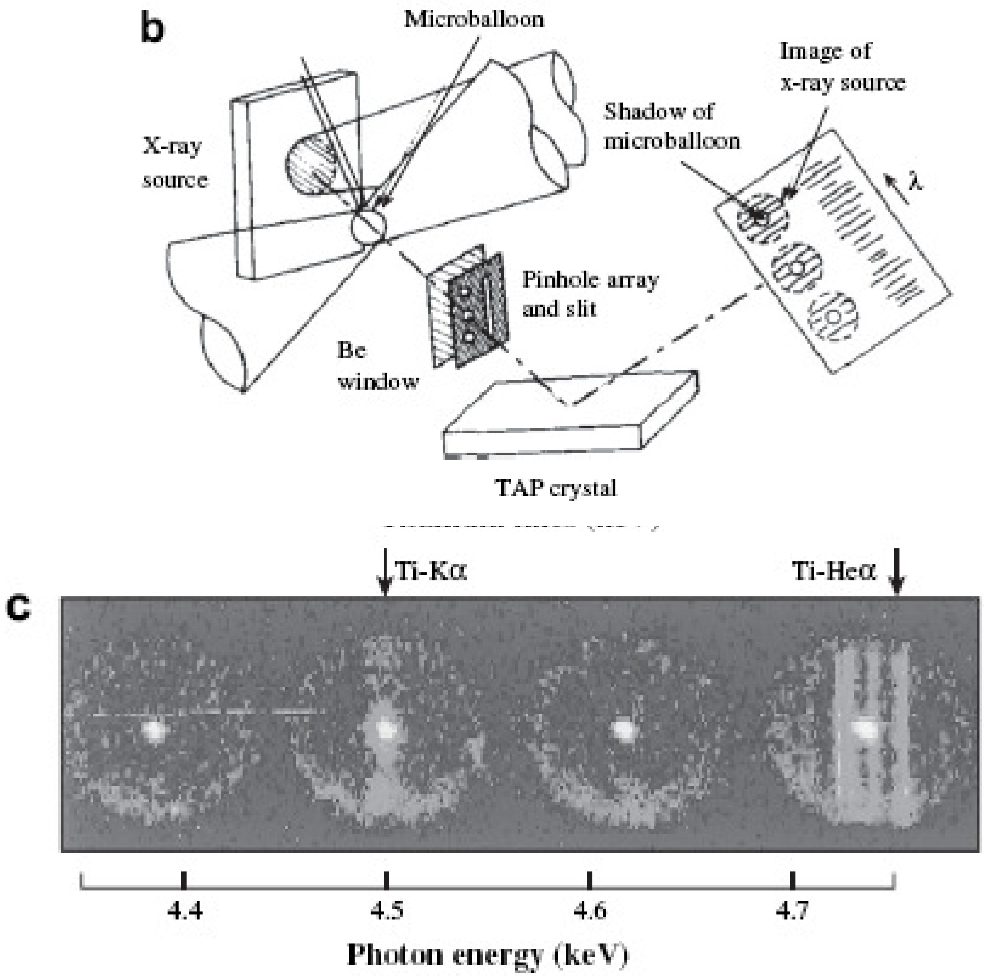


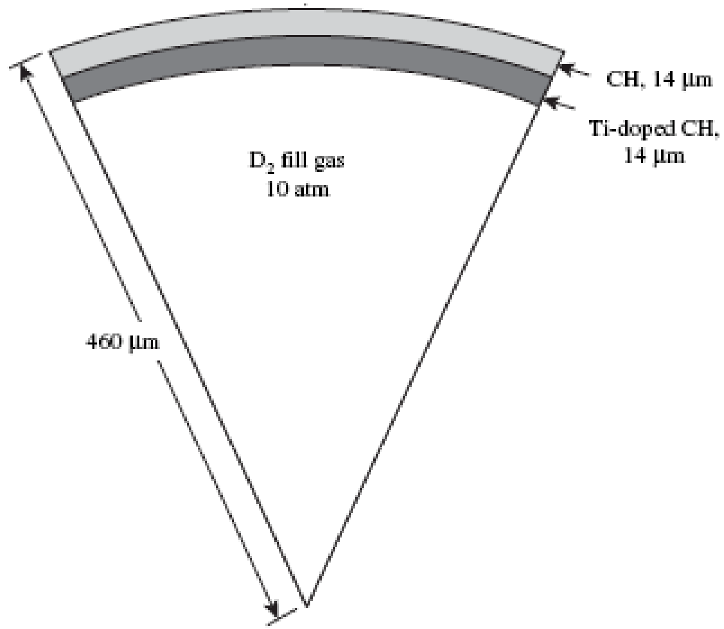


Maximum loading: 10^{16} ($\approx 10^{20}$ cm^2)

