Nuclear Reactions in High Energy Density Plasmas

L.A. Bernstein
LLNL

Workshop on Level Densities and Gamma Strength in the Continuum
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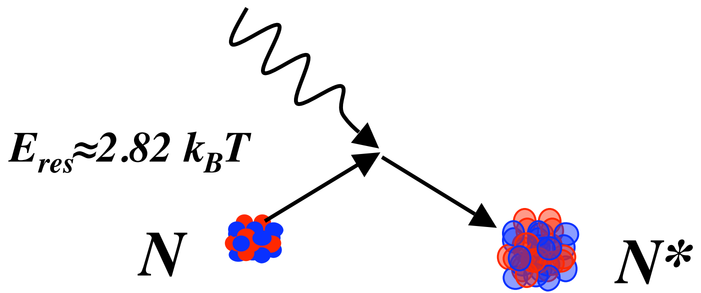
There are four types of nuclear-plasma interactions:

(M.R. Harston & J.F. Chenin, Phys. Rev. **C59** 2462 (1999))

Photon absorption

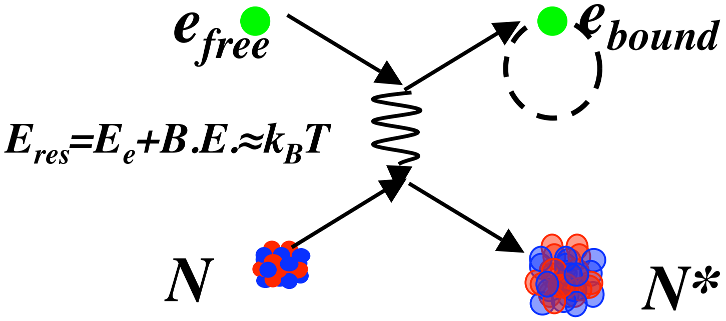
Time Reverse: γ-ray decay



Well known process - often observed

Nuclear Excitation by Electron Capture

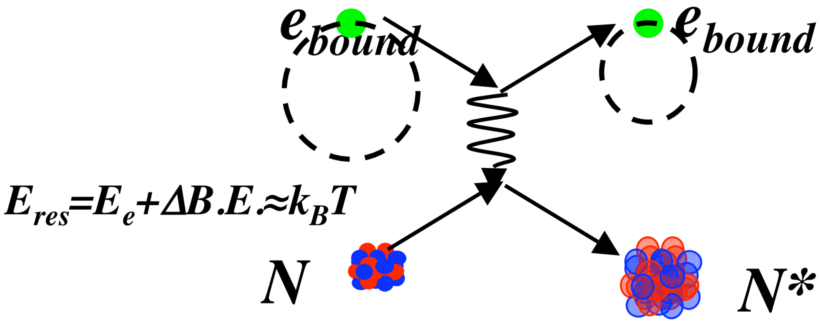
Time Reverse: IC-decay



Never observed

Nuclear Excitation by Electronic Transition

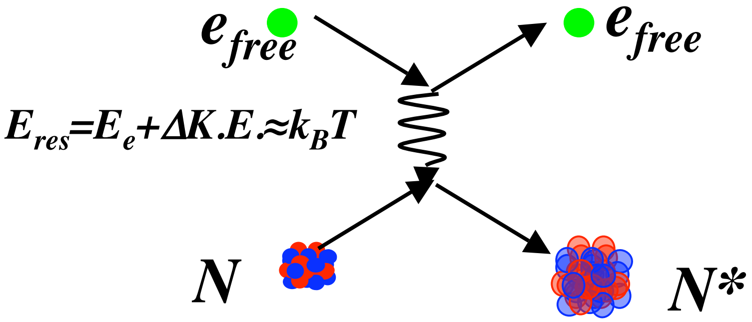
Time Reverse: BIC-decay



Limited Observation

Inelastic Electron Scattering

Time Reverse: Same

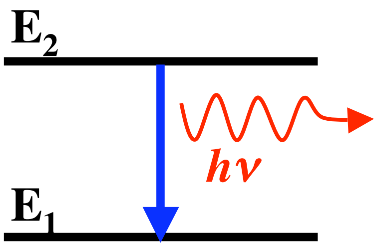


Well understood

Einstein laid out three methods by which atoms interact with blackbody radiation fields

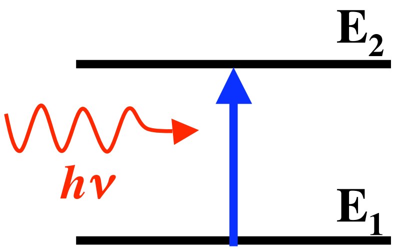
- Spontaneous Decay:

$$\left(\frac{dn_1}{dt}\right)_{A_{21}} = A_{21}n_2$$



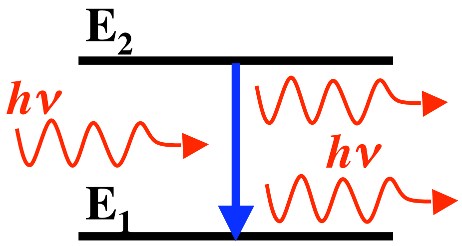
- Photo-Absorption:

$$\left(\frac{dn_1}{dt}\right)_{B_{12}} = -B_{12}n_2 I(\nu); \quad I(\nu) = \frac{2h\nu^3}{c^2\left(e^{h\nu/kT}-1\right)}$$



- Stimulated Emission:

$$\left(\frac{dn_1}{dt}\right)_{B_{21}} = B_{21}n_2 I(\nu); \quad I(\nu) = \frac{2h\nu^3}{c^2\left(e^{h\nu/kT}-1\right)}$$



Only the last two mechanisms depend on the spectral radiance

*A. Einstein Zur Quantentheorie der Strahlung, Physik Z 18:121 (1917)

In a realistic nucleus there are many finite width levels accessible above the initial state

- The photon absorption rate per nucleus then becomes:

$$R_{PA}^{Tot}\left(E_x\right) = \int_0^\infty \overline{B}(E_x + E_\gamma)\Gamma(E_x \rightarrow E_x + E_\gamma)\rho(E_x + E_\gamma)\Phi\left(E_\gamma\right)dE_\gamma$$

- The photon absorption rate on the ground state is known*:

$$R_{PA}^{Tot} = \int_0^\infty \sigma_{PA}(E_\gamma)\Phi\left(E_\gamma\right)dE_\gamma$$

- Allowing us to recognize the photon absorption (and stimulated emission) cross sections in a blackbody field as:

$$\sigma_{PA}(E_x) = \int_0^\infty \overline{B}(E_x + E_\gamma)\Gamma(E_x \rightarrow E_x + E_\gamma)\rho(E_x + E_\gamma)dE_\gamma$$

$$\sigma_{SE}(E_x) = \int_0^\infty \overline{B}(E_x - E_\gamma)\Gamma(E_x \rightarrow E_x - E_\gamma)\rho(E_x - E_\gamma)dE_\gamma$$

*Berman & Dietrich, etc. RIPL

We can now obtain a net photon absorption rate in a plasma blackbody spectrum

- For $E_x \approx S_n$ and $E_\gamma << E_x$ the *B's* (which play the role of a cross section) are identical, and
- The photo-absorption cross section is the same on the excited state as the ground state (Brink) we get:

$$\sigma_{SE}(E_x) = \sigma_{PA}(E_x) \int_0^\infty \frac{\Gamma(E_x \to E_x + E_\gamma)\rho(E_x + E_\gamma)}{\Gamma(E_x \to E_x - E_\gamma)\rho(E_x - E_\gamma)} dE_\gamma$$

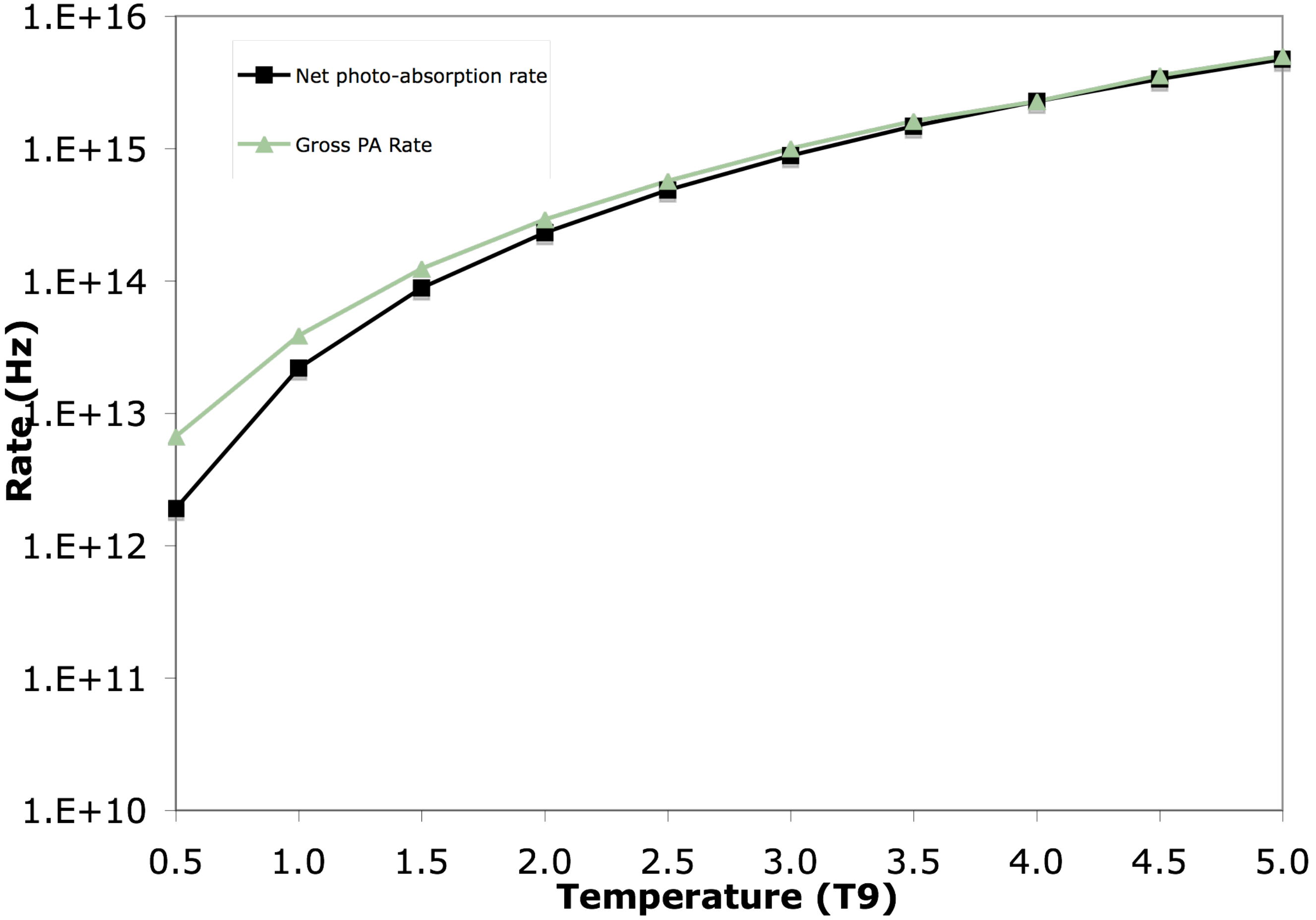
- Yielding a *net* ***P****re-statistical* ***P****hoton* ***A****bsorption (PPA) rate* of*:*

$$\Delta R(E_x) \equiv R_{photo-absorption}(E_x) - R_{stimulated\ emission}(E_x)$$

$$\Delta R(E_x) = \int_0^\infty \left(\sigma_i^{photo-absorption} - \sigma_i^{stimulated\ emission}\right)\Phi_\gamma\, dE_\gamma + \cancel{\int_{S_n}^\infty \sigma_i^{stimulated\ emission}\Phi_\gamma\, dE_\gamma}$$

