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JINA Workshop Nuclear Physics in Hot Dense Dynamic Plasmas

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Nuclear Excitation by Electron Transition and capture (NEET &NEEC) in laser produced plasmas at Omega (& NIF)

JINA Workshop - Nuclear Physics in Hot Dense Dynamic Plasmas
March 13th, London, UK

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Measuring NEET and NEEC is relevant for probing stellar cross-sections and testing atomic models in hot plasmas

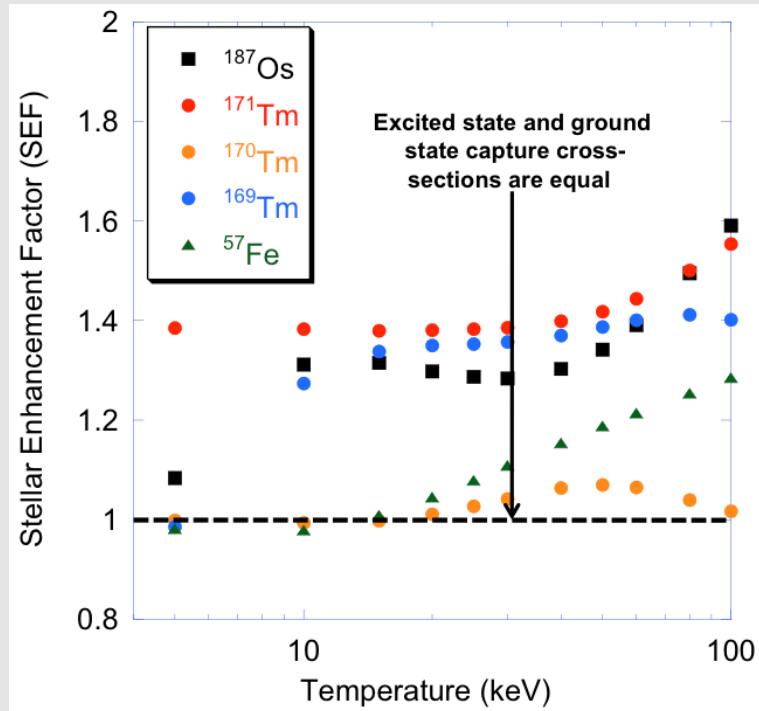
Using NEEC and NEET we can excite nuclear levels in laboratory plasmas

- *NIF:* Measure effect of excited nuclear levels on (n,γ) cross-sections
  - 60%
  - Never been measured
- *Omega:* Test cross-sections for creating these excited levels via NEEC and NEET

Will allow us to test models that estimate resonance overlap of atomic states with the nucleus

- Average Atom model (AA) (CEA&LLNL)
  - single average wave-function potential
- Super Transition Array (STA) model (LLNL)
  - More realistic individual configuration potentials

T~ keV plasmas can be created via DD laser irradiation

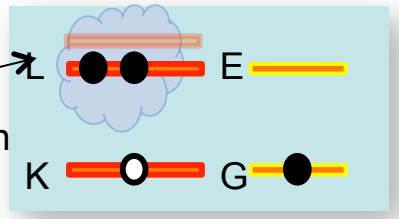


NEET experimental data is scarce and not in a plasma environment, NEEC has not yet been observed!

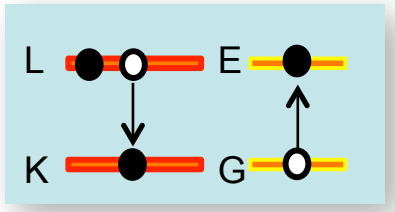
NEET is Nuclear Excitation by Electron Transition

NEET

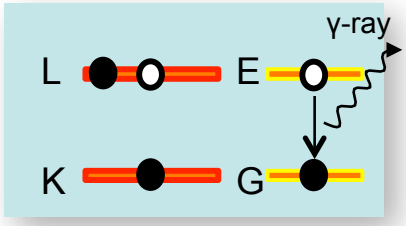
Binding energies change with the plasma charge state



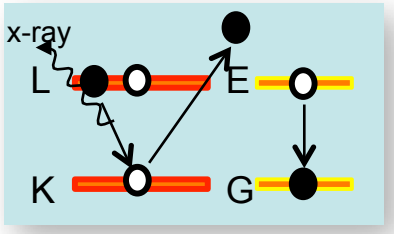
A system with the nucleus in ground state and atomic shell vacancies



Electrons transition to fill the vacancies and energy is transferred to the nucleus



Radiative decay of nucleus by gamma-ray emission



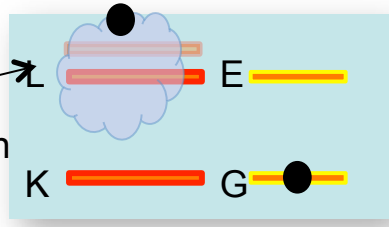
Radiative decay of nucleus by Internal Conversion electron emission

Signature for NEET:

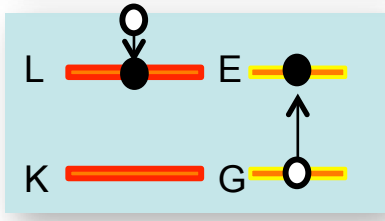
-Characteristic Gamma-rays
-Cascade of x-rays when electrons transition to fill the IC electron vacancy.

NEEC is Nuclear Excitation by Electron Capture

Binding energies change with the plasma charge state

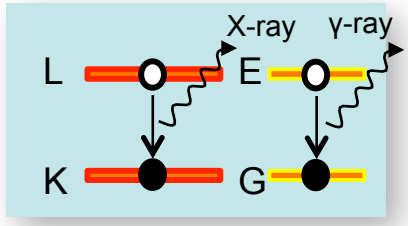


A system with an ion in the ground state and free electrons



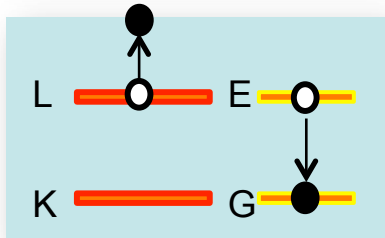
Electron is captured into an ionic state

Nucleus is excited (NEEC occurs when electron energy +BE = nucl trans E)



Radiative decay of nucleus by gamma-ray emission

or



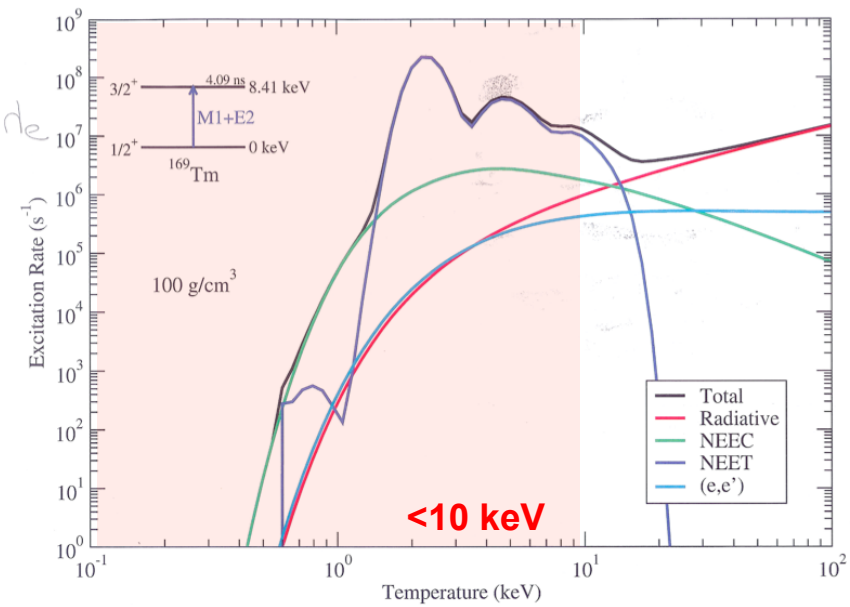
Radiative decay of nucleus by IC

Signature for NEEC:

-Characteristic Gamma-rays
-Cascade of x-rays when electrons transition to fill the IC electron vacancy.

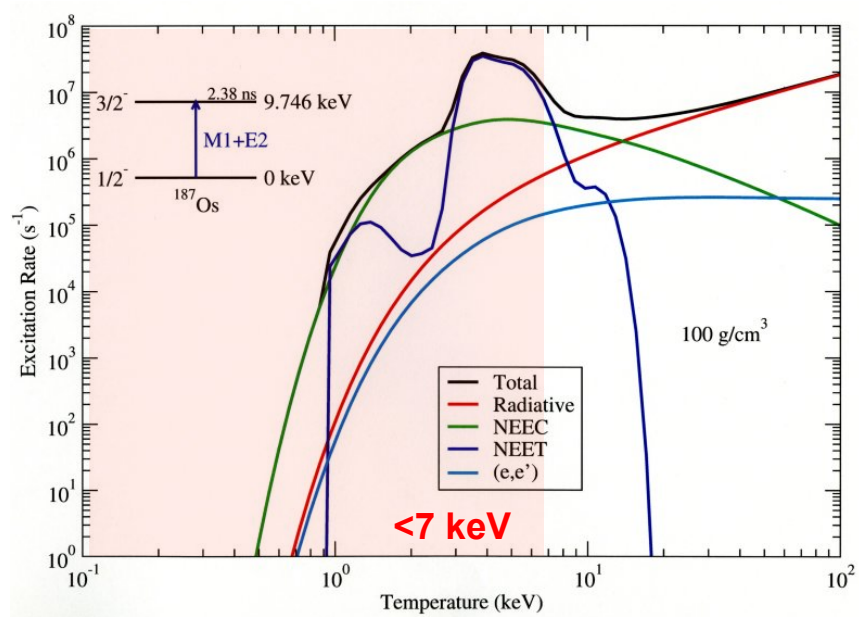
Nuclear-atomic-plasma interaction rates are important for creating excited state plasmas in the laboratory

^{169}Tm



NEEC or NEET > 10x Radiative, (e,e')