*courtesy of S. Kucheyev/A. Hamza

Step 3: The areal density (ρR) of the seeded nuclei can be determined using established X-ray imaging techniques*

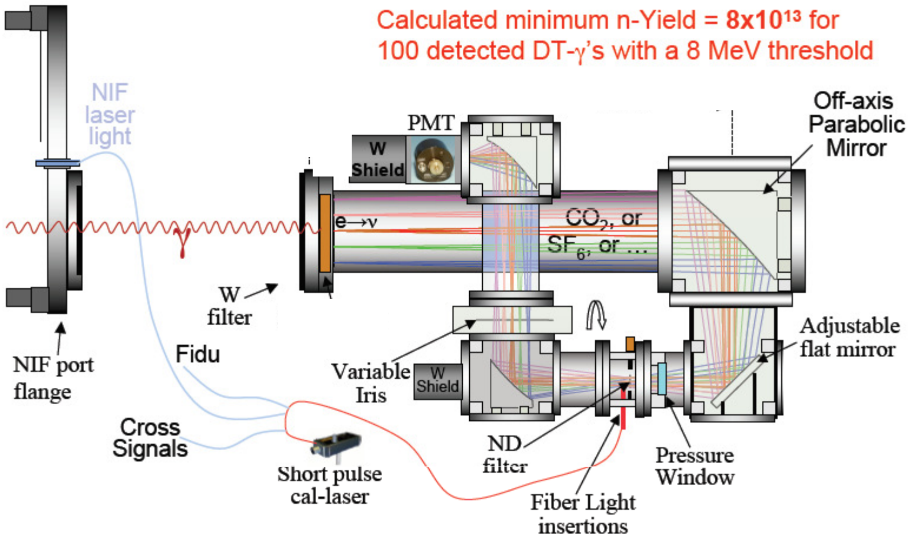


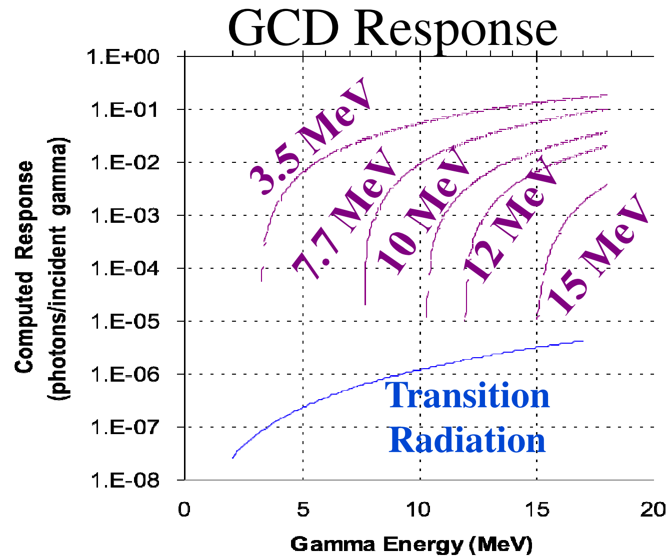


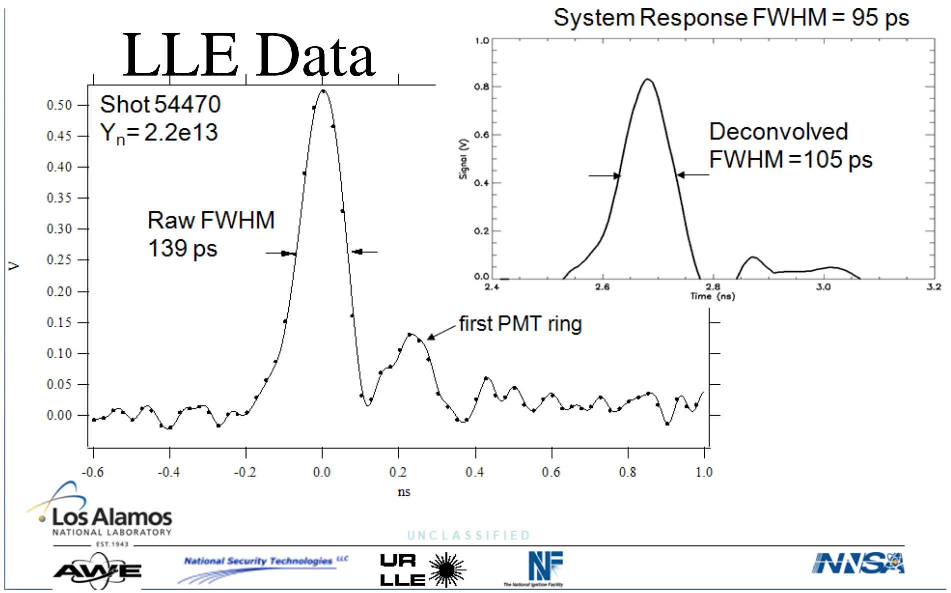
High resolution spectroscopy using crystals allows for detailed tracking of seed nuclei during compression