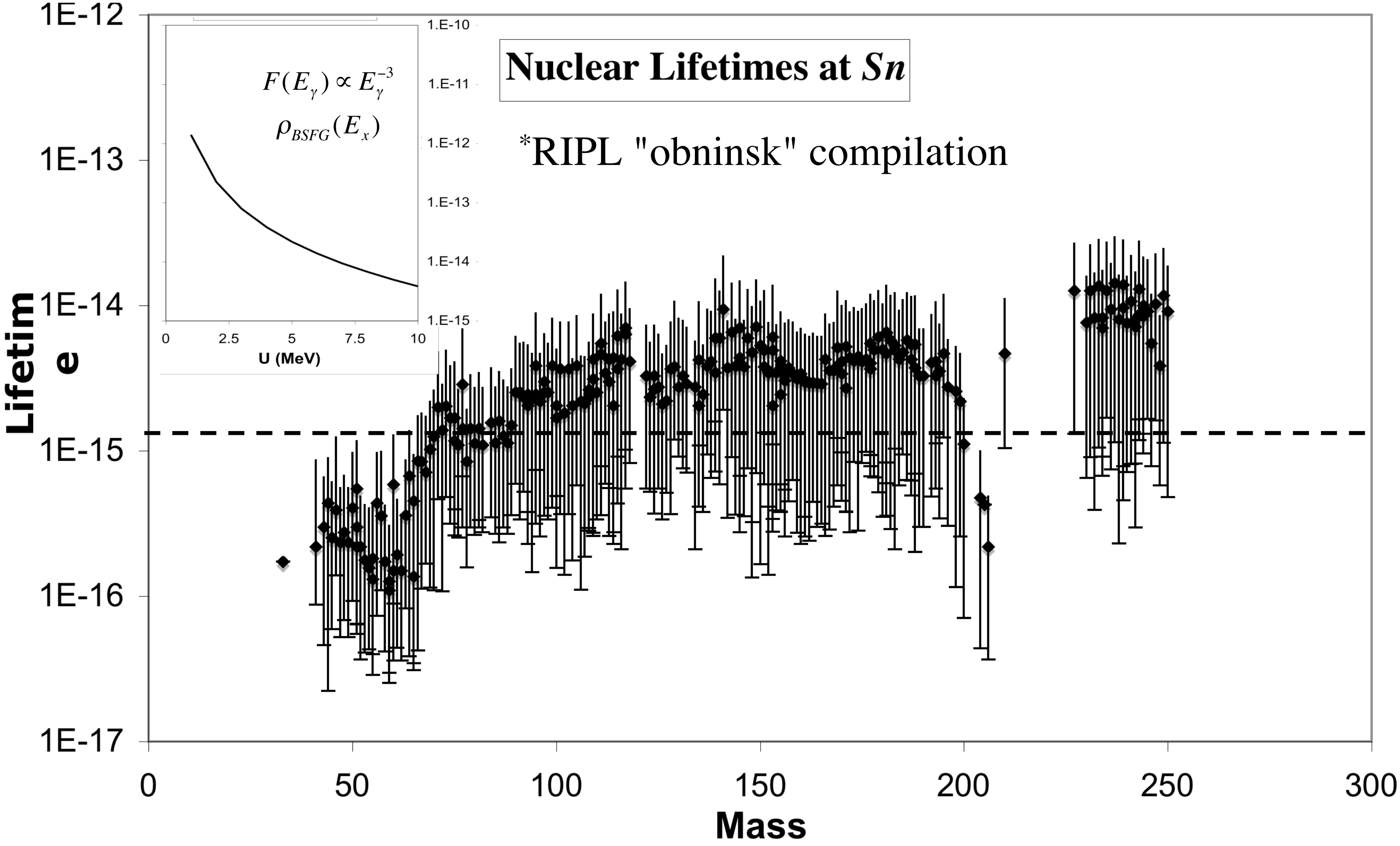
$$\boxed{\Delta R(E_x) \approx \int_0^\infty \left(1 - \frac{\Gamma(E_x \to E_x - E_\gamma)\rho(E_x - E_\gamma)}{\Gamma(E_x \to E_x + E_\gamma)\rho(E_x + E_\gamma)}\right)\sigma_i^{photo-absorption}\Phi_\gamma\, dE_\gamma}$$

Pre-statistical Photon Absorption (PPA) Rate vs. Temperature (T9=10^9K)



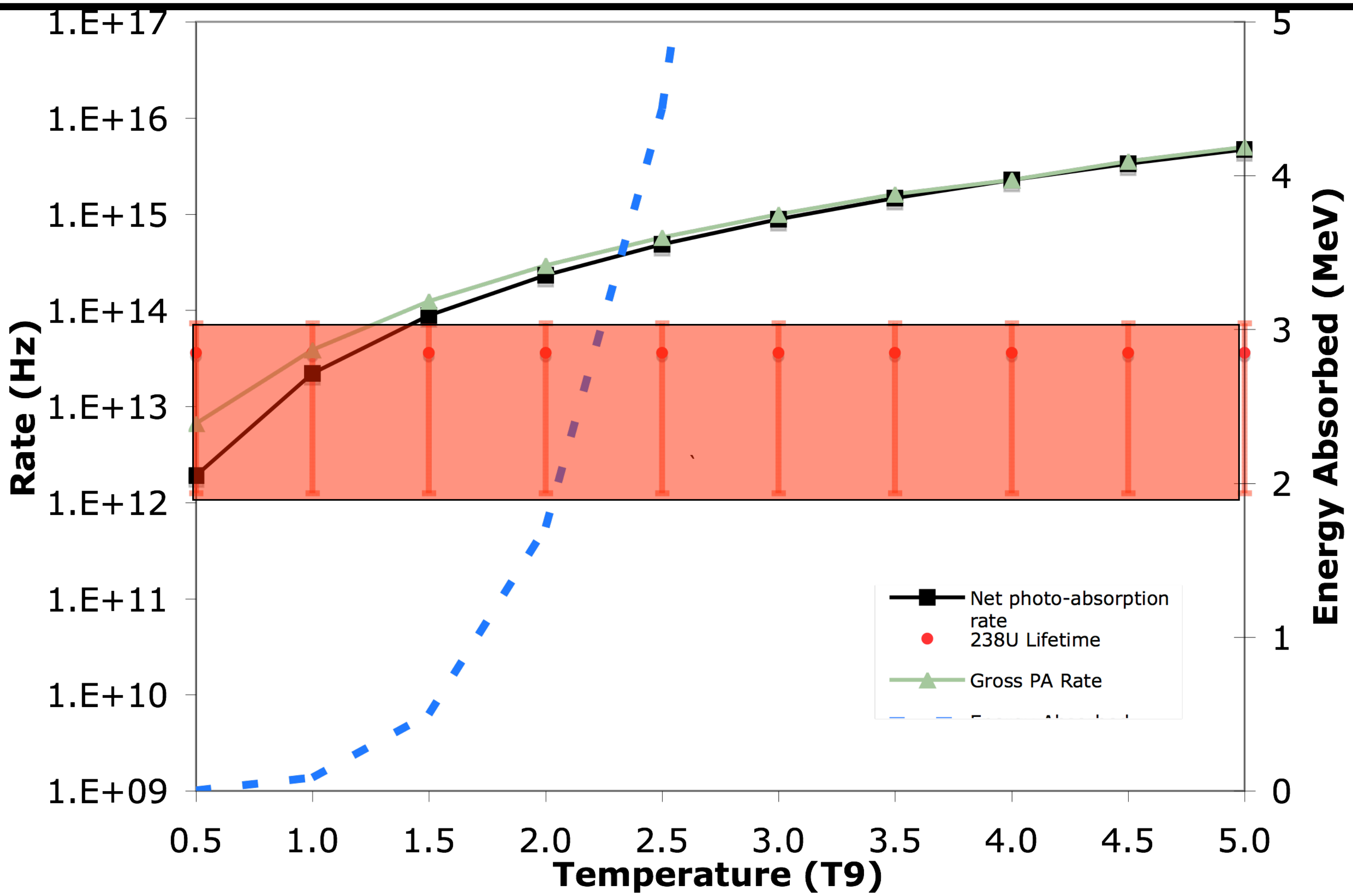
How does PPA compete with spontaneous decay?

Thermal (n,γ) resonance widths* shows that nuclear quasi-continuum lifetimes near S_n are on the order of *1-10 fs*



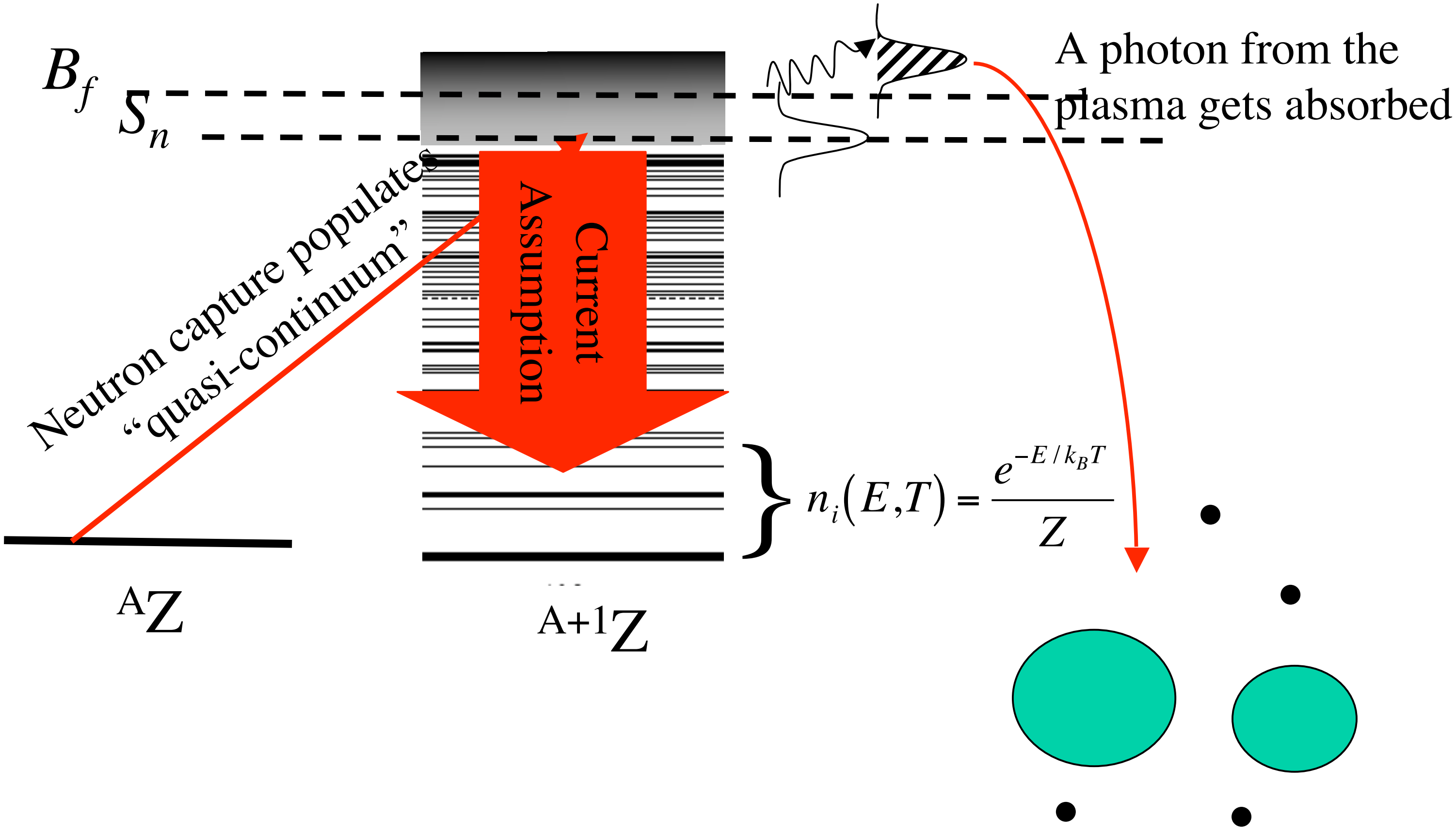
Lifetimes get longer as neutron separation energies decrease