^{187}Os



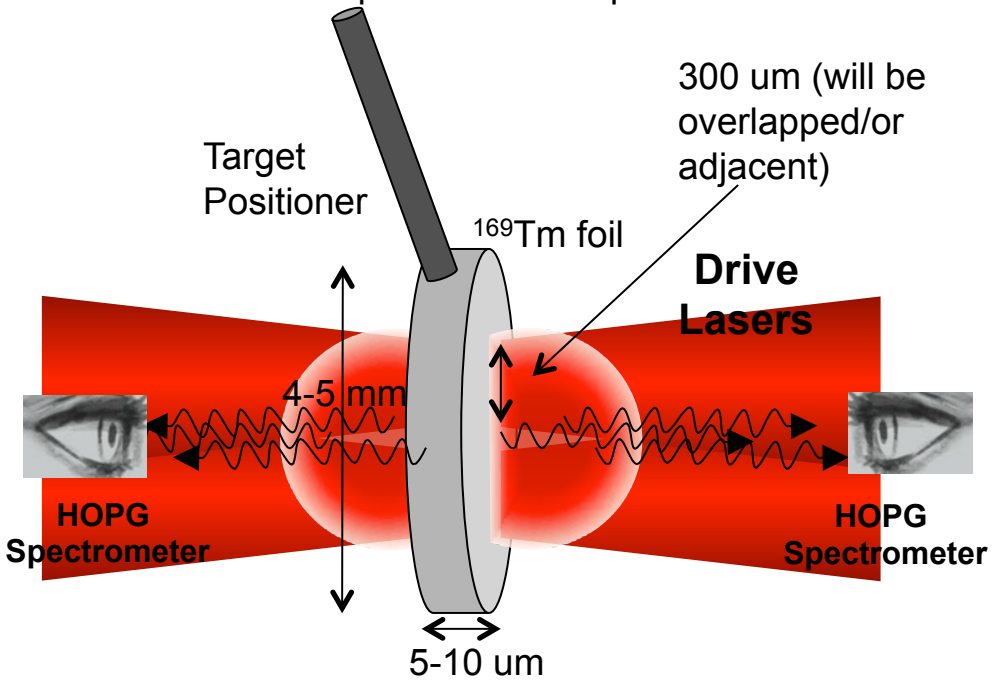
NEEC or NEET > 10x Radiative, (e,e')

- The NEET rate has resonant temperatures due to atomic transitions
- The NEEC rate is smooth because free-electrons contribute to the energy miss-match

(Calculations provided by Gosselin, Meot, Morel, CEA)

We plan to create these hot plasmas at the 30kJ Omega laser facility, LLE

Schematic of the experimental setup



Advantages of a foil target:

- High temperatures can be reached
- The target solid angle is 1/2

T~ keV plasmas can be created via DD laser irradiation

-Laser is incident on a target foil and a surface plasma is created

-Energy is coupled to hot electrons

-The surface plasma can reach temperatures of several keV (in the low density blowoff)

-We would observe NEEC/NEET via the gamma emission using:

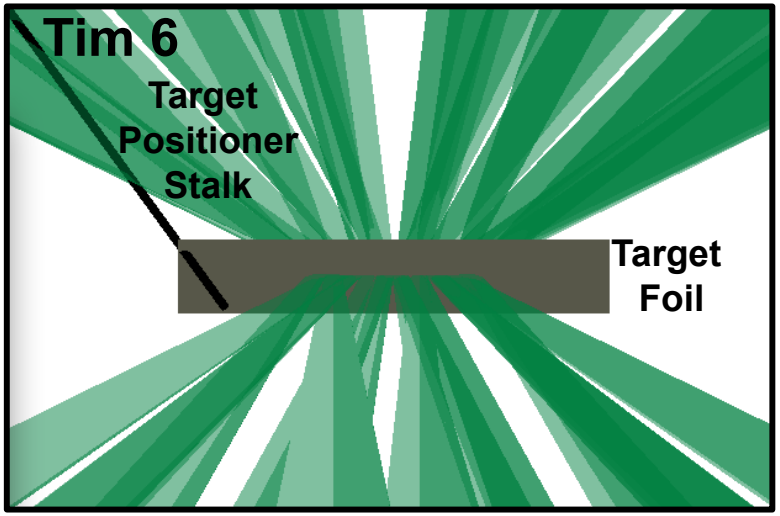
-Bragg crystal spectrometer (coupled to a framing camera and x-ray streak camera)

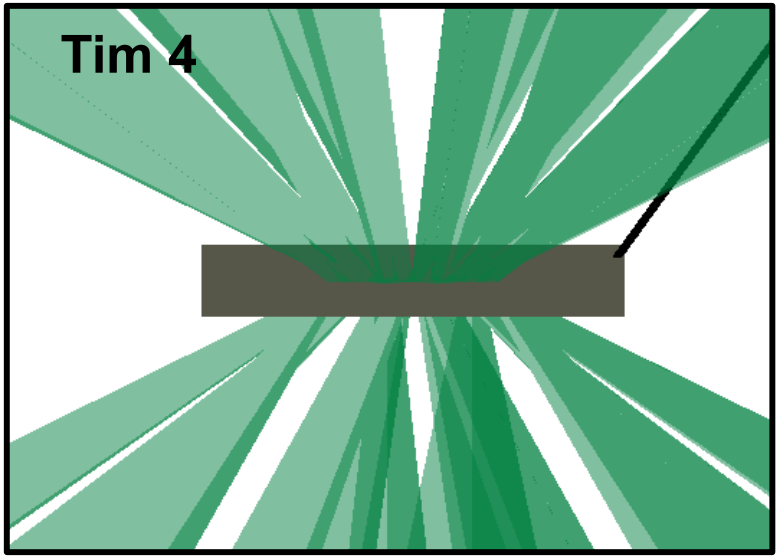
-Filtered diode

- DPPs are used to create a spatially uniform and repeatable laser spot

- Thin foils driven from both sides enables a more-uniform temperature distribution and full use of the available energy at Omega (30kJ)

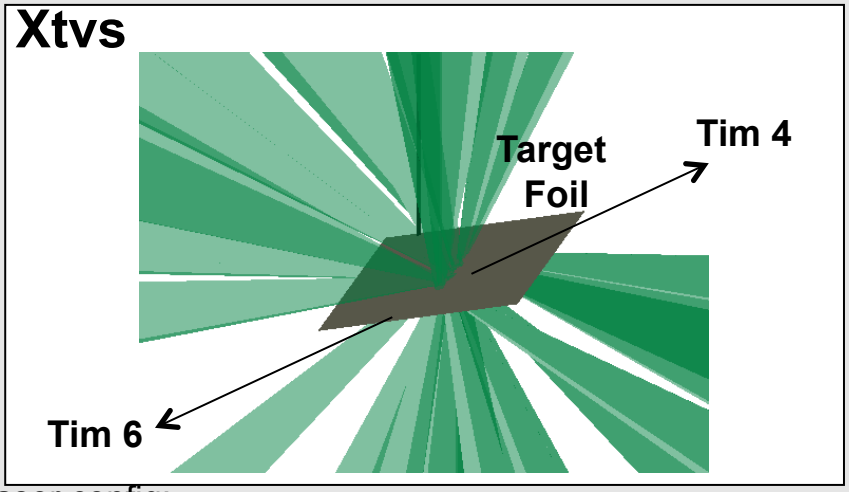
The target foils can be oriented in the chamber to enable two spectrometers with high energy resolution





Effective spot can be decreased to ~100 um

Experimental Configuration



Laser config:

Beams	CPPs	CPP size	Pulse	**Special**
44-56	44	IDI-300 DPP	SG1014	

Diagnostics:

-Tim 6: Flat Bragg Spectrometer

-Tim 4: Curved Bragg Spectrometer

-Tim 3 and Tim 2: SSCs, different resolutions

-Tim 5: Filtered pinhole cameras to look at the emission vs time

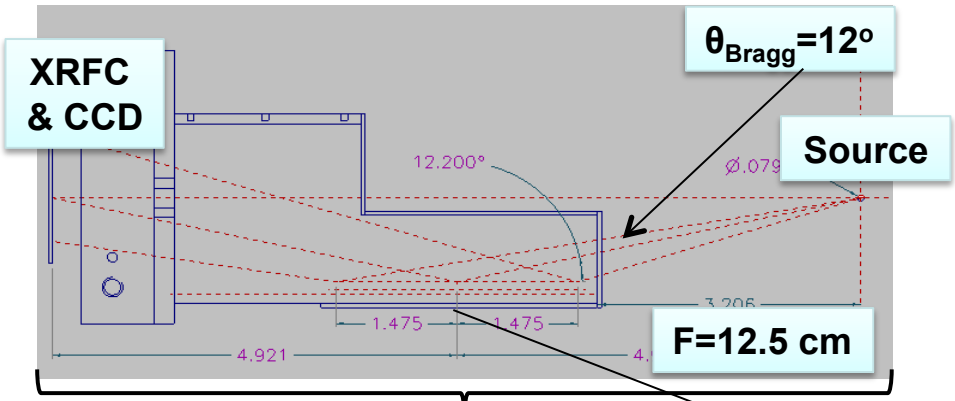
Fixed:

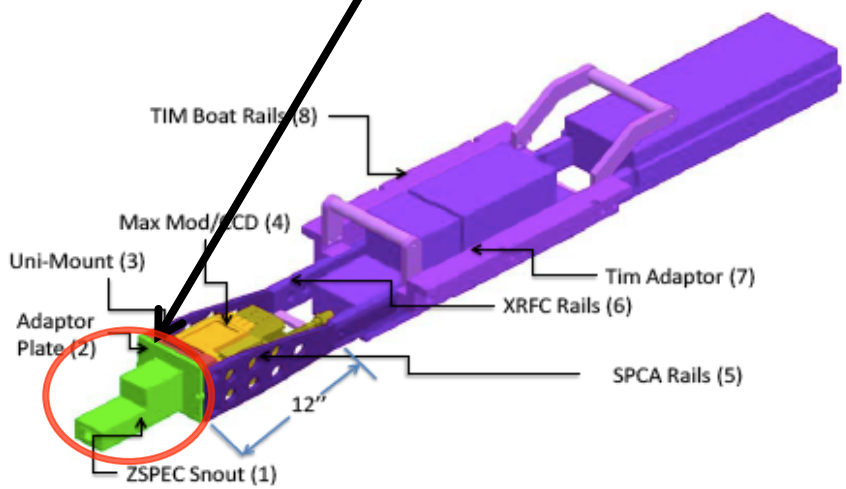
-Dante- to view emission and signal flux

-Integrated Pinhole: Emission size

The high collection efficiency of the HOPG spectrometer enables obtaining high signal to noise data

Highly Oriented Pyrolytic Graphite (HOPG) crystal has an reflectivity of ~3 mrad





XRFC: 40, 80, 200, 300, 400, 500, 1000 ps resolution

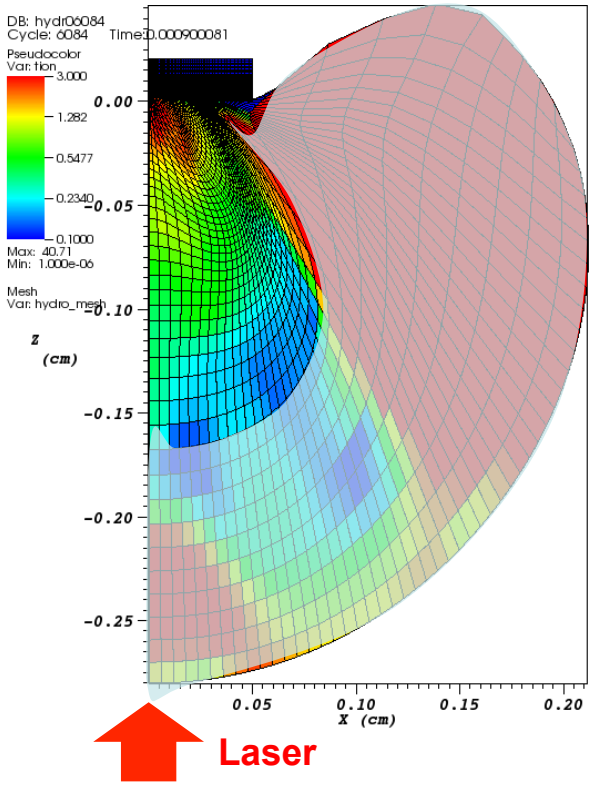
Flat HOPG crystal (50.8x25.4 mm)