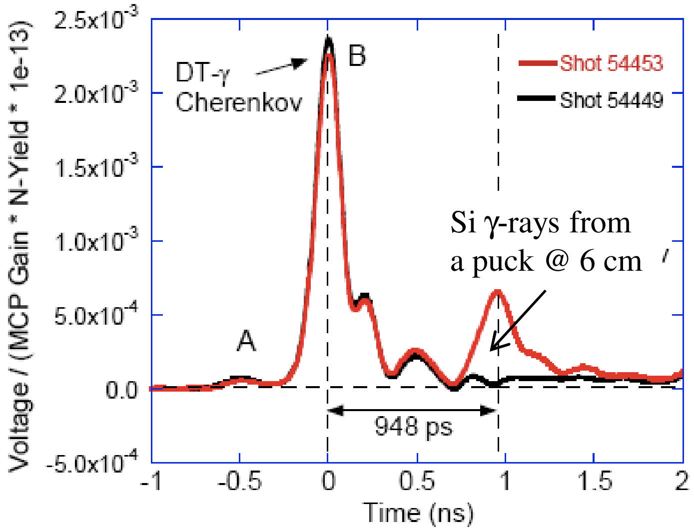
*S.P. Regan *et al.*, High Energy Density Physics 5 (2009) 234–243

Step 4: Prompt γ-rays can be measured with the Gas Cerenkov detector-based Gamma Reaction History (GRH) system