PPA is faster than spontaneous decay near S_n for fissionable nuclei for T9≥1



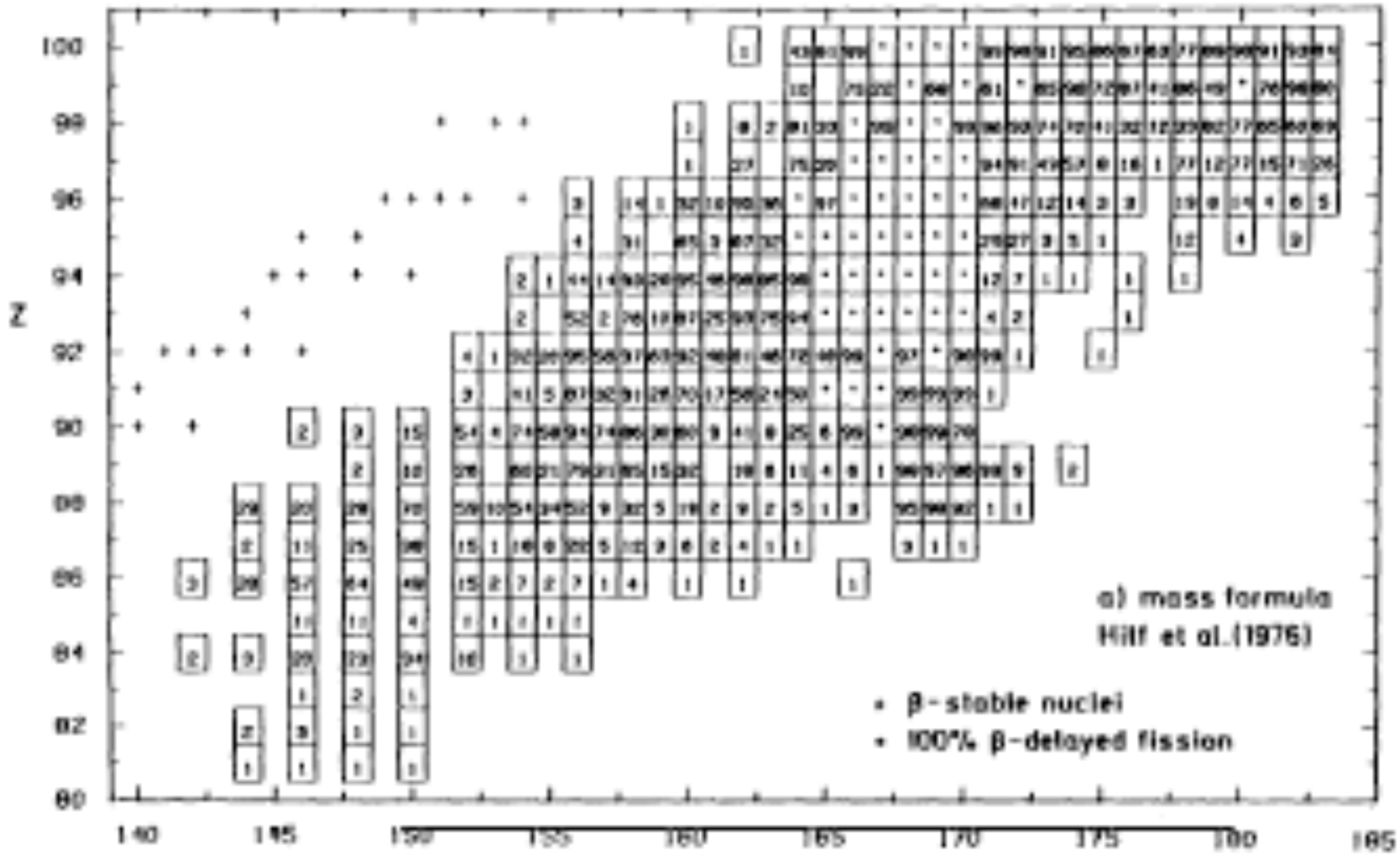
S_n near r-process path≈2 MeV

What are the effects of PPA on neutron-capture driven nucleosynthesis?



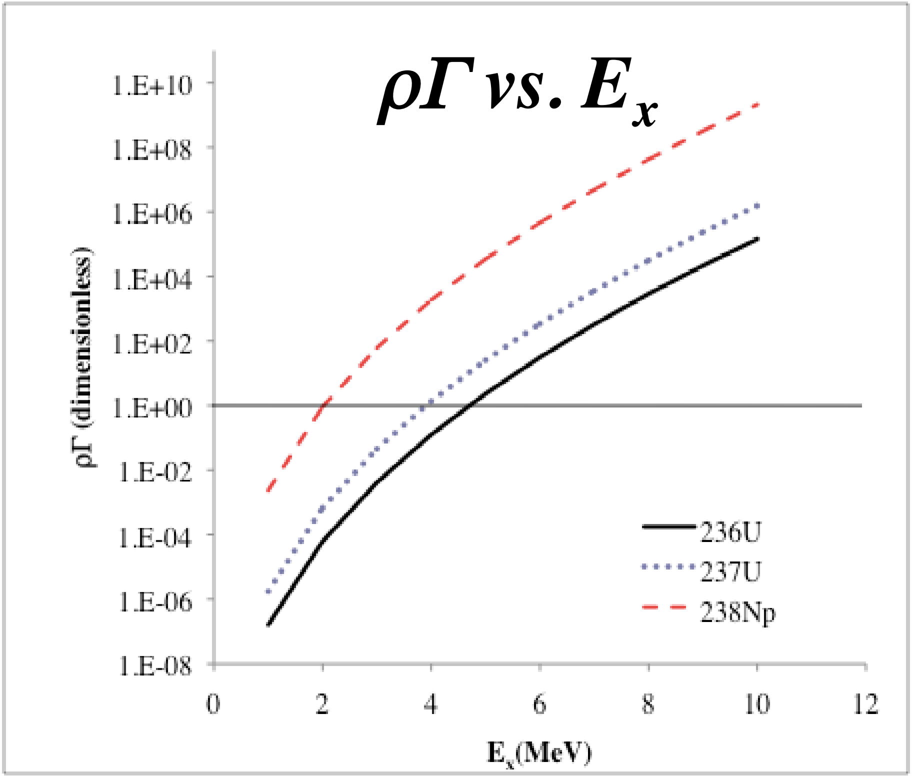
Fission could kill off the formation of A>240 nuclei

What are the effects of PPA on neutron-capture driven nucleosynthesis?



R-process models "fission recycle" A>280-300 nuclei

Even far from stability ($S_n \approx 2\ MeV$) levels overlap ($\rho^* \Gamma > 1$) for odd-odd nuclei



S_n (MeV)	Type of Nucleus	$\rho\Gamma$	R_{PPA}/R_{SPE}
2	Even-Even	0.063	0.00059
2	Odd-A	0.00068	0.0065
2	Odd-Odd	0.92	8.7
3	Even-Even	0.0042	0.014
3	Odd-A	0.046	0.15
3	Odd-Odd	62	3.3
4	Even-Even	0.12	0.20
4	Odd-A	14	1.6
4	Odd-Odd	1800	1.6

Sooner or later a photon will be absorbed that makes $E_x > B_f$

*Level density from Generalized BCS model w/o enhancements

Is $R_{NEEC/NEET} > R_{spontaneous\ decay}$? How do photon and electron fluences compare?

- The total photon flux is dependent only on the temperature given by the Stefan-Boltzmann relation:

$$P = \sigma_{SB} T^4 = \left(5.67x10^{-12}\, J/cm^2K^4s\right)\left(10^9 K\right)^4 = 5.67x10^{24}\, J/cm^2 s$$

$$\overline{\Phi}_{photon} = \frac{P}{\overline{E}_{photon}} = \frac{5.67x10^{24}\, J/cm^2 s}{\left(3.83 k_B T\right)\left(1.6x10^{-16}\, J/keV\right)}$$

$$\overline{\Phi}_{photon} = 1.1x10^{38}\ photons/cm^2 s$$

- In contrast, the electron flux, which is Fermi-Dirac in form, is dependent on both the temperature and the matter density:

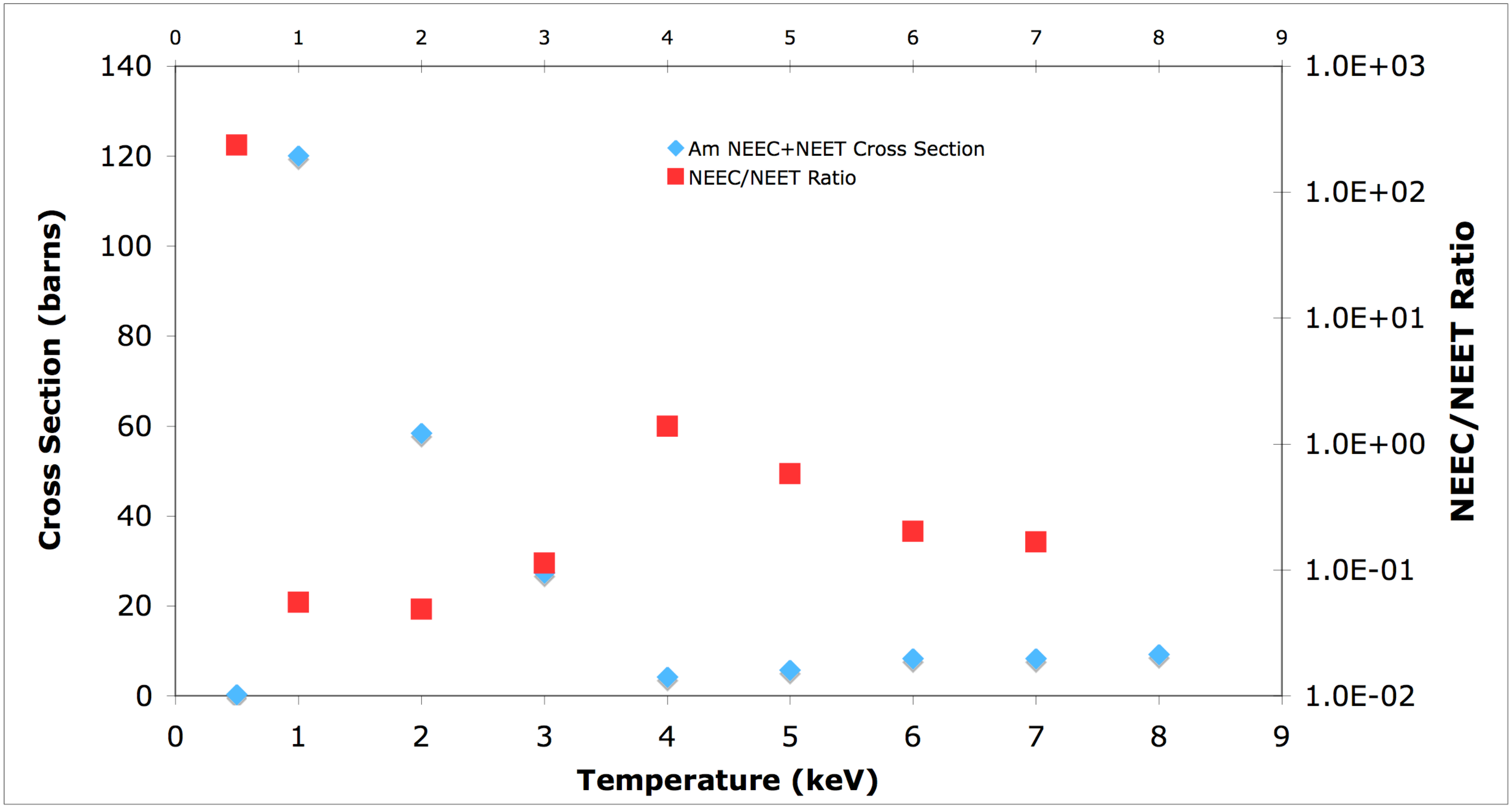
$$\overline{\Phi}_{electron} = \rho_e v_e = \left(1000\, g/cm^3\right)\left(\sqrt{\frac{2k_B T}{m_e}}\right)$$

$$\overline{\Phi}_{electron} = 7x10^{36}\ electrons/cm^2 s$$

$$\boxed{\frac{\overline{\Phi}_{electron}}{\overline{\Phi}_{photon}} = 6.5\% \Rightarrow if\ \frac{\overline{\sigma}_{NEEC/NEET}}{\overline{\sigma}_{photo-absorption}} \geq 150\ then\ R_{NEEC/NEET} > R_{photon}}$$