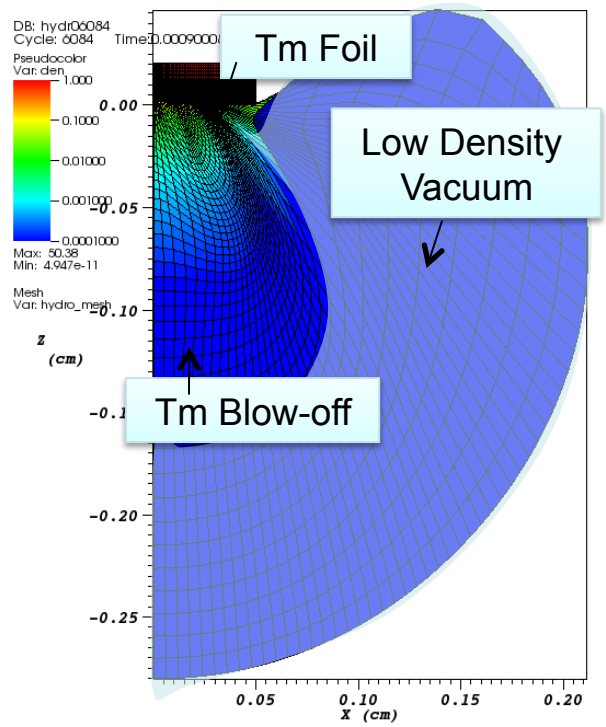
$$\Omega = \frac{rd}{2F}\frac{1}{4\pi} = \frac{.003 \text{ x } .6}{2(12.5)}\frac{1}{4\pi} \sim 6\text{x}10^{-6}$$

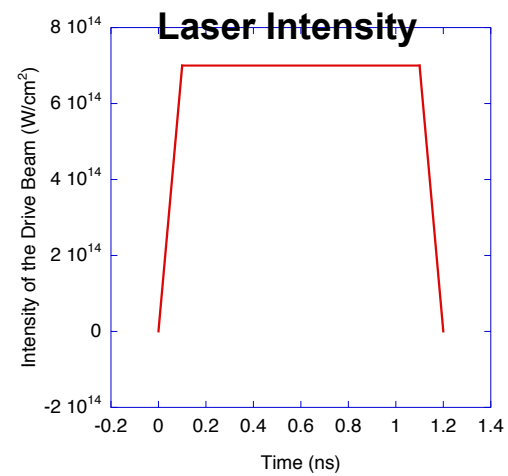
Curved HOPG crystal (50.8x25.4 mm)

$$\Omega = \frac{rd}{F}\frac{1}{4\pi} = \frac{.003 \text{ x } 2.54}{(12.5)}\frac{1}{4\pi} \sim 5\text{x}10^{-5}$$

2D Hydra simulations are used to estimate the mass density and temperature for laser conditions at Omega/NIF







Laser Parameters:
-1kJ in 1.1 ns
-Spot size is 200 um in diameter (1/2 of spot is shown on the HYDRA target, which is mirrored about X=0)

Density and Temperature will be optimized:
-Varying the laser intensity
-Simulating foils driven from both sides enables a more-uniform temperature distribution and full use of the available energy at Omega (30kJ)
-Comparing non-LTE DCA calculations with rates vs charge state (will be provided by S. Libby, M. Chen, and B. Wilson, LLNL)

Post-processing of 2D Hydra simulations are used to estimate the NEET'd signal for 169Tm

Detailed estimate of # of excited Tm:
Matlab to post-process HYDRA results:

$$N_{NEET} = \frac{\rho}{A} N_A V_{ol} * 360\deg * R_{NEET}$$

$$V_{ol} = Vol\ of\ Cell$$

$$R_{NEEC} = Neec\ Rate\ (T)$$

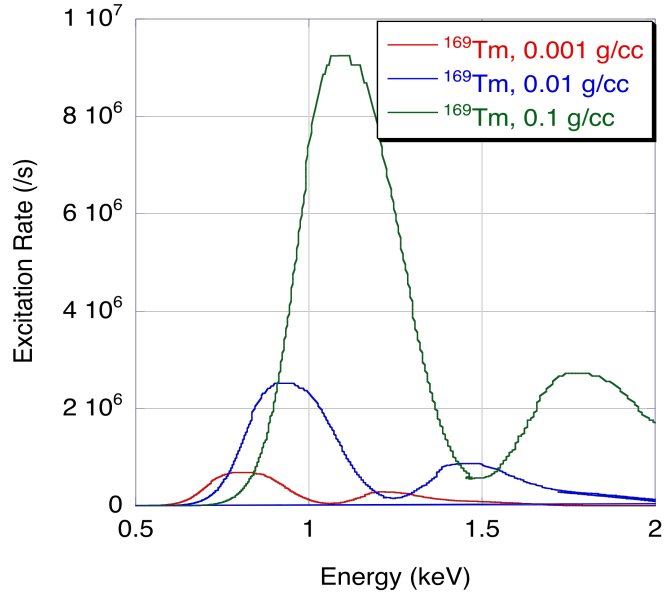
$$N_{NEEC} = Number\ NEEC'd\ nuclei$$

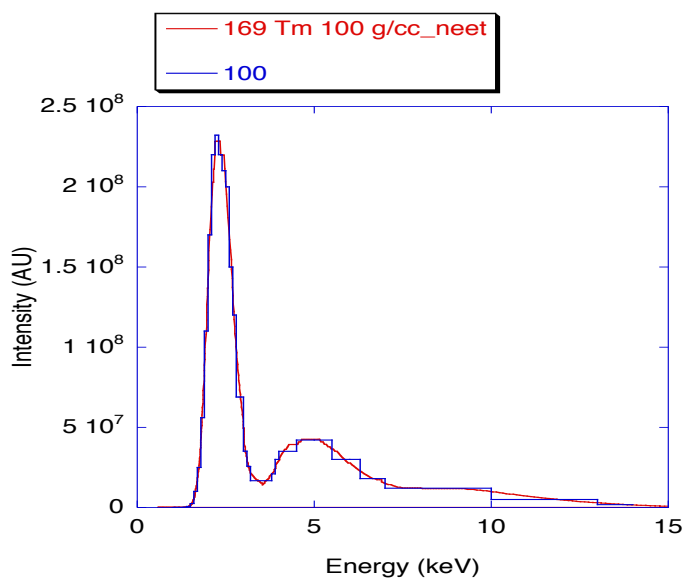
Rates calculated for each cell, with corresponding density and temperature rates, and summed over all.

Then, total NEEC'd number is multiplied by 15 because we will have 15 spots at 1 kJ

For these laser conditions the total number of NEET'd ^{169}Tm nuclei is:

$$N_{NEET} = 7x10^{13}$$





(Calculations provided by Gosselin, Meot, Morel, CEA)

We only have to worry about Non-LTE effects for ~35% of the signal

Contributions to the total rate vs Mass Density:

Fraction of the rate from 0.1 g/cc:

$$= 63.58\%$$

Fraction of the rate from 0.01 g/cc:

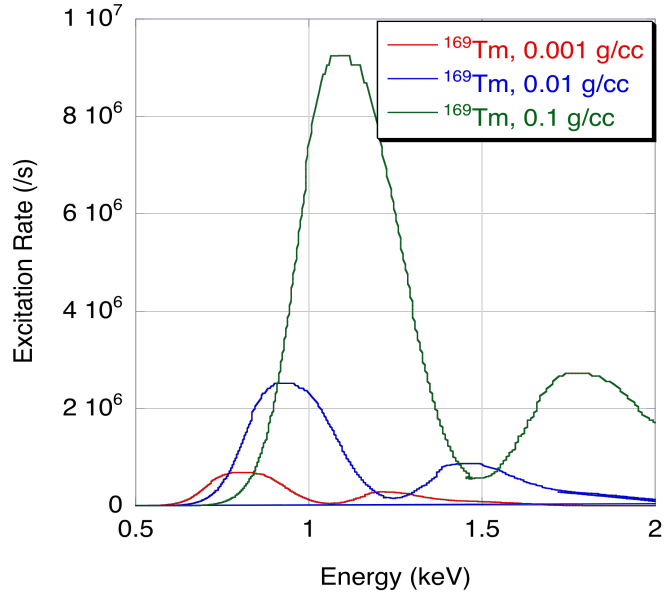
$$= 25.4\%$$

Fraction of the rate from <100 g/cc:

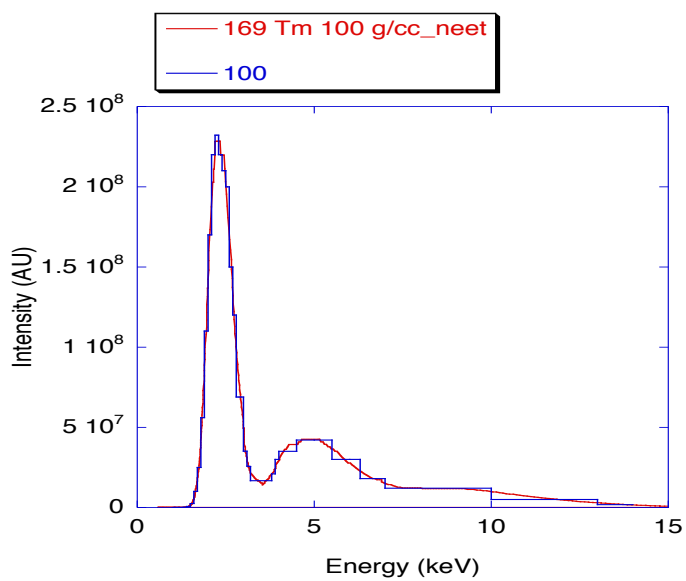
$$= 0.02\%$$

Fraction of the rate from 0.001 g/cc:

$$= 11\%$$



~No Contribution from compressed region



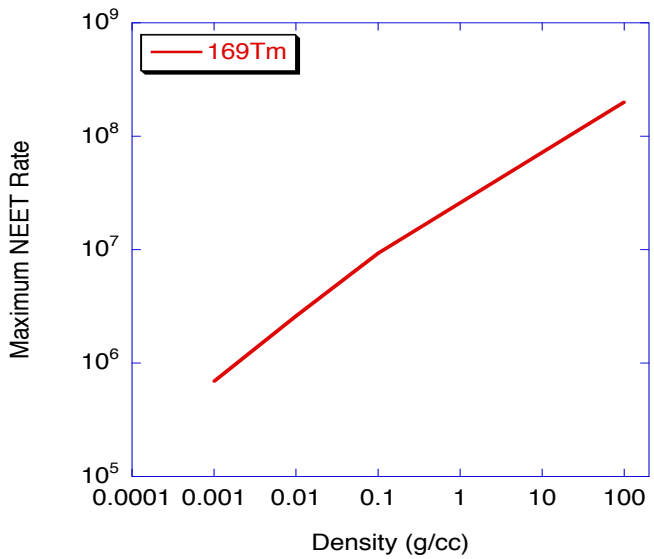
(S. Libby, M. Chen, B. Wilson will provide LTE vs non-LTE rates)