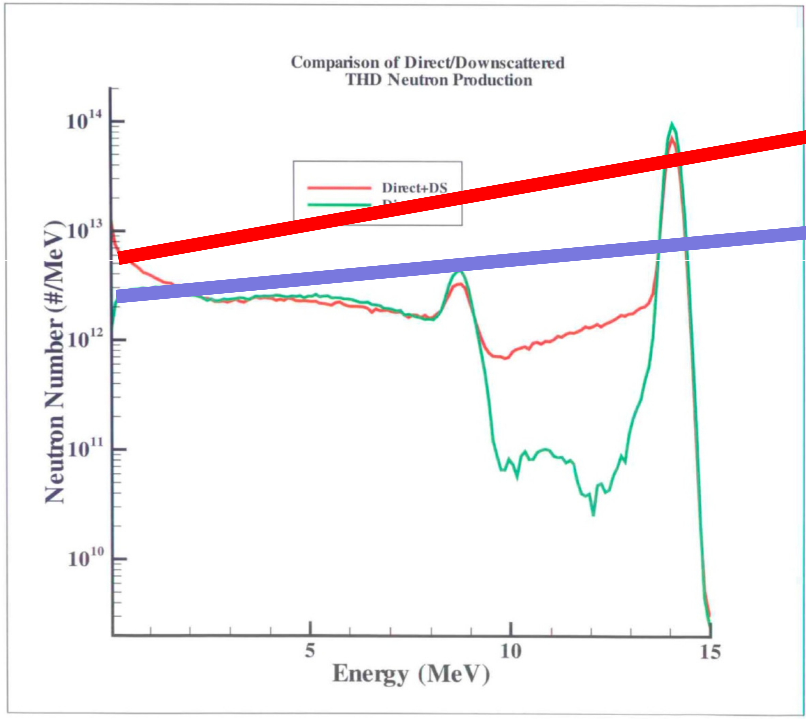


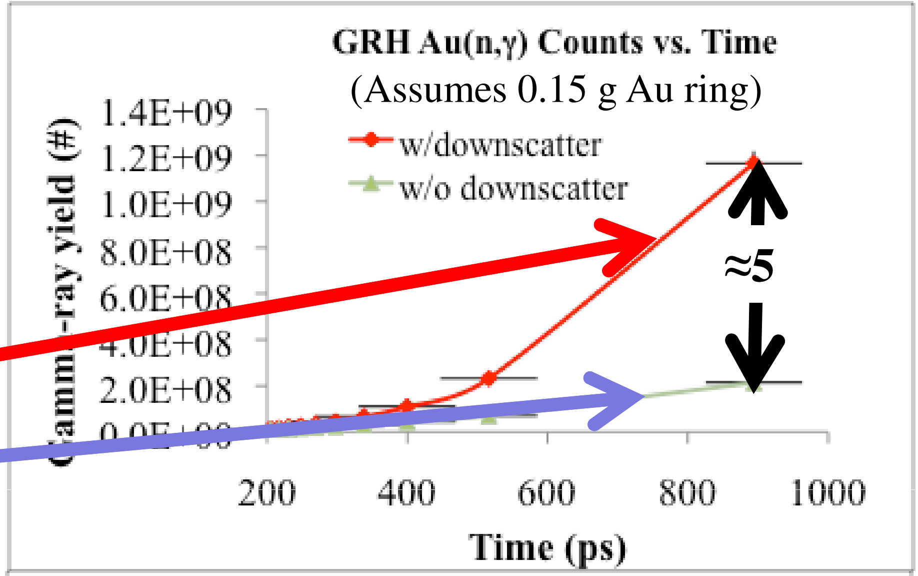


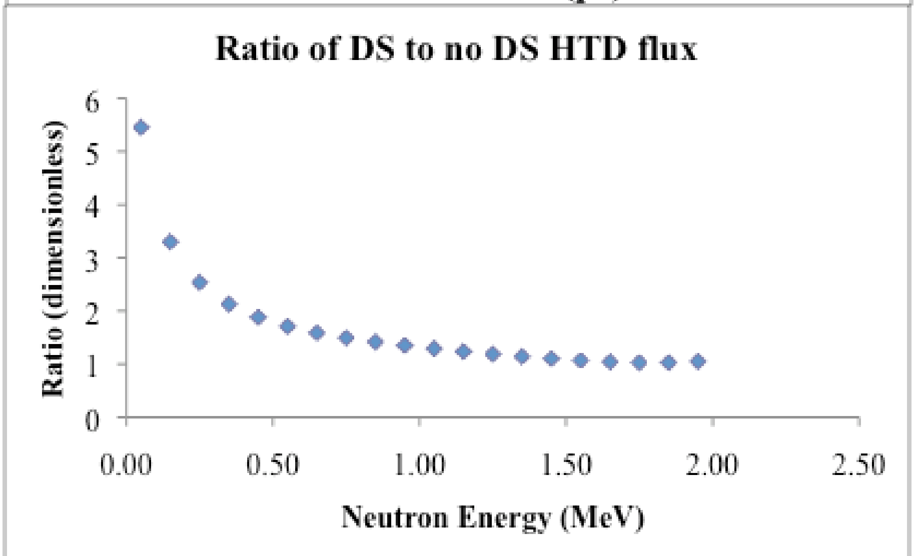
(compliments of W. Stoeffl)

Step 4: Late-time γ-rays (>250 ps) seen in GRH can also be used to measure E_n > 100 keV via Au(n,γ)

From C. Cerjan

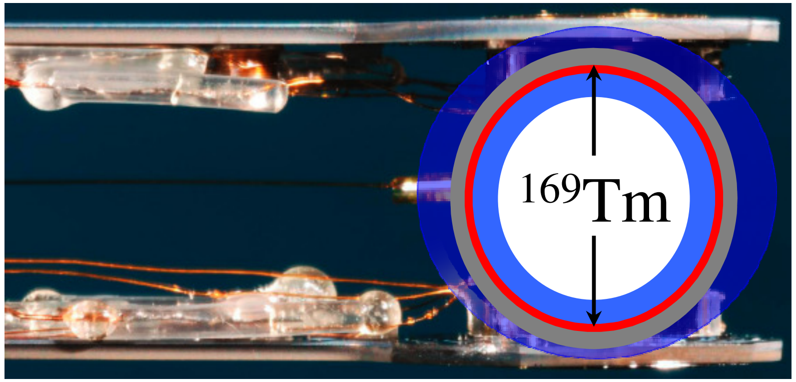


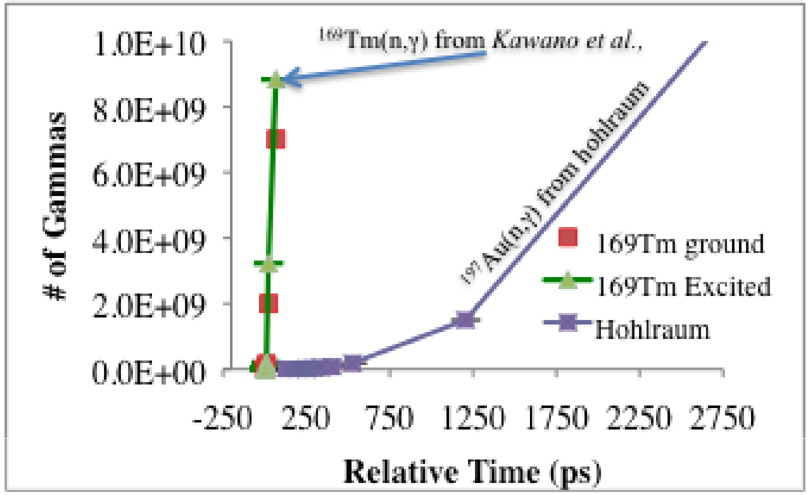




This can be used as a *ρR* diagnostic

What γ-ray production rate does GRH see for a D-fuel capsule loaded with a (n,γ) "seed" nucleus