We need to calculate these rates for *K, L, M* atomic shells. Right now I have only *M*

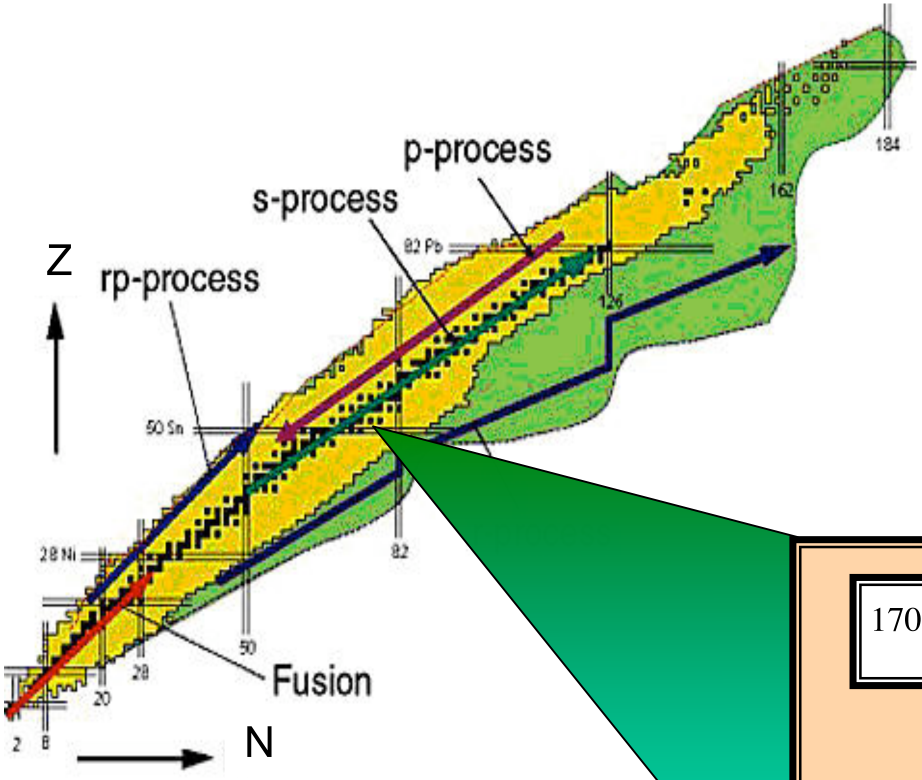
^{242m}Am 4.1 keV $5^{-} \rightarrow 3^{-}$ NEEC/NEET (assuming no K-hindrance)



Note that this cross section is ≈ 2-3 orders of magnitude bigger than σ_{PA} at the relevant energies

*Courtesy of M. Chen - Dirac-Hartree-Slater Average Atom Model

Pre-statistical *electron* absorption (PEA) could also play a role in s-process nucleosynthesis

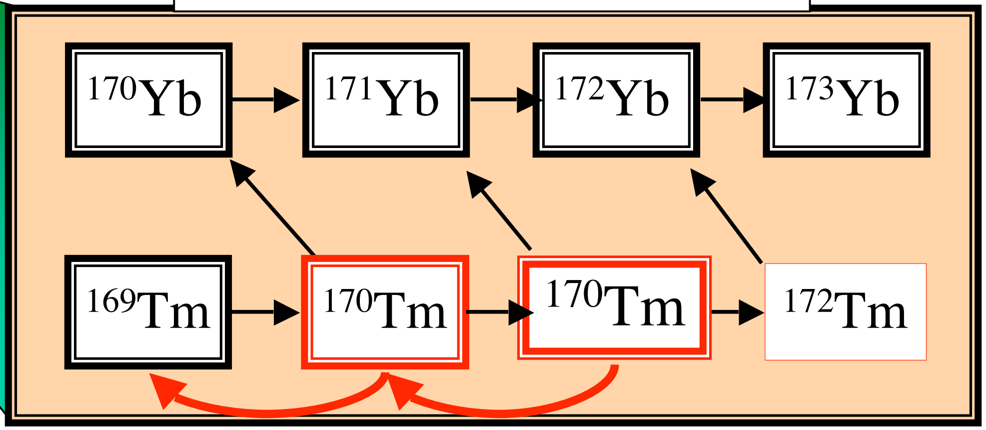


S-process conditions

$k_B T \approx 8, 30$ keV

$\rho \approx 50\text{-}100$ g/cm^3

s-process path near Tm



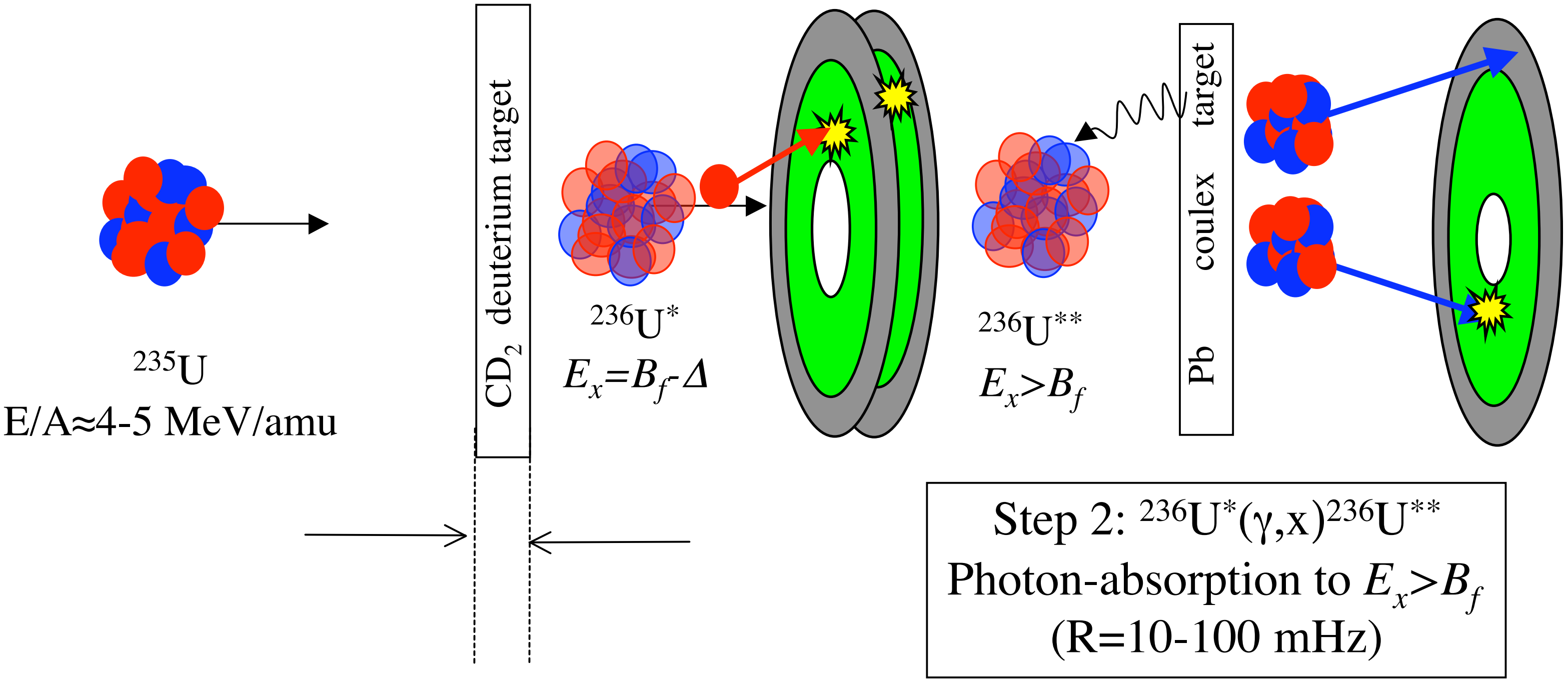
^{170}Yb → ^{171}Yb → ^{172}Yb → ^{173}Yb

^{169}Tm → ^{170}Tm → ^{170}Tm → ^{172}Tm

Help is needed once again from atomic physicists

Pre-statistical photon absorption on states with $E_x \approx S_n$ might be observable in inverse kinematics

Step 1: $D(^{235}U, ^{236}U^*)p$ with $E_x < B_f$
Proton measured in Si telescope
(R≈1 kHz)



β≈10% c
Δt ≈ 10 fs
Δx ≈ 0.4 μm

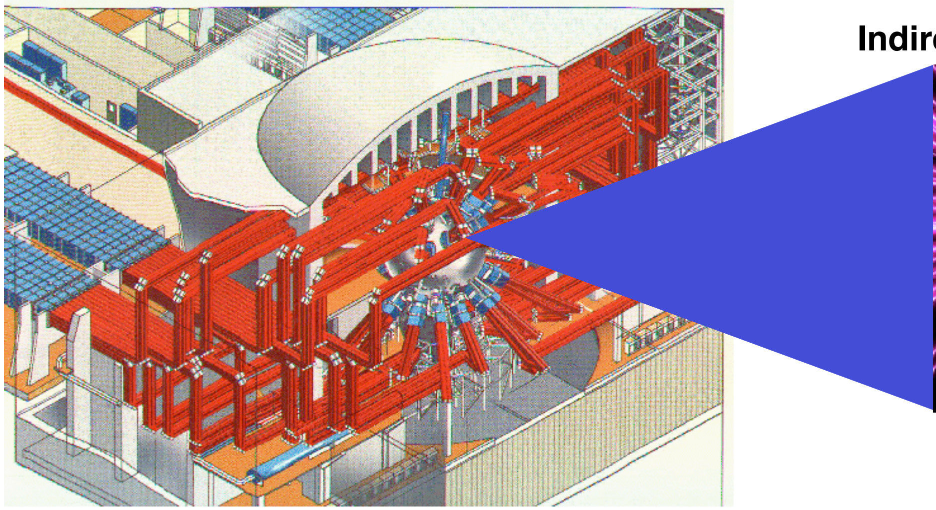
Step 2: $^{236}U^*(\gamma, x)^{236}U^{**}$
Photon-absorption to $E_x > B_f$
(R=10-100 mHz)

Step 3: Repeat for a 5 μm CD_2
To Pb separation – no fission
$R_{random} \approx 0.1$ mHz

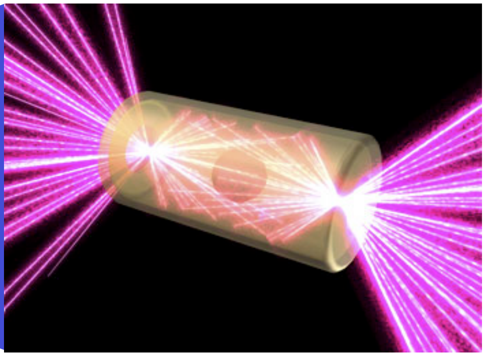
At NIF we could observe changes in (n,γ) and look for evidence of PPA

NIF is designed to implode DT (or HTD) pellets to achieve thermonuclear fusion

Standard ignition configuration: 192 beams, 1.8MJ in 3ω light - NOW OPERATIONAL!!!