(Calculations provided by Gosselin, Meot, Morel, CEA)

Estimates of the number of detected photons, is high enough for current Omega detectors

-The rate decreases by about 70-80% for each order of magnitude (Also Roughly for Hg)

-This is used as a scaling for Fe and Os *(we only have 100g/cc calculations, S. Libby, M. Chen, B. Wilson will provide)*



Check this scaling with ^{169}Tm:

Rate for all densities: $N_{All} = 7\text{x}10^{13}$

Rate for all densities: $N_{\gamma 100} = 2\text{x}10^{15}$

$$N_{\gamma All} / N_{\gamma 100} \sim 0.035$$

$$R_{0.1} / R_{100} \sim 0.027$$

~30% more signal because the resonance temps downshift in E

An estimate for the detected photons at **Omega**

$$N_{Detected} = N_{NEET} \Omega_{\text{target}} \Omega_{\text{detector}} (1/\alpha)$$

X-rays at Dante $= 5\text{x}10^8$ *photons*

ϒ at flat xtal $= 2\text{x}10^6$ *photons*

ϒ at curved xtal $= 1\text{x}10^7$ *photons*

Flat Crystal Solid Angle: $\Omega_{\text{detector}} = 6\text{x}10^{-6}$

Curved Crystal Solid Angle: $\Omega_{\text{detector}} = 5\text{x}10^{-5}$

Dante Solid Angle: $\Omega_{\text{detector}} = 7\text{x}10^{-6}$

Target Solid Angle: $\Omega_{\text{target}} = 1$

Conversion Coefficient: $\alpha = 263.5$

-Target Ω is 1 because N atoms is calc for ½ target

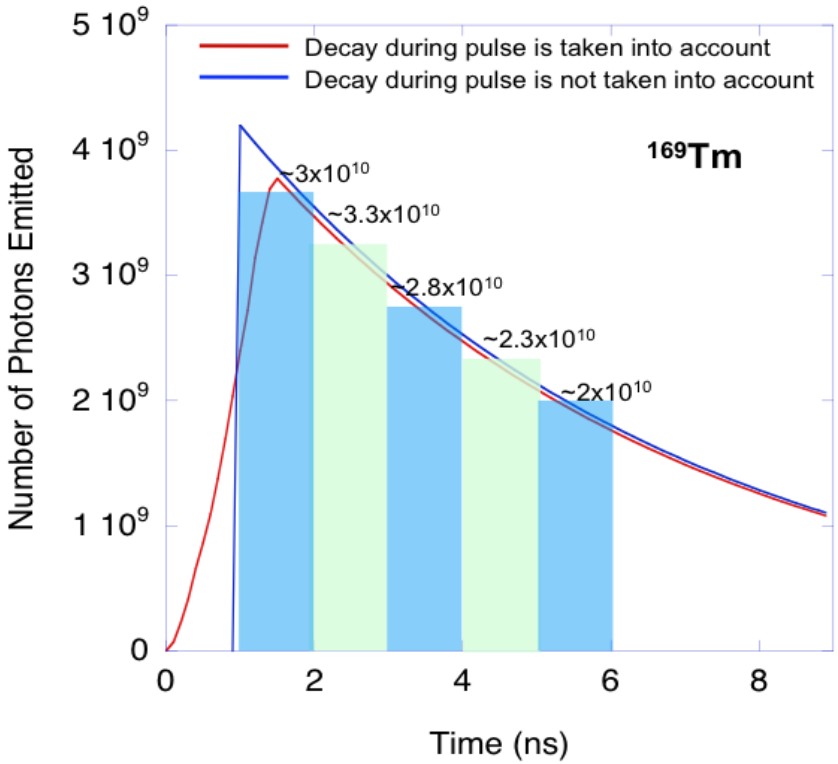
-(MCP QE is 0.05 at ~8-9 keV)

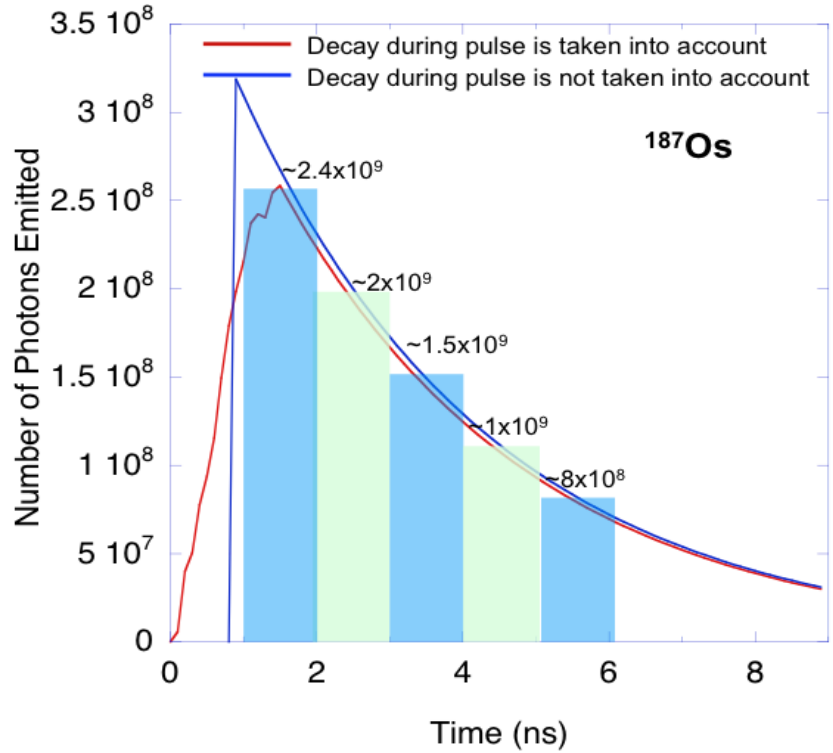
-We have XRTS data measured with HOPG of ~ same signal strength ($1\text{x}10^6$ photons) and a bandwidth of >140 eV

(S. Libby, M. Chen, B. Wilson will Os and Fe rates at low density)

Summary of candidates for observing NEEC/ NEET in a laser-produced plasma

Target Isotope	NEET/ NEEC per shot	Conv Coeff	Photon E (keV)	Half Life (ns)	# Photons Emitted	Flat x-tal sigma	Curved x-tal sigma	Dante Sigma	Photons Flat x-tal	Photons Curved x-tal	Photons Dante
^{169}Tm	7 x10^{13}	263.5	8.41	4.10	2.5x10^{11}	6x10^{-6}	5x10^{-5}	7x10^{-6}	1.6x10^{6}	1.3x10^{7}	5.0x10^{8}
^{57}Fe	3 x10^{9}	8.56	14.41	98.3	3.5x10^{8}	6x10^{-6}	5x10^{-5}	7x10^{-6}	2.0x10^{3}	1.8x10^{4}	2.0x10^{4}
^{187}Os	3 x10^{12}	280	9.76	2.38	1 x10^{10}	6x10^{-6}	5x10^{-5}	7x10^{-6}	6.4x10^{4}	5.4x10^{5}	2x10^{7}





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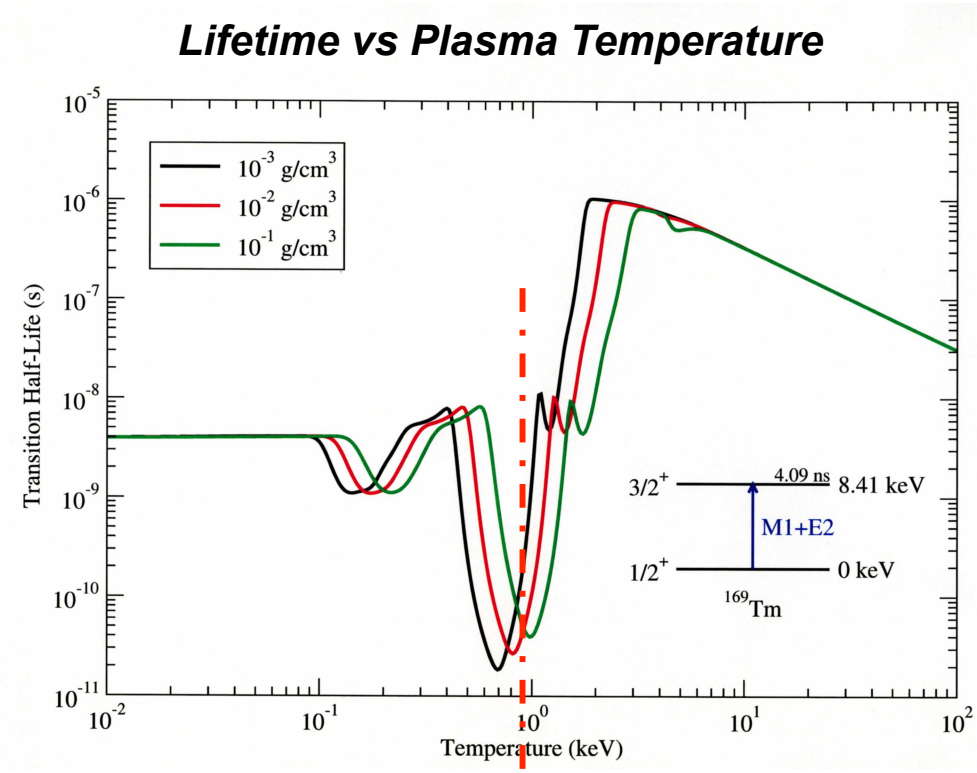
^{57}Fe	3×10^{9}	8.56	14.41	98.3	3.5×10^{8}	6×10^{-6}	5×10^{-5}	7×10^{-6}	2.0×10^{3}	1.8×10^{4}	2.0×10^{4}
^{187}Os	3×10^{12}	280	9.76	2.38	1×10^{10}	6×10^{-6}	5×10^{-5}	7×10^{-6}	6.4×10^{4}	5.4×10^{5}	2×10^{7}

Summary of possible issues:

Target Isotope	*Photon Energy*	*Signal*	*Spectral Response (plasma expansion)*	*Background*	*Radiative Ex Interference?*
169Tm	8.4 keV	**1E+07**	**Ok**	**? (*"short lifetime"*?, may be atomic emission interference)**	**No**
57Fe	14 keV	**2E+04**	**? (long lifetime, may blurr Bragg spec response, other det options?)**	**Ok**	**? (Waiting for CEA calcs)**
73Ge	13.28 keV	**<1.E+02**	**? (long lifetime, may blurr Bragg spec response, other det options?)**	**Ok**	**No**
187Os	9.76 keV	**5E+05**	**Ok**	**? (*"short lifetime"*?, may be atomic emission interference)**	**No**
201Hg	1.56 keV	**<7.6E+02**	**? (long lifetime, may blurr Bragg spec response, other det options?)**	**Ok**	**No**

Possible issue: ^{169}Tm Half-Life decreases with plasma temperature and with mass density Density



The half-life is predicted to decrease to 30 ps!