From X-rays: $\sigma_{\rho R\text{-}Tm} \approx 10\%$

What we want

What we need

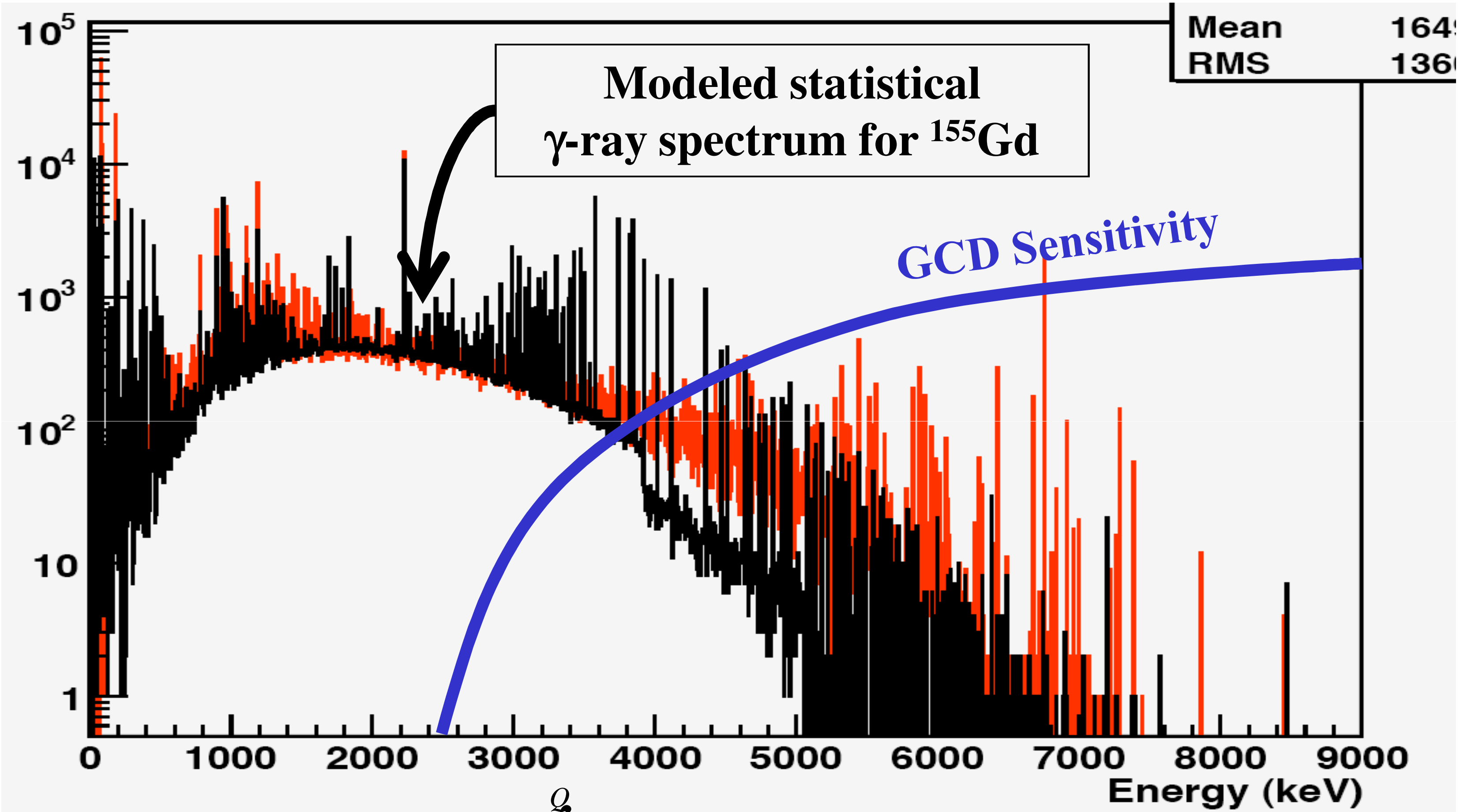
From hohlraum
Late time signal

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

$\sigma_{\rho R\text{-}Au} \approx 5\%$

$\sigma_{Au} \approx 2\%$

The main uncertainty in GRH's ability to "tag" (n,γ) is the production of statistical γ-rays from the CN