Indirect drive: X-rays drive implosion

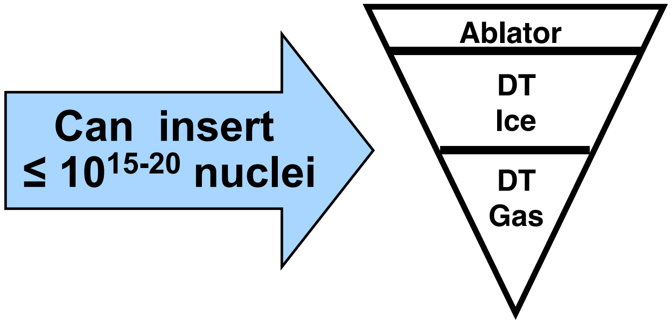


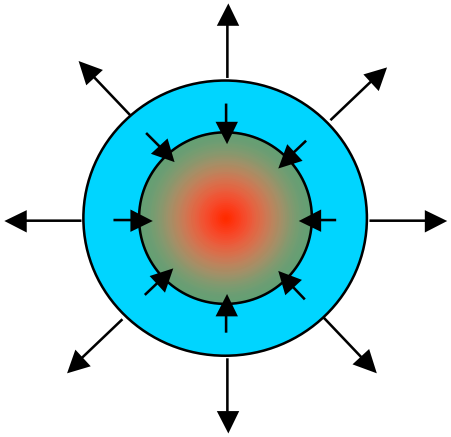
Hohlraum ~ 10 mm long

Target ~ 1 mm radius

Optical pulse ~ few ns

Burn ~ few ps





$r_{initial} = 1$ mm

$r_{final} = 30\ \mu$m

NIF achieves electron densities above SN levels and temperatures near it (10-30 keV)

Conclusions

- Nuclei after (n,γ) are likely to interact with photon fields ***prior*** to statistical γ-ray decay leading to:
  - An increase in fission for high mass nuclei
  - A decreased ability to retain captured neutrons
- Future theoretical work will include:
  - Proper treatment of electron-nuclear interactions (Courtesy of atomic theorist M. Chen)
  - Discuss implications for s- and p-processes
- Important physical parameter is $\sigma_{(\gamma,x)}$
- Future experimental work could utilize inverse kinematics U beams and NIF.

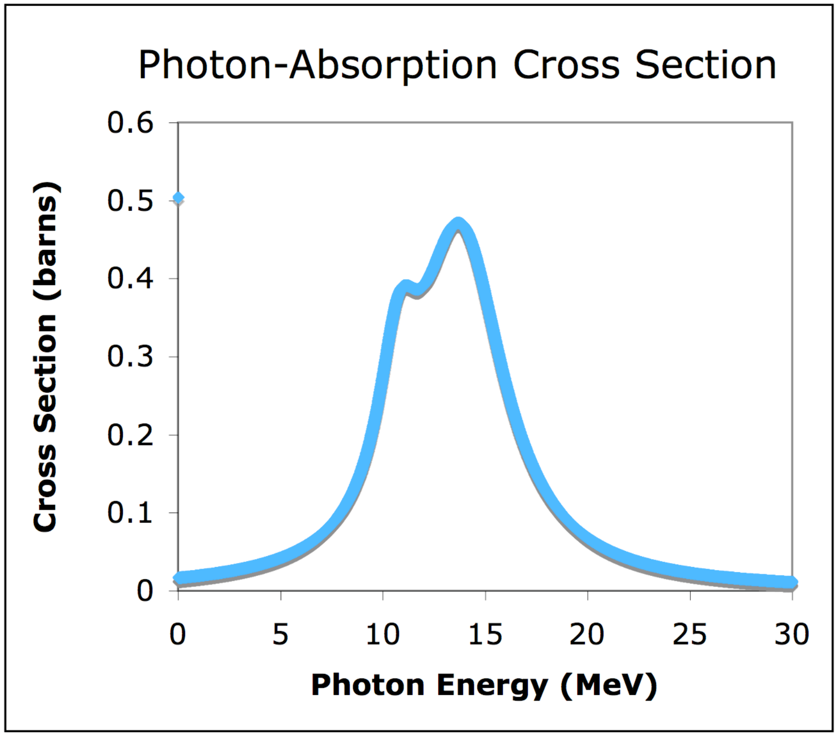
F(E_γ<750 keV) could potentially rule out some r-process settings

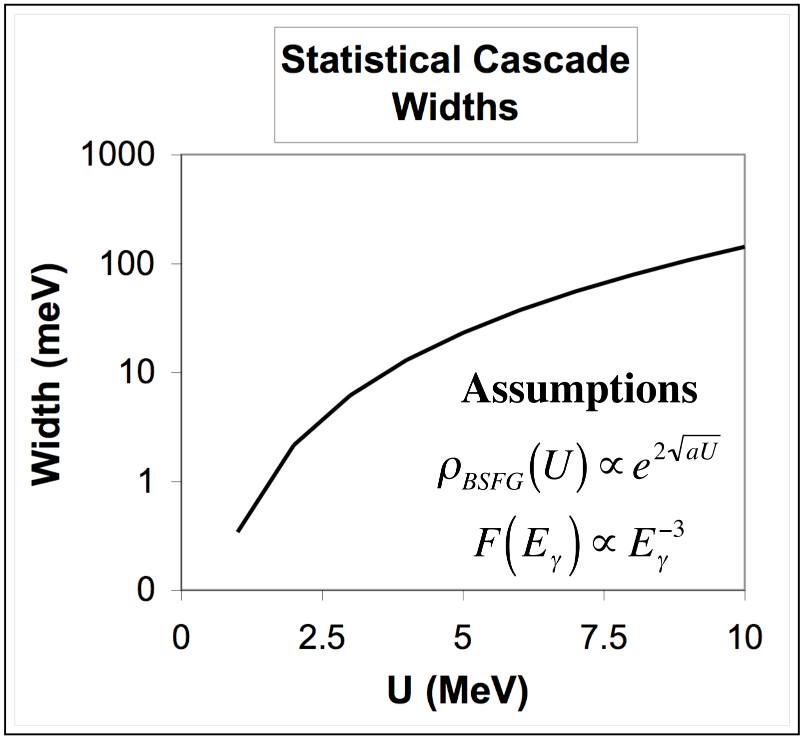
Collaborators

D.L. Bleuel, D.H.G. Schneider, J. Pruet, R.D. Hoffman,
C. Cerjan, R. Fortner
LLNL

L.W. Phair, I.Y. Lee
LBNL

Input is the (γ,x) cross section from Berman & Dietrich* + ρ_{BSFG} level density





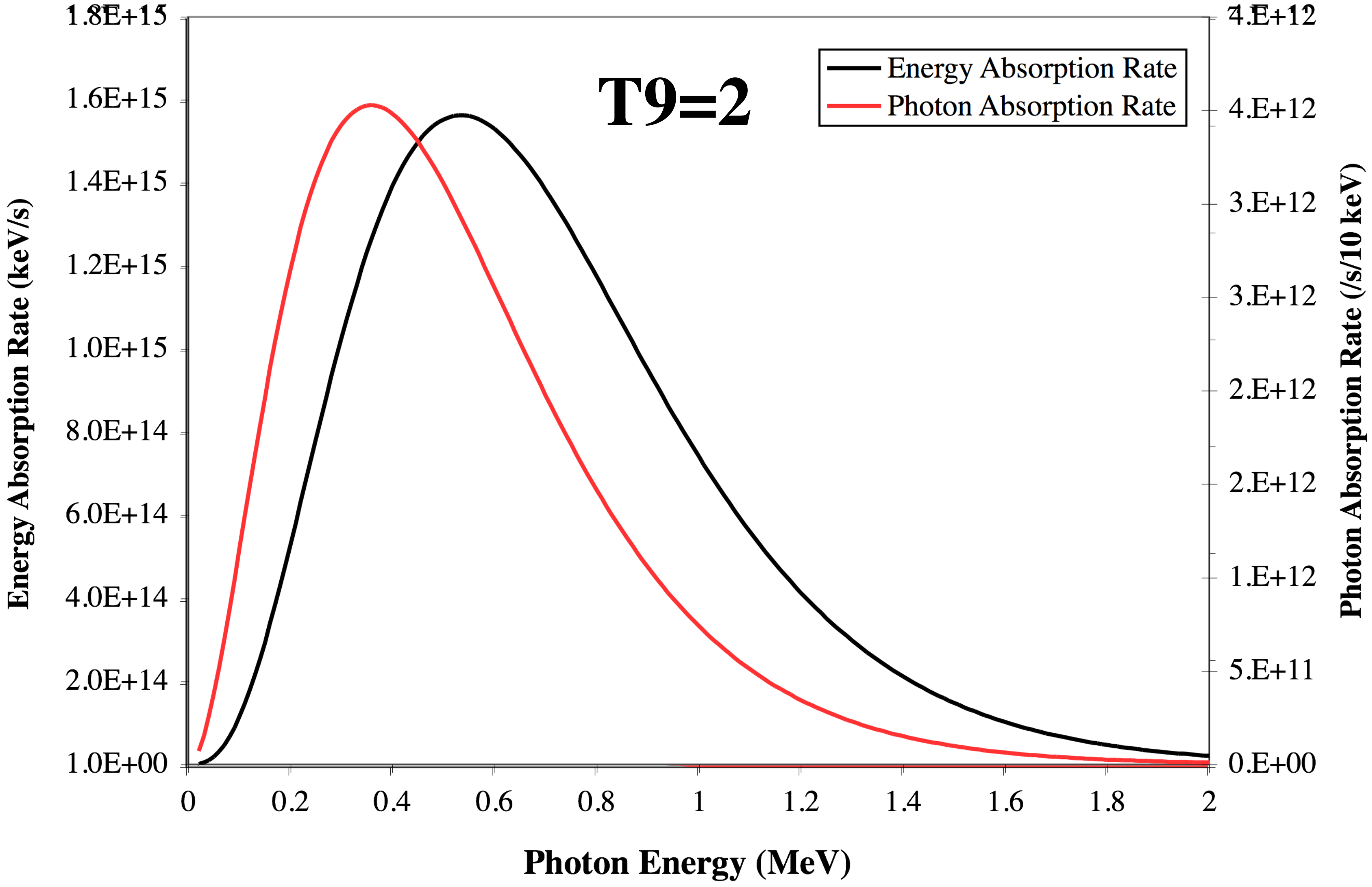
$$\rho_{BSFG}(U) \propto e^{2\sqrt{aU}}$$

$$F(E_\gamma) \propto E_\gamma^{-3}$$

What does all photo-absorption look like @ 250 keV?

* Varlamov RIPL compilation used as a "place holder"

Net PPA integrand vs. photon energy

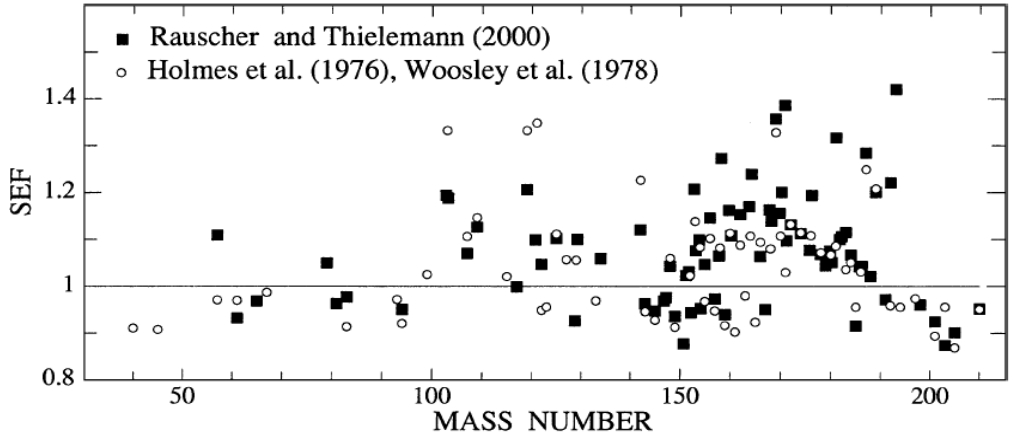


Some of the most important* s-process branch point nuclei have HEDP-populated low-lying excited states

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

$$sef = \frac{\sum_{states} C_i \sigma^i_{(n,\gamma)}}{\sigma^g_{(n,\gamma)}}, \; where \; C_i = \frac{e^{-\Delta E_i / k_B T}}{Z}$$