Issue Because: we don't want to look during the laser pulse due to background and atomic line emission (shown on the next slide)

Possibilities:

-Can we keep the temperature low enough so that line atomic emission doesn't interfere with our signal?

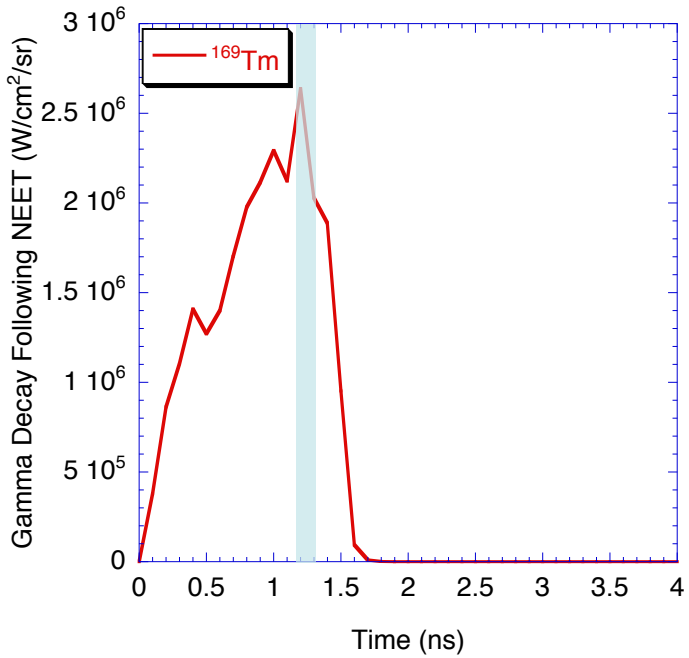
-We can probe during and after the laser beams turn off to test this lifetime prediction.

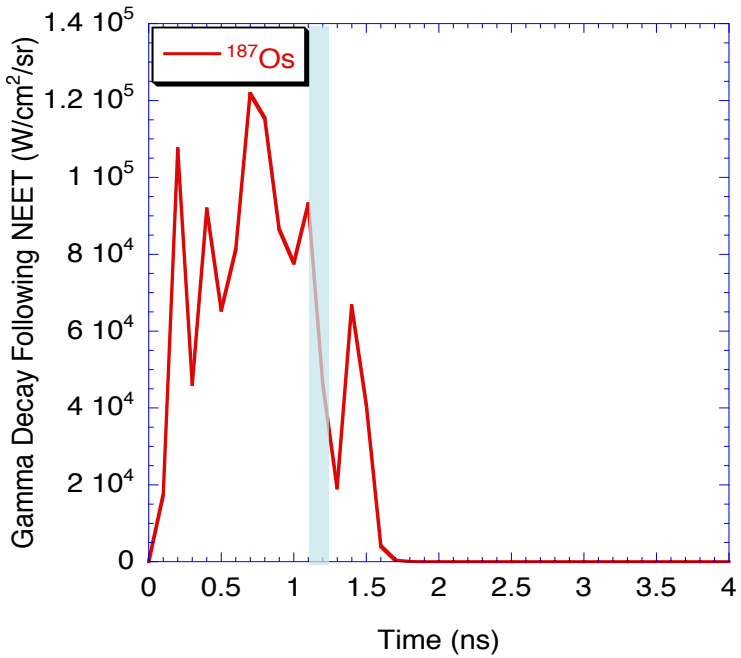
(Calculations provided by Gosselin, Meot, Morel, CEA)

Signal estimate over the plasma lifetime for the decrease in half-life to 30 ps

-HYDRA was considered for 100 ps time steps

-We can gate the XRFC with a 0.5ns or 100ps integration time to maximize signal to background (the background is changing in time as the plasma conditions change

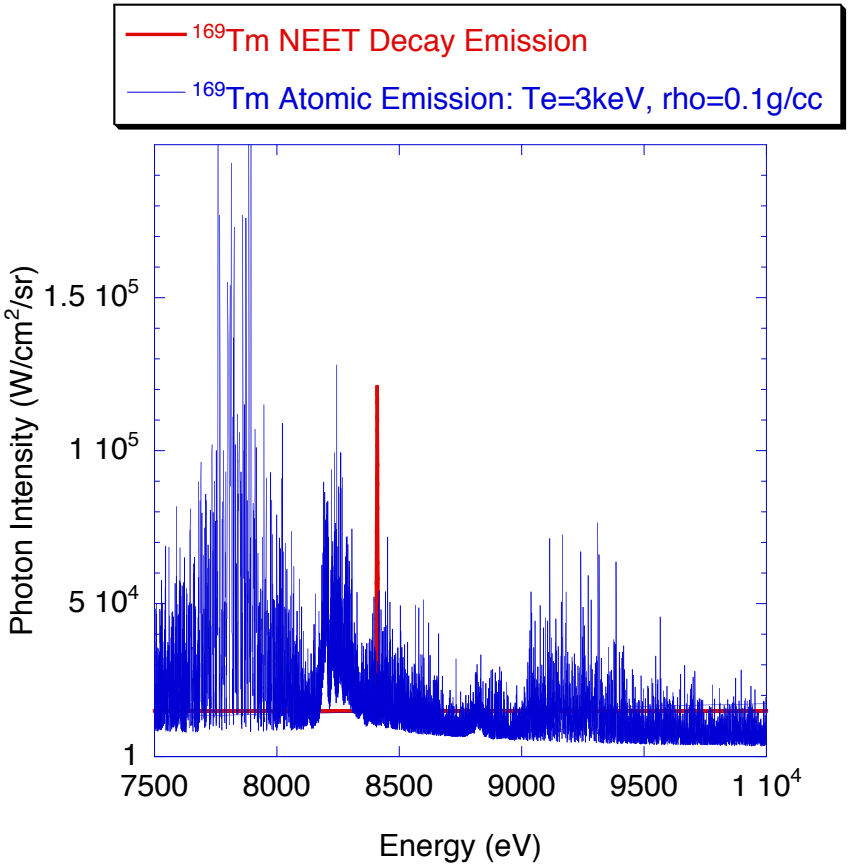




From 1.0-1.1 ns: T~5keV and ~0.1g/cc

From 1.1-1.2 ns: T~3keV and ~0.1g/cc

We can estimate the background from Atomic processes using FLYCHK



Spectral Intensity Analysis

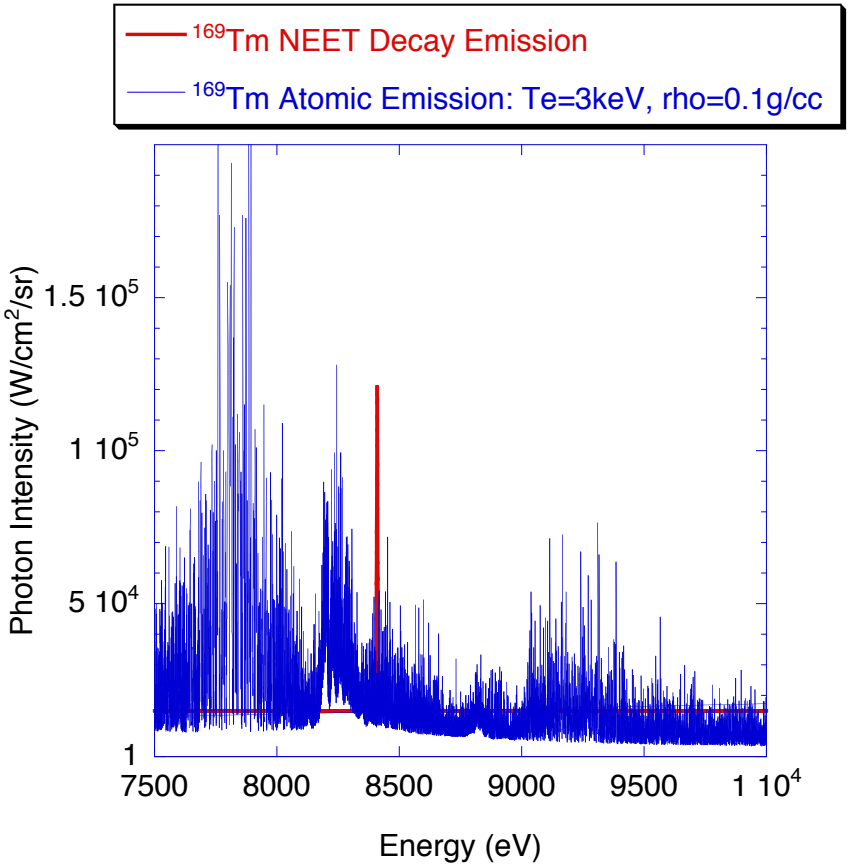
-Bound-bound transitions
Energy difference between two bound levels

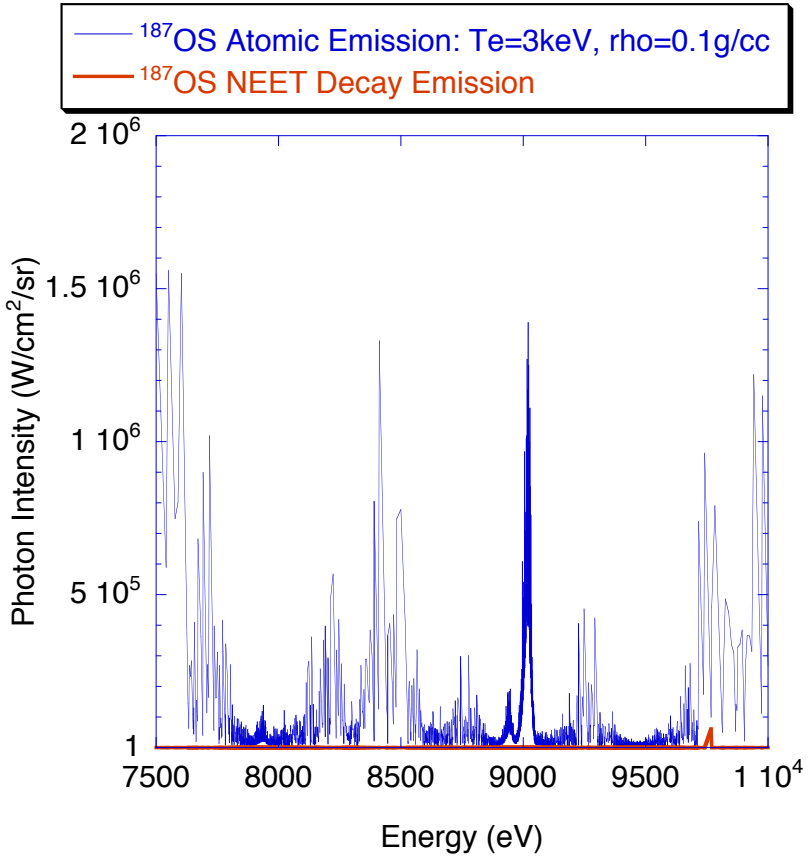
-Bound-free transitions
Recombination radiation: sum of the kinetic energy of the recombining electron and the binding energy of the shell.