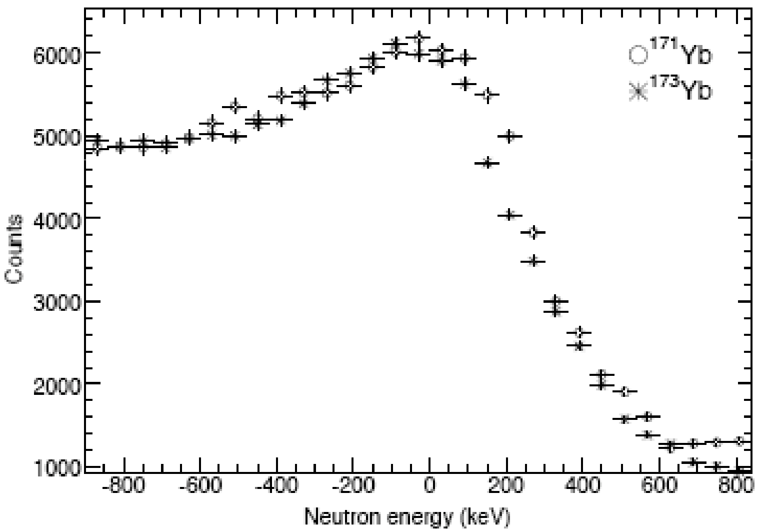


$$\varepsilon_{stat}^{i} = \int_{E_{th}}^{Q} \varepsilon_{GCD}\left(E_\gamma\right) \otimes S_i^\gamma\left(E_\gamma\right) dE_\gamma$$

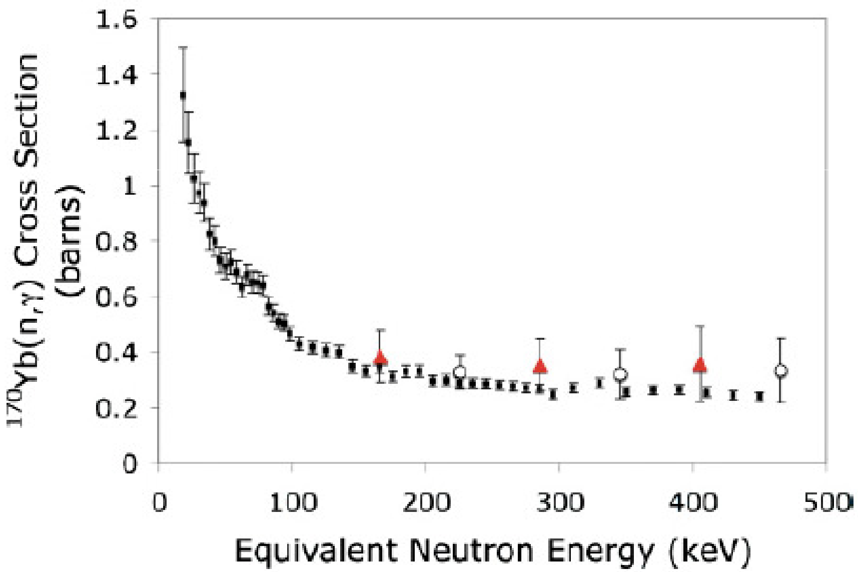
We would like to measure S_γ for $E_\gamma \gtrsim 3$ MeV at the 10% level

The statistical γ-ray spectrum for a (n,γ) product could be measured as part of a surrogate reaction experiment