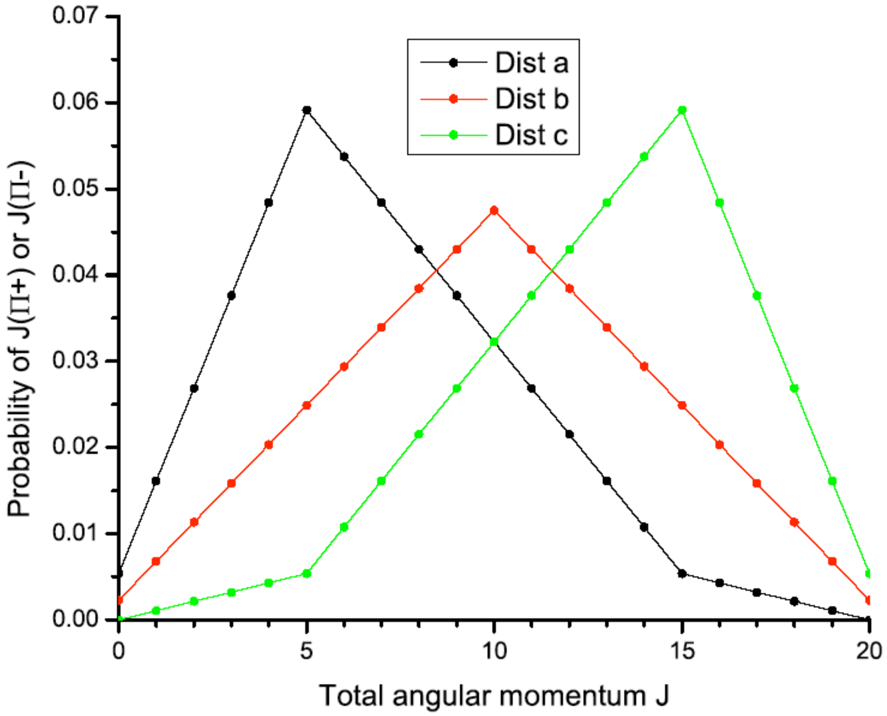
*Bao & Kappeler At. Dat. Nucl. Dat. Tables **76,** 70–154 (2000)

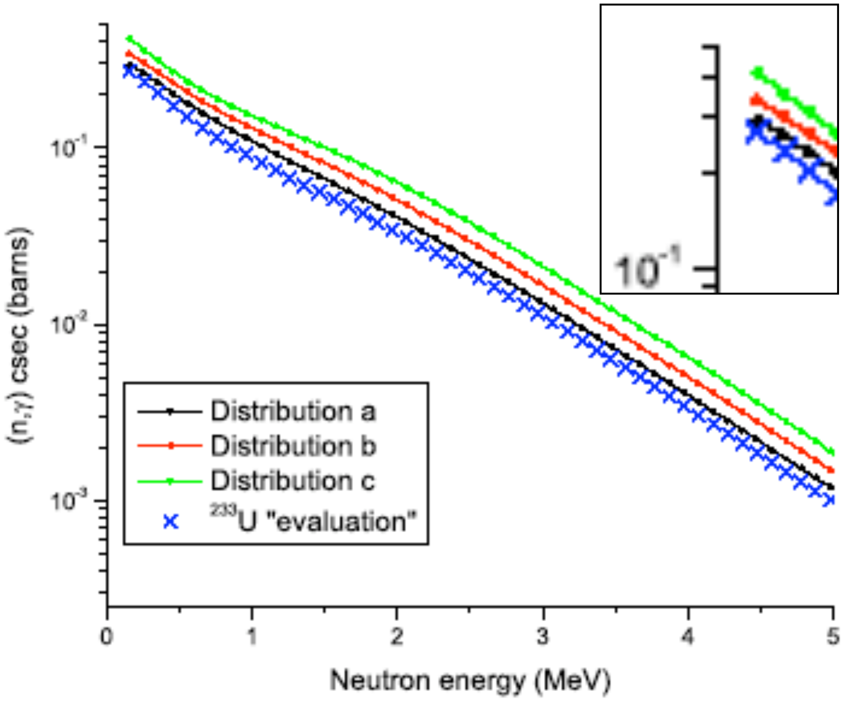


Branch Point	Gnd State J^π	1st Exc. State E_x (keV)	1st Exc. State J^π
^{79}Se	7/2+	95.77	1/2-
^{85}Kr	9/2+	304.871	1/2-
^{147}Pm	7/2+	91.1	5/2+
^{151}Sm	**5/2–**	**4.821**	**3/2-**
^{163}Ho	7/2–	100.03	9/2-
^{170}Tm	**1-**	**38.7139**	**2-**
^{171}Tm	**1/2+**	**5.0361**	**3/2+**
^{179}Ta	**7/2+**	**30.7**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

^{171}Tm(n,γ) is ideal for NIF since target and product are both radioactive

Hauser-Feshbach reaction models* indicate that (n,γ) is very sensitive to J (for ^{233}U)





Differences of 20-100% might be expected

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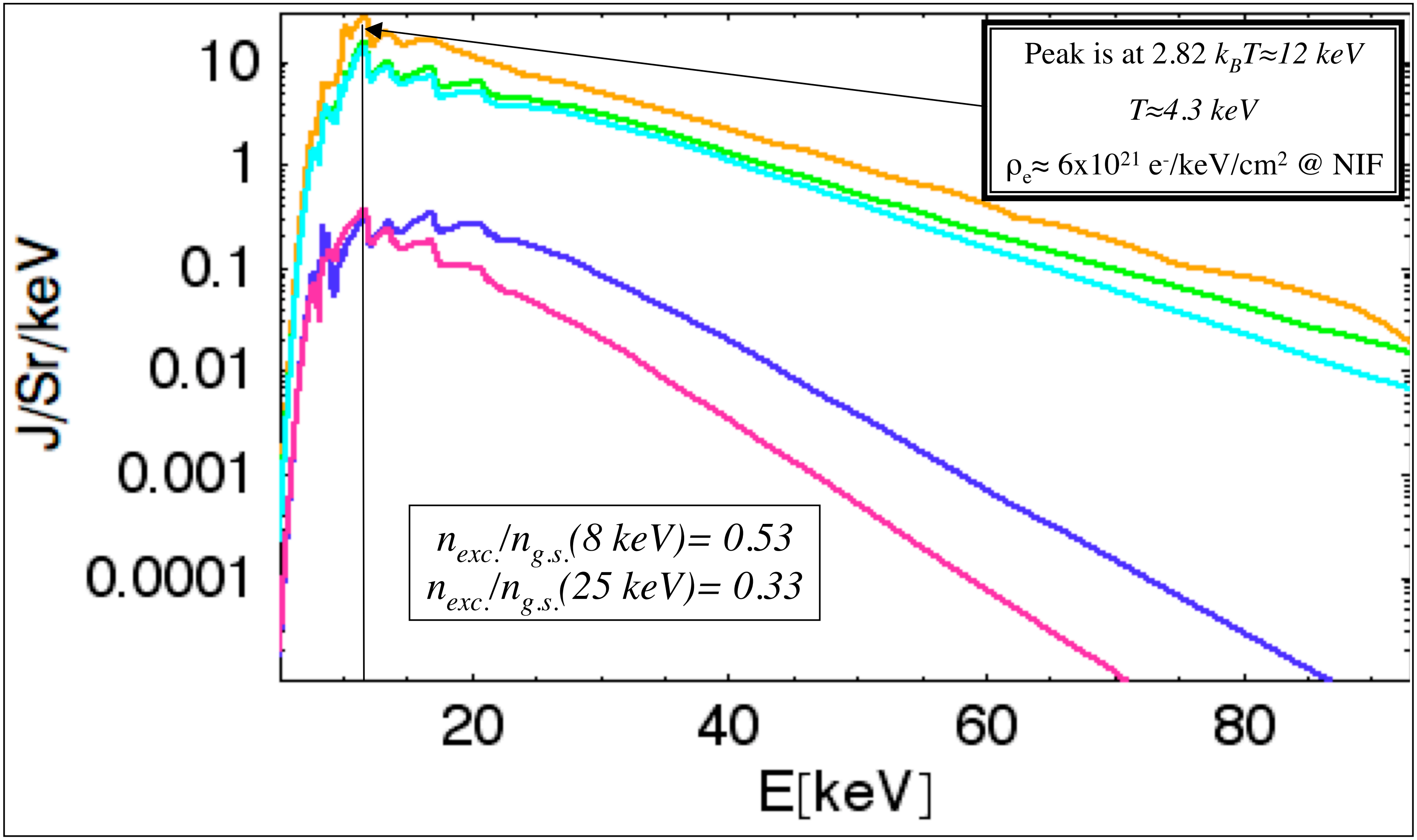
*J. Escher & F.S. Dietrich: UCRL-TR-212509

What does the NIF photon spectrum* look like?



Peak is at 2.82 $k_BT \approx 12\ keV$

$T \approx 4.3\ keV$

$\rho_e \approx 6 \times 10^{21}$ e^-/keV/cm^2 @ NIF

$n_{exc.}/n_{g.s.}(8\ keV) = 0.53$

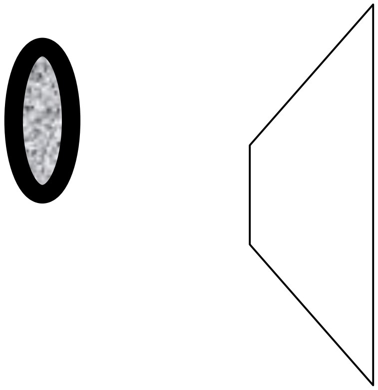
$n_{exc.}/n_{g.s.}(25\ keV) = 0.33$

Temperatures of 2-6 keV are typical for HT+0.5% D shots

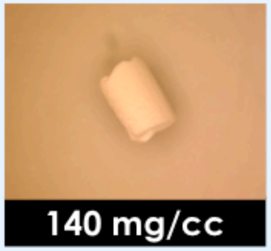
*Calculations courtesy of R. Tommasini

What would in ideal capsule look like?

1. Capsule should NOT be cryogenic
   - Minimizes spread in temperature
2. Tracer should be mixed in with fuel
   - Ensures peak temperature
3. Symmetry of the shot is less important
   - Direct drive is OK



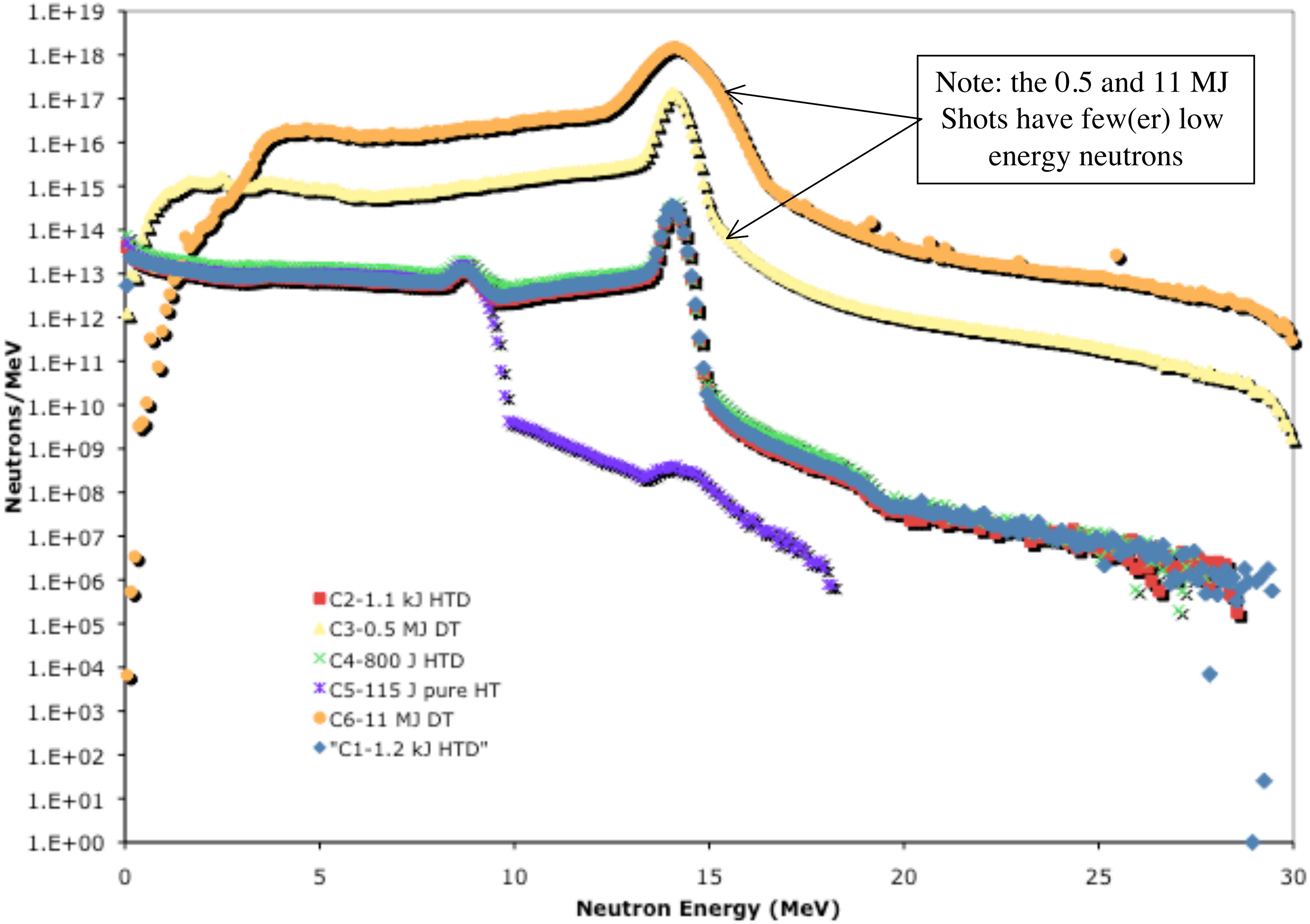
Ta_2O_5 **(10^{15} atoms)** ***Hund et al.,***