-Free-free transitions
Bremsstrahlung: free-free transitions when a free electron loses its kinetic energy in a collision with electrons and ions. (E corresponds to change in electron kinetic energy, is distributed continuously over all frequencies)

- Broadening of the emitted gamma-rays (red) due to Doppler broadening ~2eV

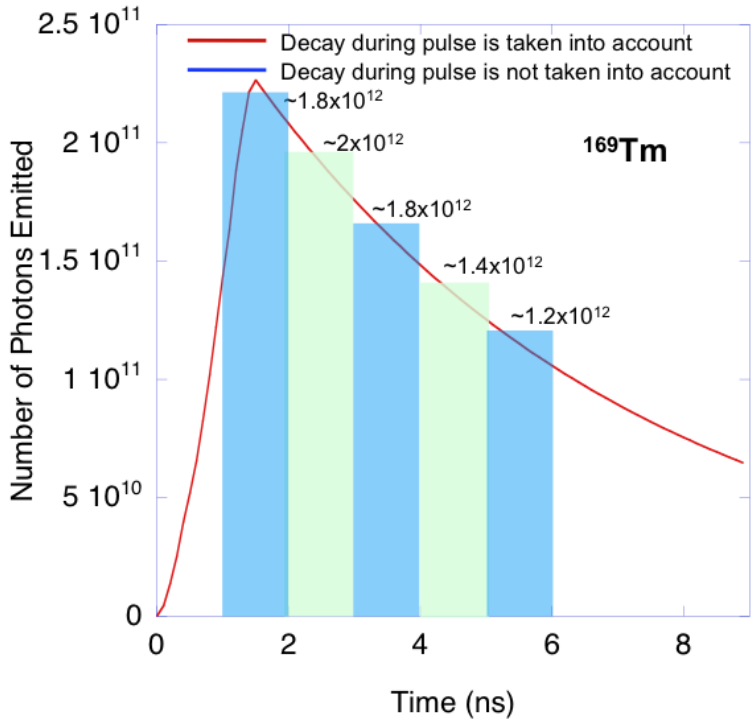
We can estimate the background from Atomic processes using FLYCHK

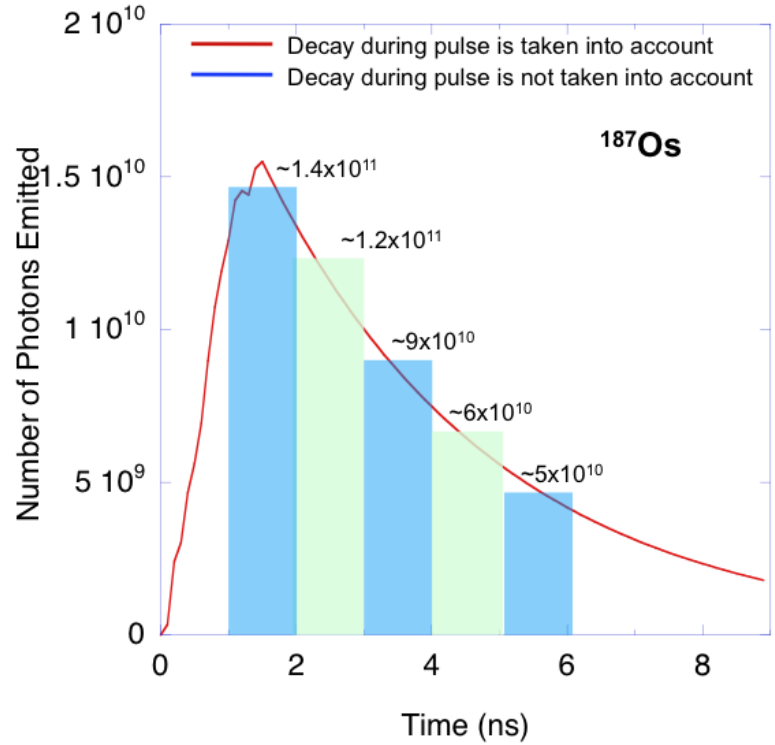




- Broadening of the emitted gamma-rays (red) due to Doppler broadening ~2eV
- May have a chance to see the emission with Tm but not with Os

Scaling of NEET and NEEC signal to NIF





•NIF has 60x more energy than Omega → study NEEC and NEET from more uniform plasma conditions (Collimate sections of blow-off plasma)

•Measure NEEC and NEET in dense plasmas from capsule implosions

•Create 60x more excited nuclei for capture cross-section measurements

Summary

Experiments:

1) ^{169}Tm (NEET)
2) ^{57}Fe (NEEC)
3) 73Ge (NEEC)
4) ^{187}Os (NEEC/NEET)
5) 201Hg (NEET)

Facilities:

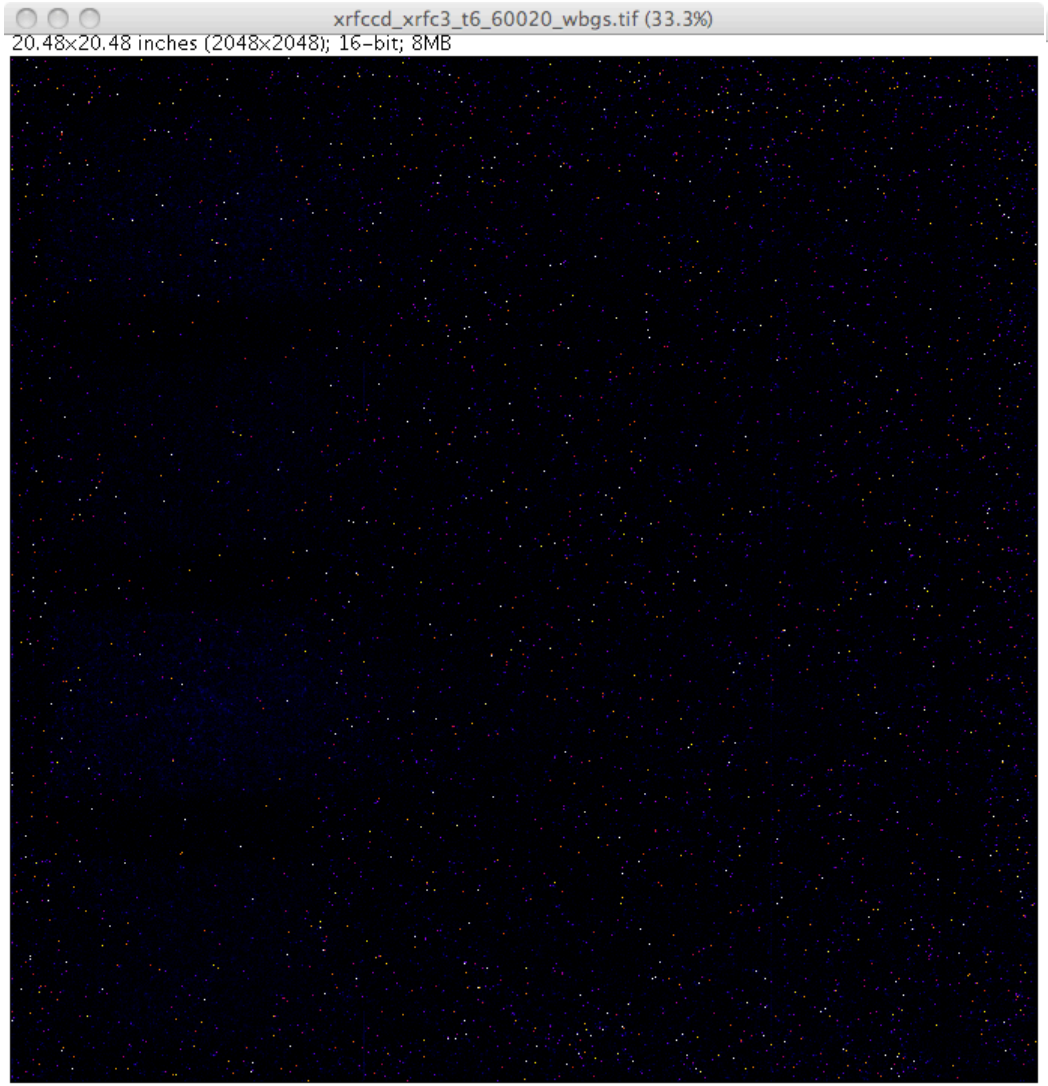
1) These experiments can be fielded at Omega with current detectors
2) These experiments can be fielded at NIF with additional spectrometer development

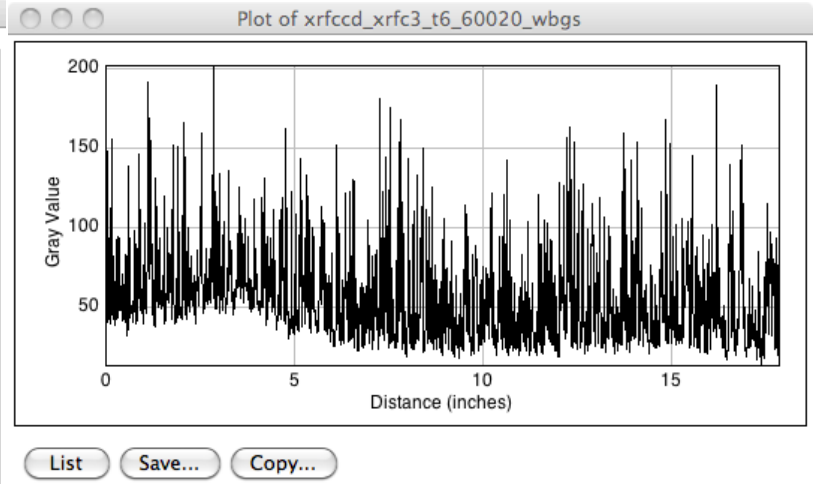
Possible issues:

1) If the lifetime is too short we need to be concerned about atomic line emission, and thus plasma temperature
2) If the lifetime is too long we may have too much spectral blurring from the plasma ploom *(Calculate with HYDRA)*
3) We need rate calculations for a non-LTE plasma
4) We need to be able to distinguish radiative excitation from NEEC or NEET

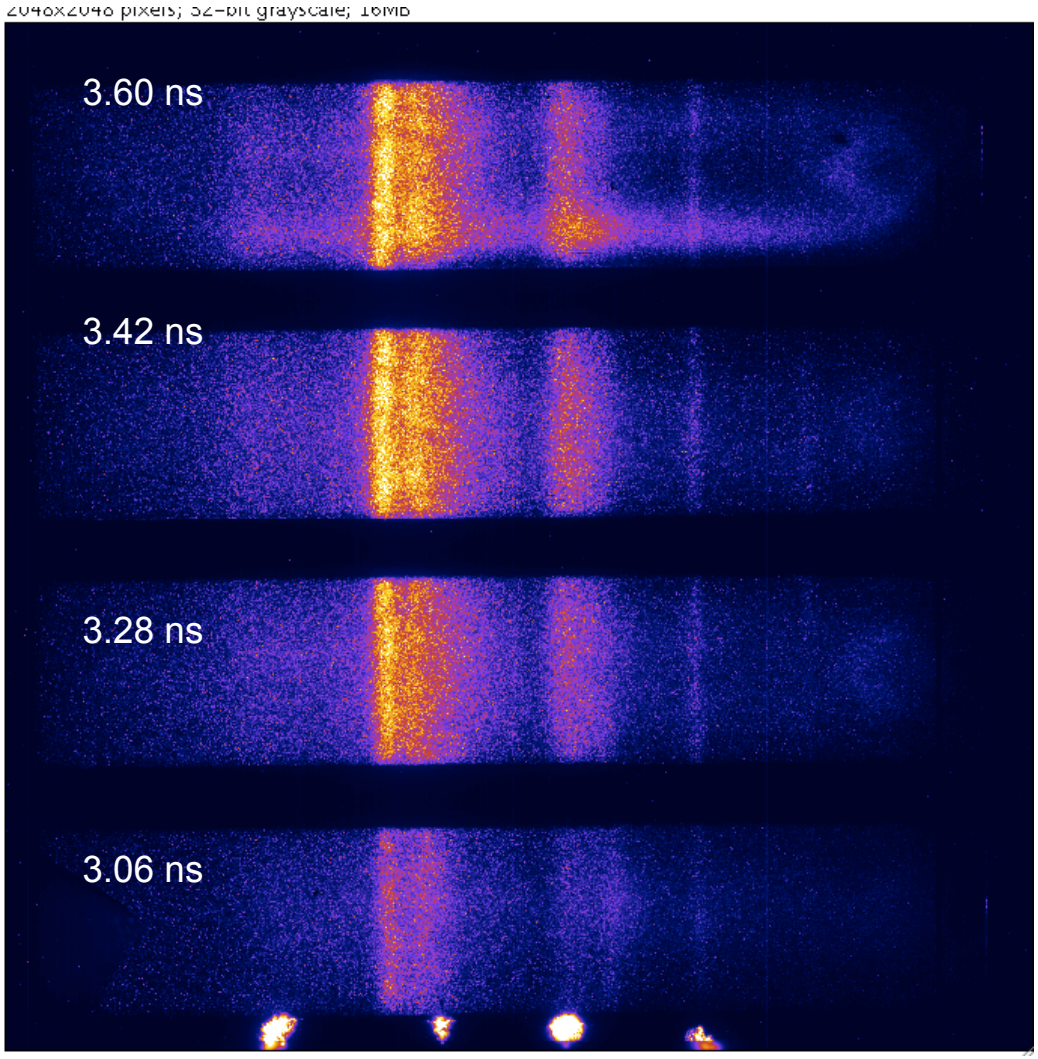
*Backup Slides

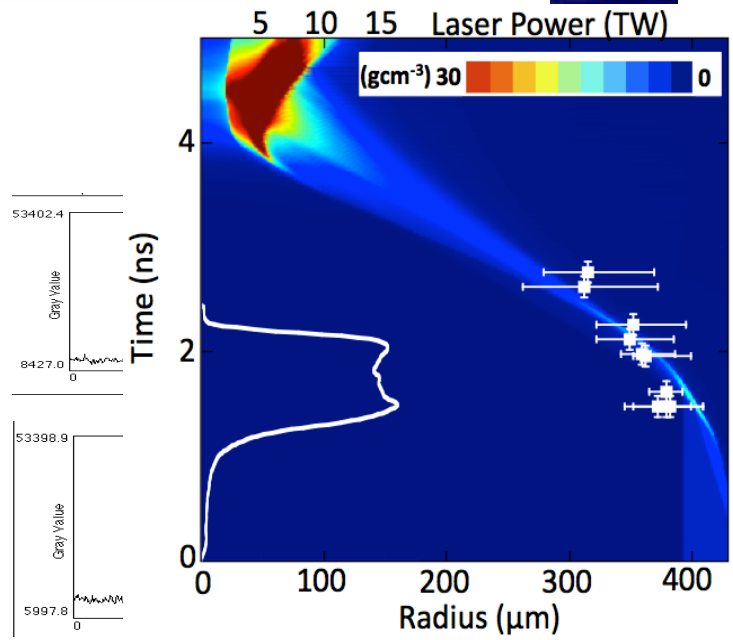
Background from CH shell at 20 ns

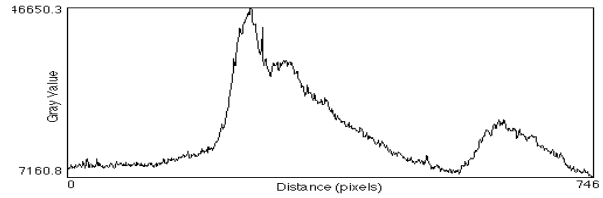


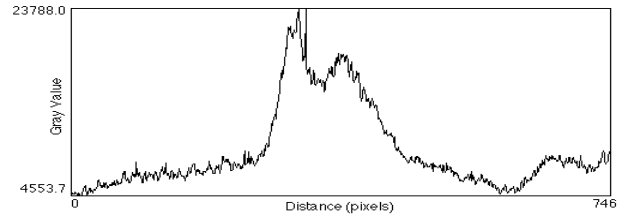


Shot ID: 56600
Description: Be shell, GTS on this shot

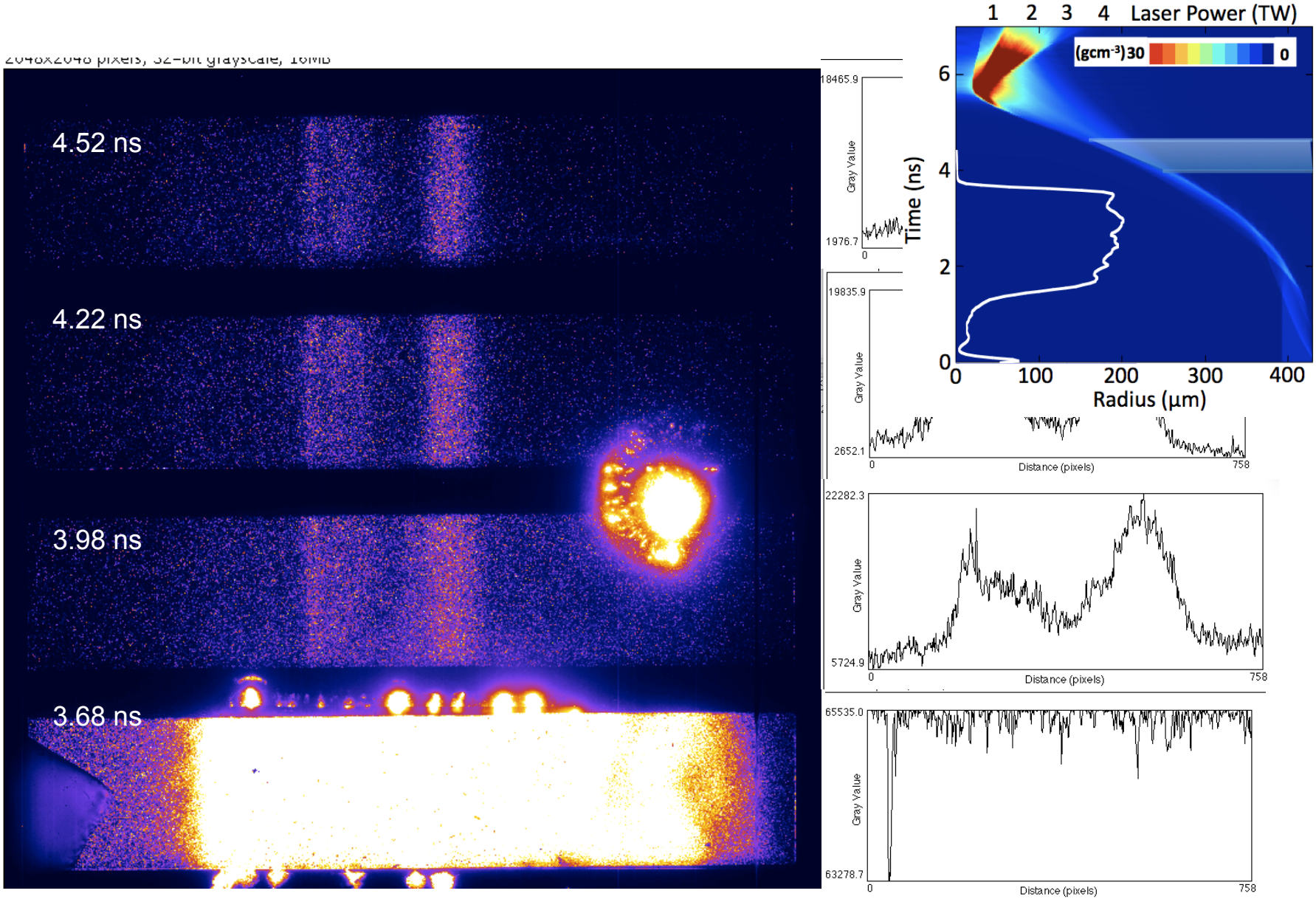








Shot ID: 56591
Description: CH sphere
Pulse Shape and Energy: LA370901p (275J)



The HOPG spectrometer enables high-energy resolution measurements

Energy Resolution of the HOPG Bragg Spectrometer

Energy Dispersion

$$\frac{\Delta E}{\Delta x} = \frac{E}{2F\tan(\theta_B)} = \frac{\sim 9000}{2(125)\tan(12°)} \sim 170\ \text{eV/mm}$$