Surrogate (n,γ) cross section from ^{171}Yb(d,p)^{172}Yb using STARS+LIBERACE*



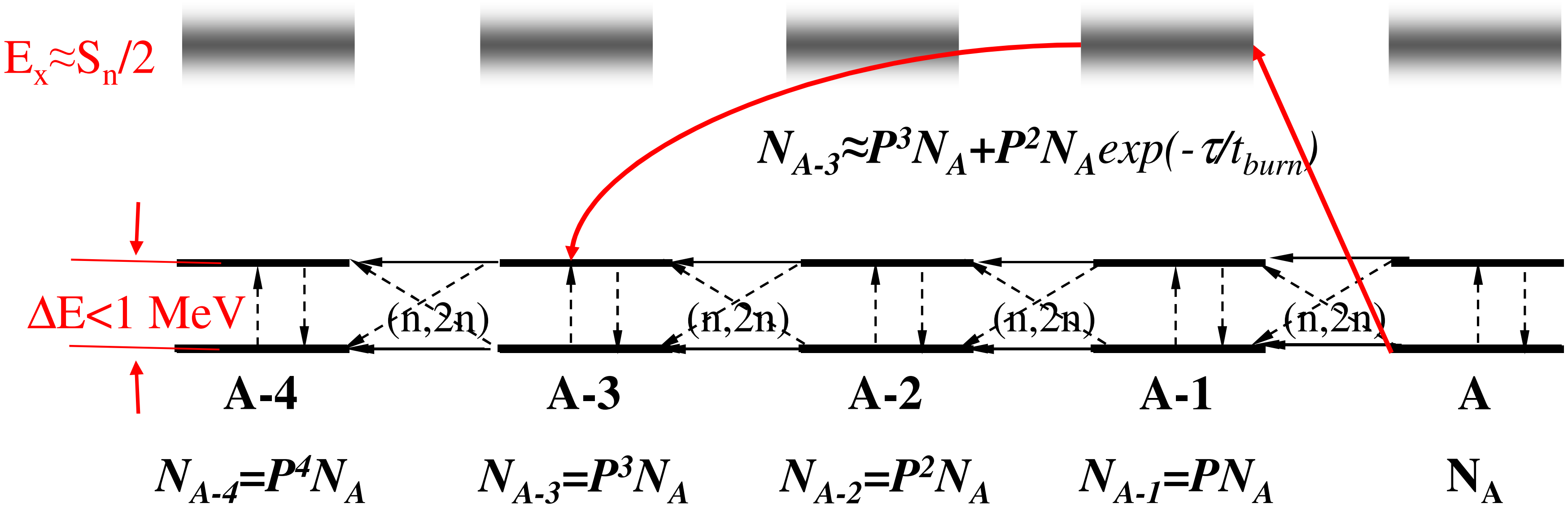
Surrogate (n,γ) cross section from ^{170}Yn(^{3}He,α)^{171}Yb using CACTUS (Oslo)**



"Killing two birds with one stone"

*R. Hatarik. et al., Phys. Rev. **C81** 011602(R) (2010)
B.F. Lyles, *et al.,* Phys.Rev. **C78, 064606 (2008)

Topics #2: In a DT-capsule the huge 14 MeV neutron flux means that highly-excited states could become targets



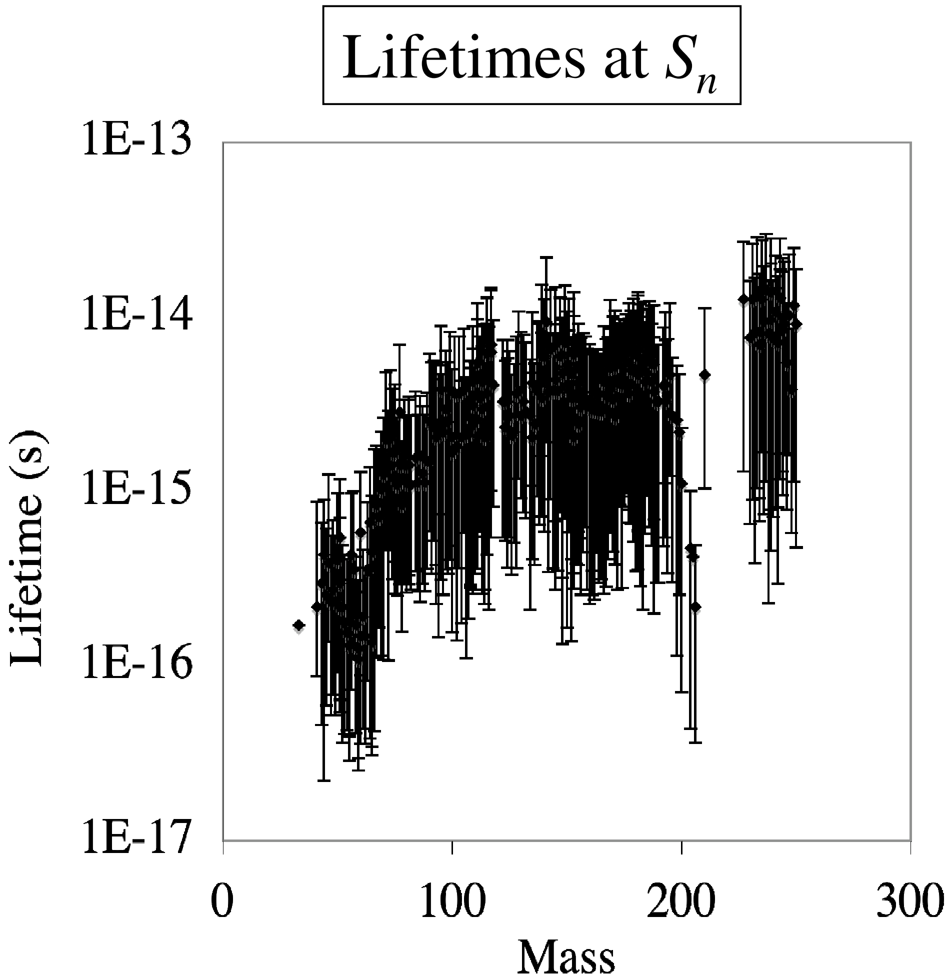
- The probability that a nucleus *A* will be converted via (n,2n) to a nucleus *A-1* is given by:

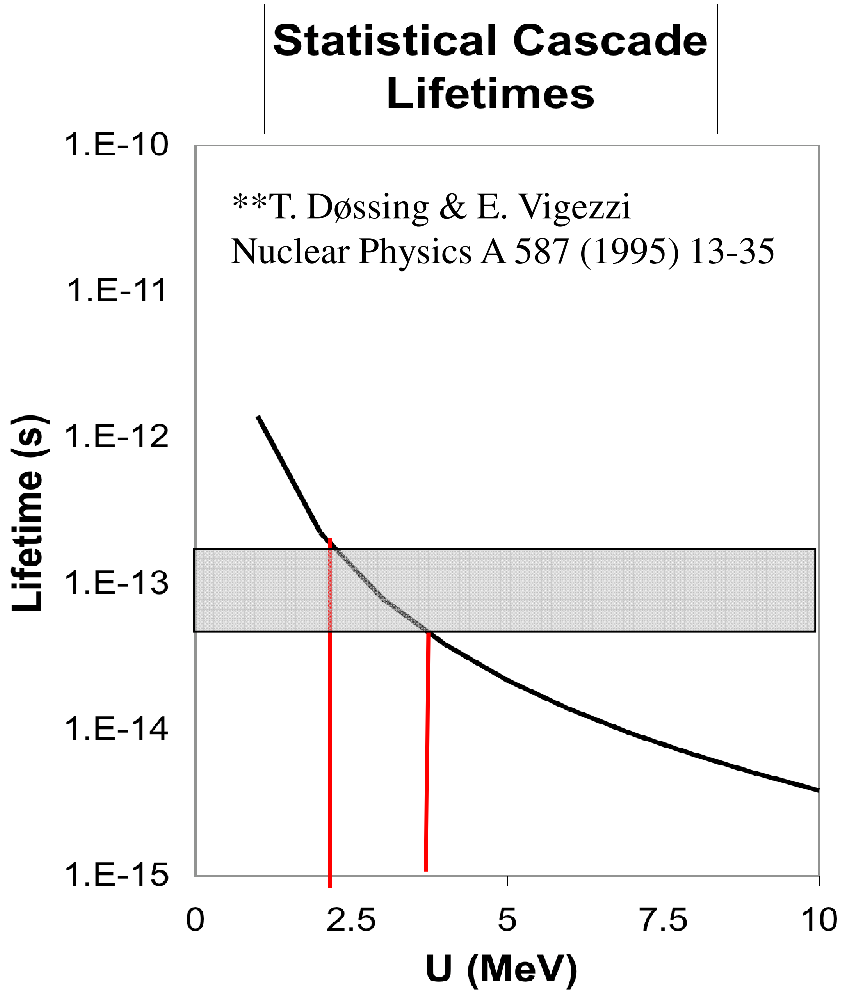
$$P_A = \sigma_{(n,2n)} \rho R_A \Phi_n \approx 10^{-1} - 10^{-4} \; for\, NIF\; DT\; capsules$$

- Only long-lived isomers need to be considered as "targets"
  - Isomers generally have low E_x → reaction Q-value only slightly affected

Reactions on highly excited states need to be considered if $P \leq exp(-\tau/t_{burn})$

A survey of (n,γ) resonance widths* shows that $E_x \approx 4\text{-}5\ MeV$ quasi-continuum lifetime are on the order of $\tau_{DT\text{-}burn}/P$





Product yields are ***very*** sensitive to quasi-continuum lifetimes

*RIPL-2 "obninsk" compilation

Conclusions

- NIF is a totally novel laboratory for studying nuclear physics in a stellar-like environment
  - A large suite of diagnostics are operational at NIF now and more are planned for the next 2+years
- (n,γ) reactions can be studied at NIF using prompt γ-ray detection using the GRH detector system
  - Statistical γ-ray spectra are required to interpret this data.
- (n,x) on quasi-continuum states can occur in DT capsules
  - These reactions are highly dependent on quasi-continuum lifetimes (which are in turn dependent on photon strength and level densities for $E_x < S_n$)
- Statistical nuclear properties are critical for interpreting these results

Early "calibration" experiments (using Ge in the capsule) are planned for 2011

A collaboration is being established to explore nuclear physics @ NIF & statistical γ-ray spectra

Plus any of you that are interested