Tantalum oxide (Ta_2O_5) aerogels

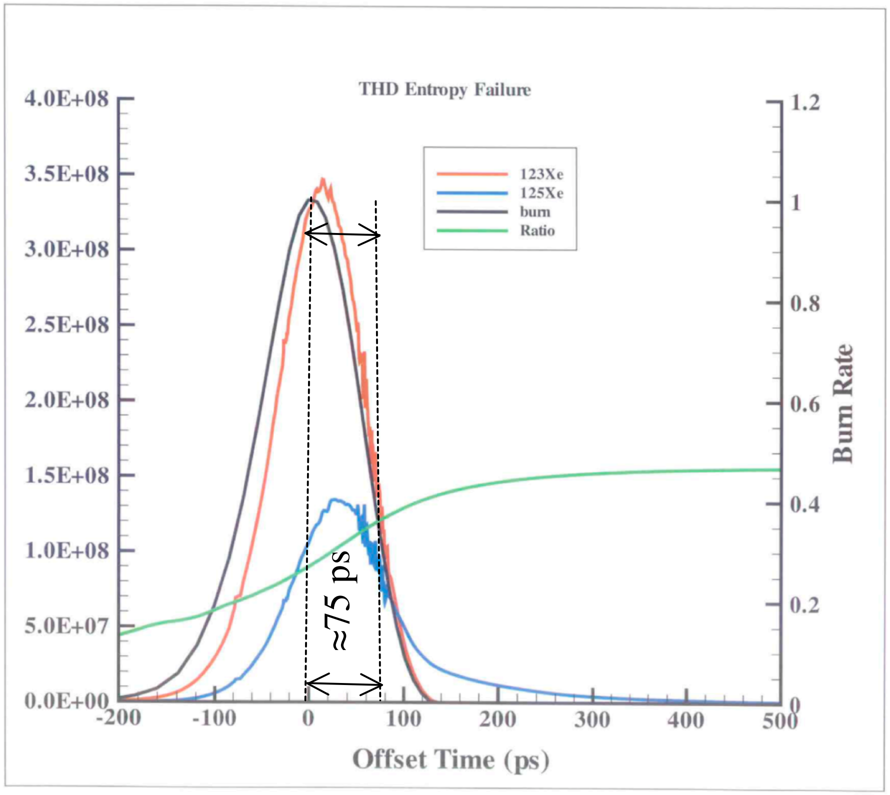
Application: HED and emission experiments

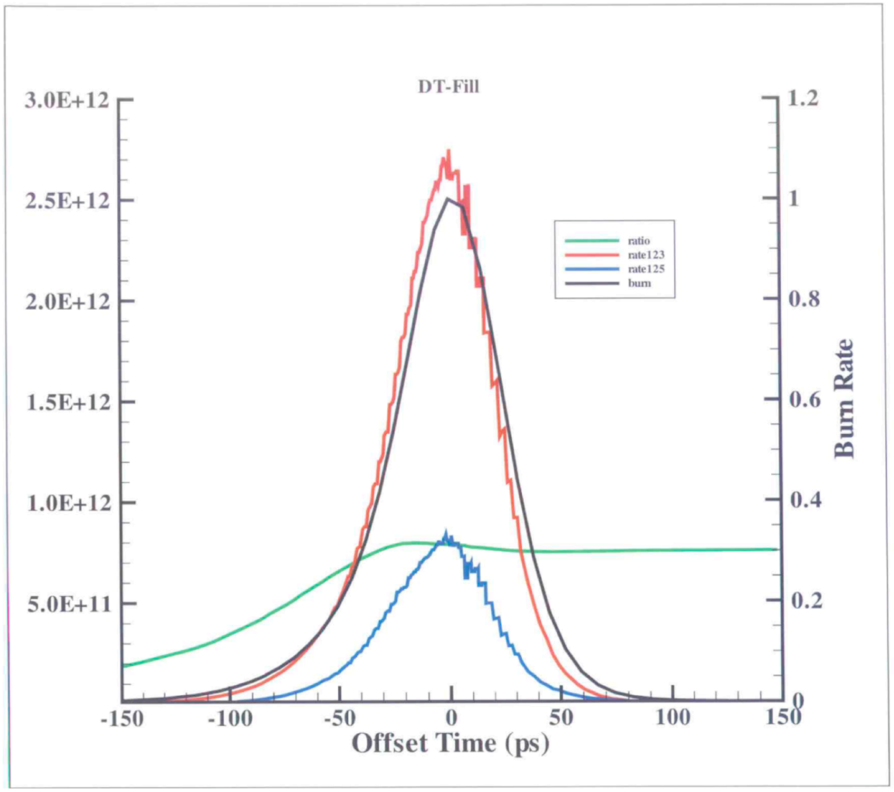
What does the NIF neutron spectra look like (Modeling courtesy of C. Cerjan)



Note: the 0.5 and 11 MJ Shots have few(er) low energy neutrons

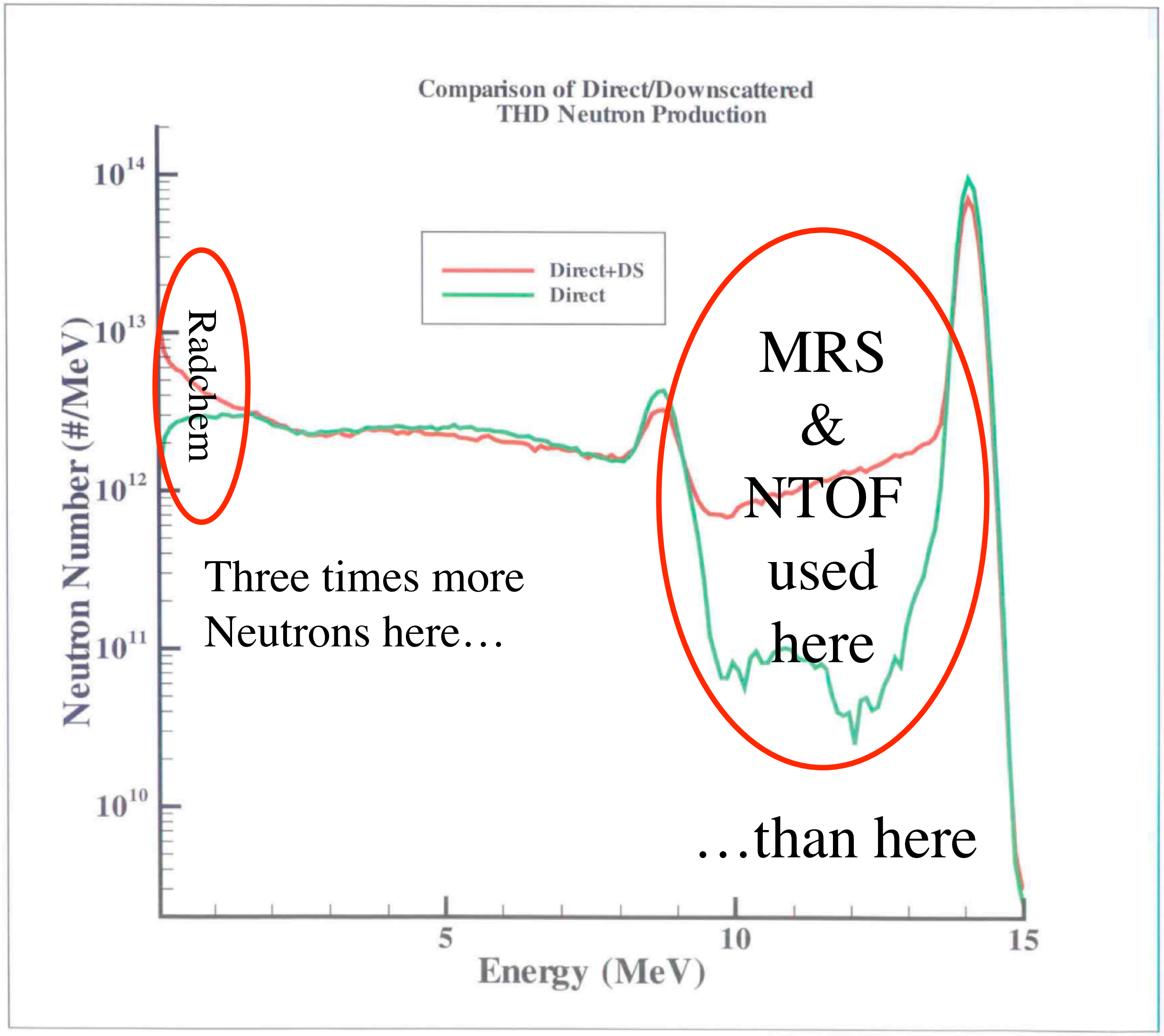
HTD shots produce (n,γ) much later than DT because the capsule holds together longer





In 75 ps a 200 keV neutron crosses the capsule >500 times
Low energy neutrons (n,γ) dominate in HTD shots

Simulations show that low energy neutrons in HTD are from downscattered primaries



Radchem

Three times more Neutrons here…

MRS & NTOF used here

…than here

Measure ^{171}Tm*(n,γ) *relative to* ^{169}Tm*(n,γ) at NIF

Where/when the tracers are

Cross Section

$$N_{172} = \varepsilon_{solid\,collection} \iiint_{shot} \phi_n(\vec{r},t,E_n) \times N_{171}(\vec{r}) \times \sigma^{171}_{(n,\gamma)}(E_n)\,d\vec{r}\;dt\;dE_n$$

Where/when the neutron are

***T_n* Determined using NTOF/MRS**

$$\Downarrow$$

$$\frac{N_{172}}{N_{170}} = \frac{\displaystyle\iiint_{shot} \phi_n(\vec{r},t,E_n) \times N_{171}(\vec{r}) \times \sigma^{171}_{(n,\gamma)}(E_n)\,d\vec{r}\;dt\;dE_n}{\displaystyle\iiint_{shot} \phi_n(\vec{r},t,E_n) \times N_{169}(\vec{r}) \times \sigma^{169}_{(n,\gamma)}(E_n)\,d\vec{r}\;dt\;dE_n}$$

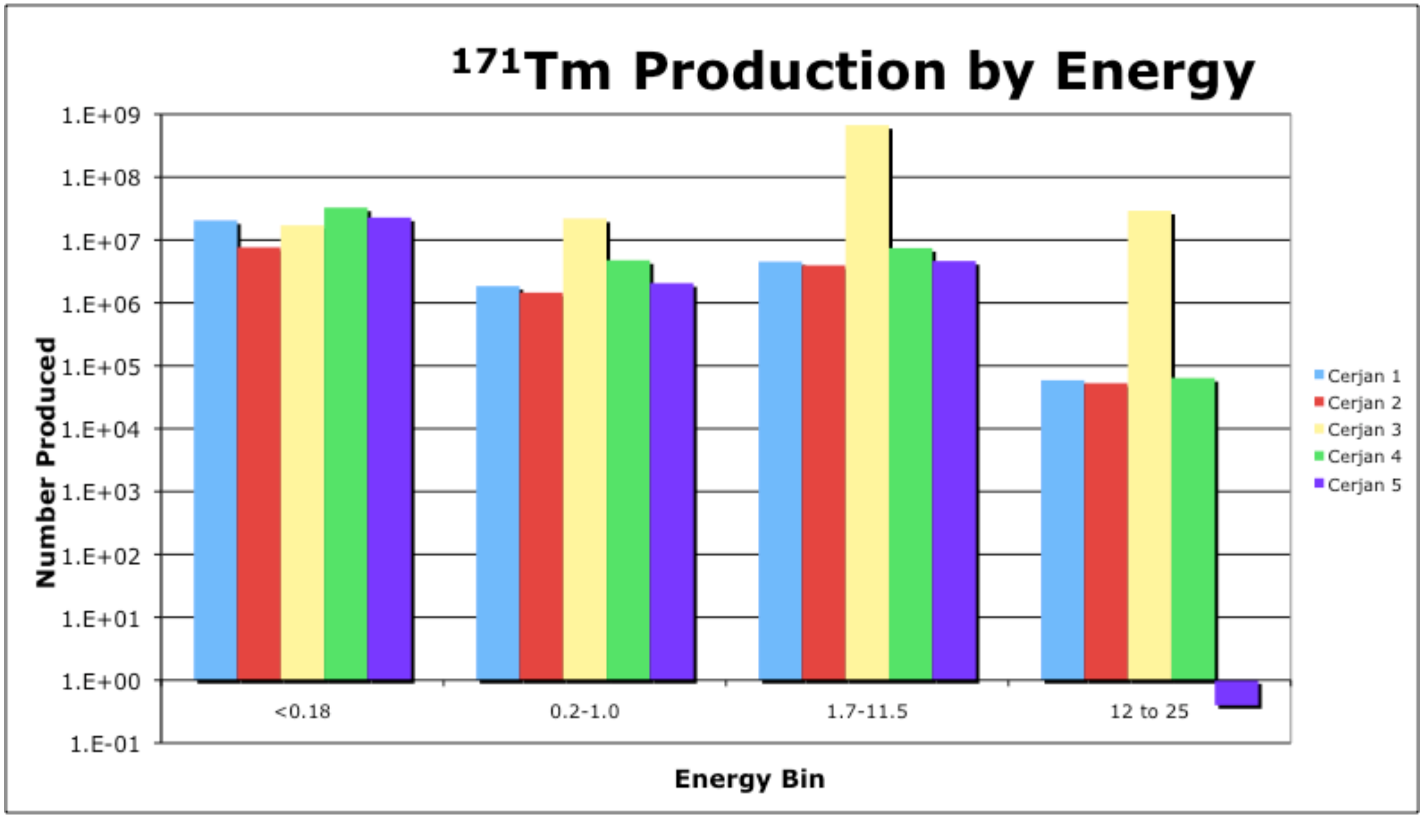
$$\boxed{\frac{N_{172}}{N_{170}} = \frac{\overline{\sigma}^{171}_{(n,\gamma)}}{\overline{\sigma}^{169}_{(n,\gamma)}}}$$

"Average" Cross Sections

≈3/4^{ths} of the (n,γ) comes from low energy (2-200 keV) neutrons

Loading 10^{14} tracer atoms → $5\text{x}10^{5}$ atoms of (n,γ) product

Most of the (n,γ) reactions come from low energy neutrons



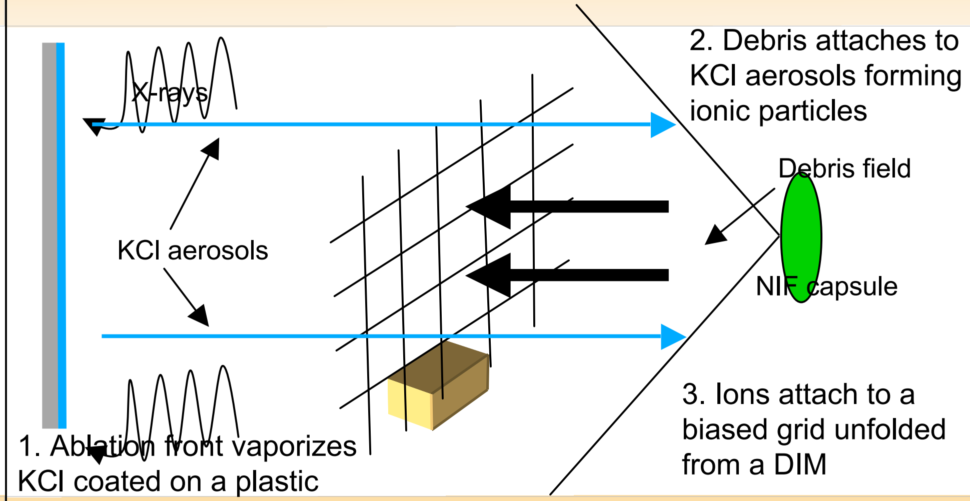
Neutron Energy	HTD: C4	DT: C3	Pure HT: C5
<0.18	72.78%	2.32%	77.29%
0.2-1.0	10.57%	2.98%	7.00%
1.7-11.5	16.51%	90.75%	15.71%
12 to 25	0.14%	3.95%	0.00%

Current Ideas for Collection of Solid Debris at NIF
(compliments of D. Shaughnessy, U. Greife, R. Rundberg)

Solid Debris Collection Will Be Very Challenging

- Requires high efficiency and large solid angle
- Collector must be able to survive ablation and shock
- Ease of deployment into the chamber and post-shot removal must be considered
- Plasma condensation chemistry, debris velocities and temperatures are not known for the NIF environment

LLNL Idea – Ion Collection on a Biased Grid

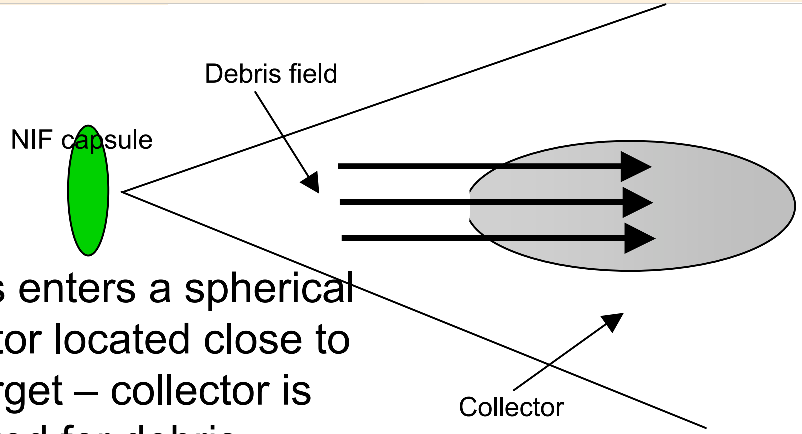


2. Debris attaches to KCl aerosols forming ionic particles

3. Ions attach to a biased grid unfolded from a DIM

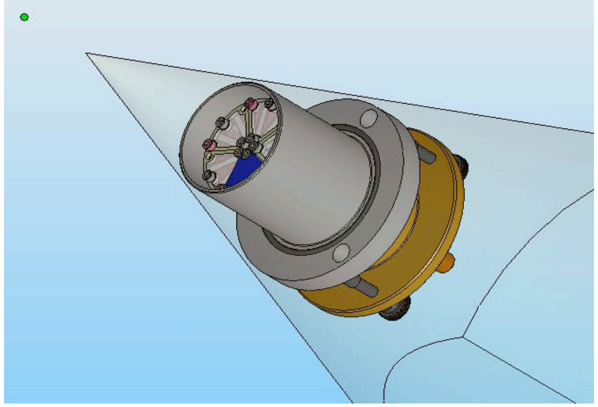
1. Ablation front vaporizes KCl coated on a plastic

Colorado School of Mines (U. Greife)



Debris enters a spherical collector located close to the target – collector is removed for debris analysis

LANL Debris Collector – Testing at Omega



Combination debris collector / beta detector will be fielded inside the NIF chamber for measuring triton reactions *in situ*

Option 1: ^{242m}Am was suggested as an ideal case* for measuring NEEC by *Palffy et al.*,

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Isomer Triggering via Nuclear Excitation by Electron Capture

Adriana Pálffy,* Jörg Evers,† and Christoph H. Keitel‡
Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

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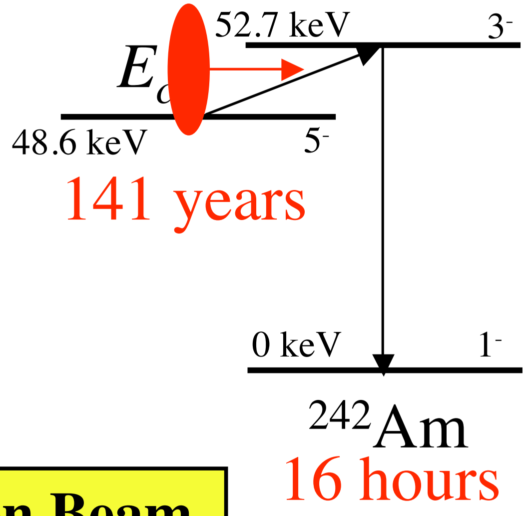
Triggering of long-lived nuclear isomeric states via coupling to the atomic shells in the process of nuclear excitation by electron capture (NEEC) is studied. NEEC occurring in highly charged ions can excite the isomeric state to a triggering level that subsequently decays to the ground state. We present total cross sections for NEEC isomer triggering considering experimentally confirmed low-lying triggering levels and reaction rates based on realistic experimental parameters in ion storage rings. A comparison with other isomer triggering mechanisms shows that, among these, NEEC is the most efficient.

$$S \approx \frac{2\pi^2}{k^2}\frac{g_f}{g_i}\Gamma_{52.7\rightarrow 48.6}$$

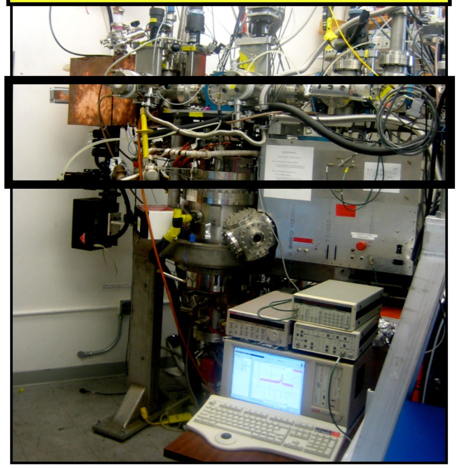
TABLE II. Total resonance strengths S for NEEC and x-ray triggering of isomers. NEEC occurs in the nl_j orbital. The continuum electron energy at the resonance is denoted by E_c.

^A_ZX	nl_j	E_c (keV)	$S^{I\to F}_{\text{NEEC}}$ (b eV)	$S^{I\to F}_{\text{x ray}}$ (b eV)
$^{93}_{42}$Mo	$3p_{3/2}$	2.113	9.1×10^{-6}	1.4×10^{-8}
$^{152}_{63}$Eu	$2s_{1/2}$	5.204	3.4×10^{-4}	6.5×10^{-5}
$^{178}_{72}$Hf	$1s_{1/2}$	51.373	2.0×10^{-7}	5.4×10^{-8}
$^{189}_{76}$Os	$1s_{1/2}$	131.050	1.2×10^{-3}	2.2×10^{-2}
$^{204}_{92}$Pb	$2p_{3/2}$	55.138	4.9×10^{-5}	8.7×10^{-6}
$^{235}_{92}$U	$2p_{1/2}$	21.992	1.3×10^{-1}	1.3×10^{-2}
$^{242}_{95}$Am	$5p_{3/2}$	0.135	3.6×10^{-3}	2.4×10^{-8}



Electron Beam

Ion Trap



Joint venture

With

LLNL

Youngstown

Surrey