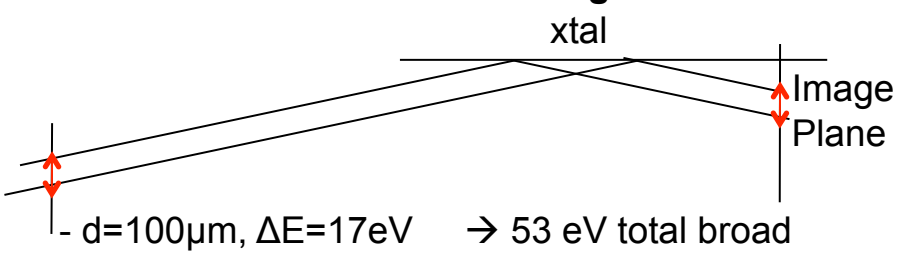
For 18μm/pxl: ~3.2 eV/pxl

Depth Broadening

$$\lambda_{mfp} \approx 1500\,\mu m$$

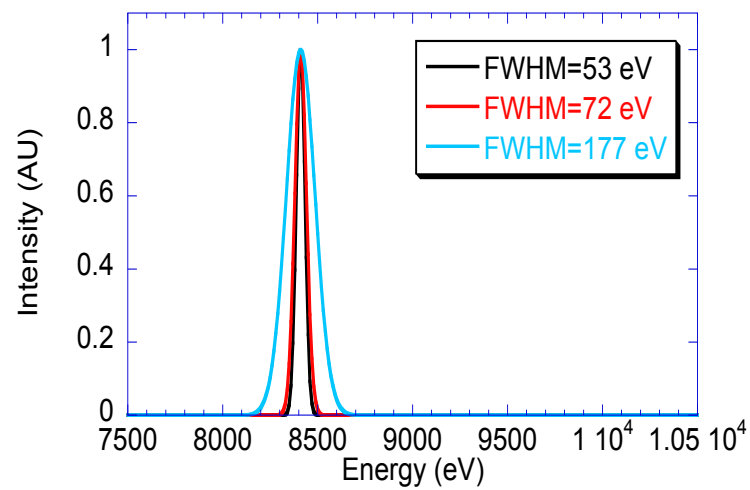
$$\frac{\Delta E}{E} \approx \frac{\lambda_{mfp}}{2F}\cos^2(\theta_B) \sim 50\ \text{eV}$$

Source Broadening

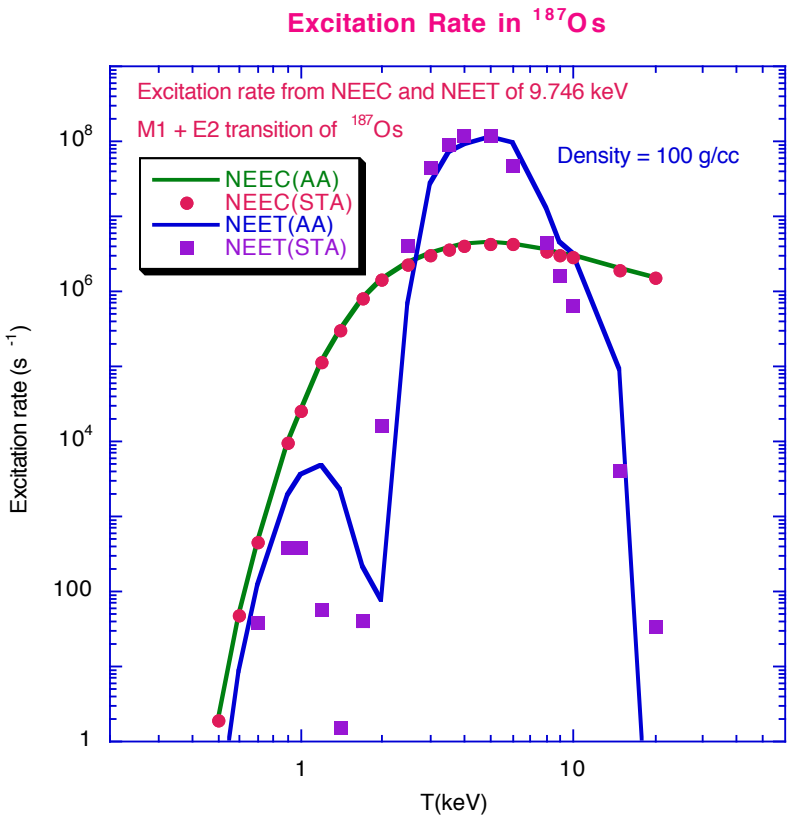


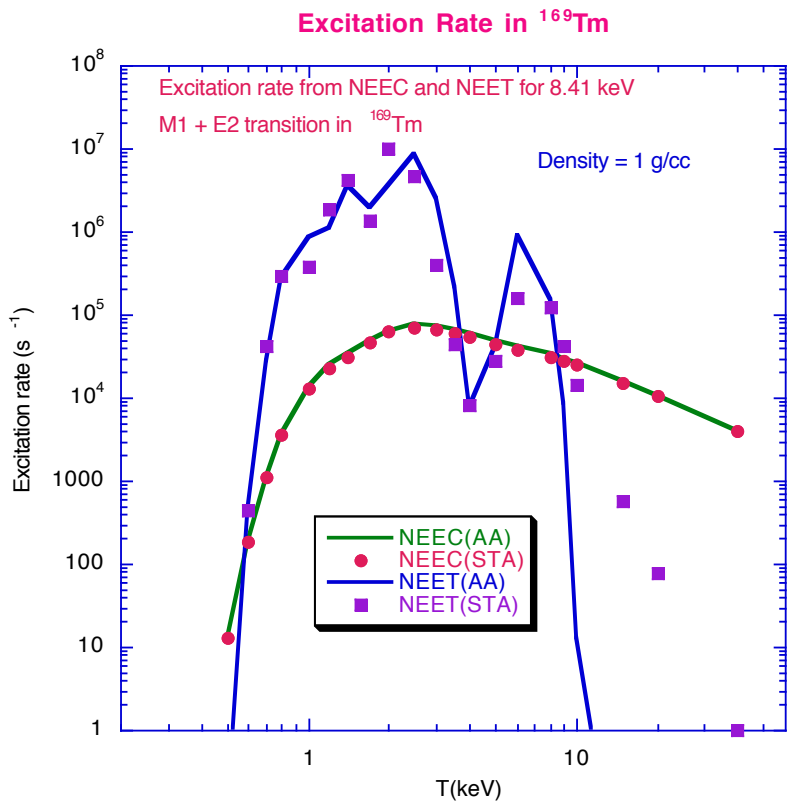
- d=100μm, ΔE=17eV → 53 eV total broad
- d=300μm, ΔE=51eV → 72 eV total broad
- d=1000μm, ΔE=170eV →177 eV total broad

Gamma Line Width (~few 10^{-7} eV), the observed width is limited by depth and source broadening

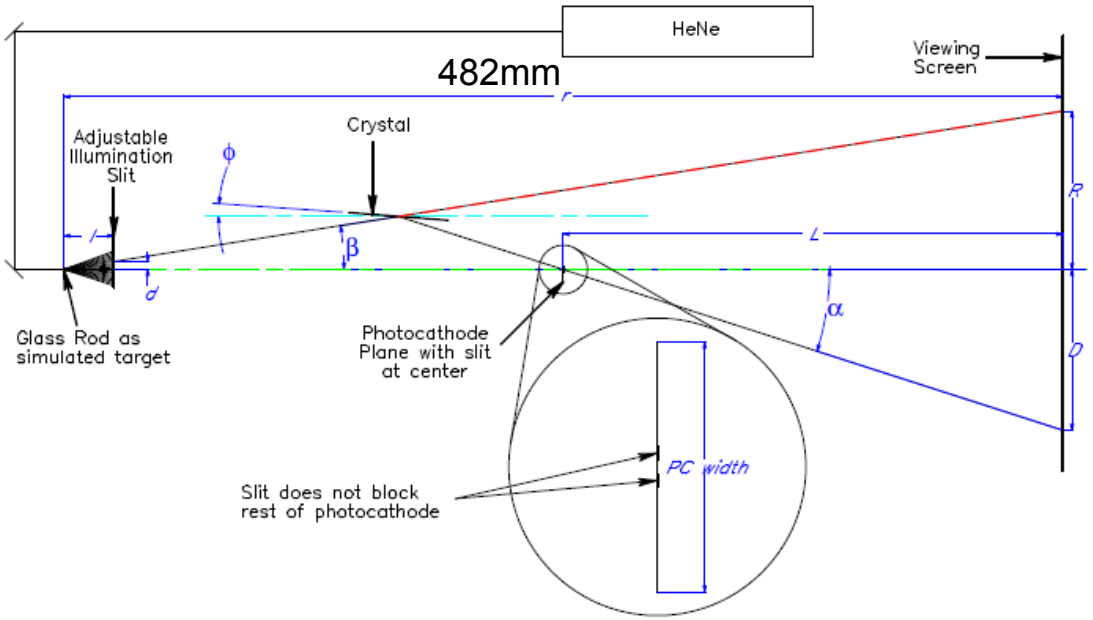


Sensitive Energy range of the Spectrometer


Excitation Rate in ^{187}Os
Excitation rate from NEEC and NEET of 9.746 keV
M1 + E2 transition of ^{187}Os
Density = 100 g/cc
NEEC(AA)
NEEC(STA)
NEET(AA)
NEET(STA)
Excitation rate (s^{-1})
T(keV)


Excitation Rate in ^{169}Tm
Excitation rate from NEEC and NEET for 8.41 keV
M1 + E2 transition in ^{169}Tm
Density = 1 g/cc
NEEC(AA)
NEEC(STA)
NEET(AA)
NEET(STA)
Excitation rate (s^{-1})
T(keV)

We can also employ a streak camera to look at the emission as a function of time



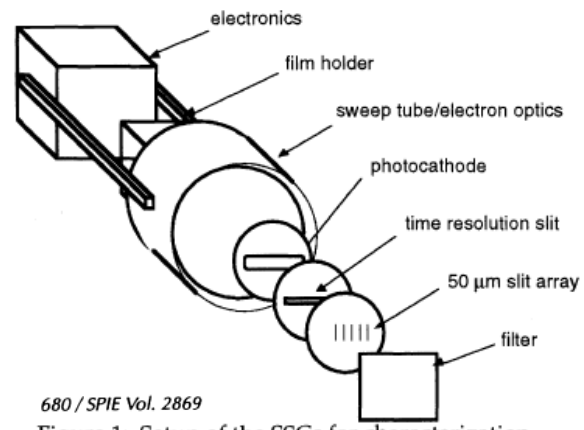


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Figure 1: Setup of the SSCs for characterization on Nova disk target shots.

-Electrons are created in the photo-cathode

-The electrons are focused with optics

-The 1D image (or 1D energy information) is swept across the phosphor screen as a function of time

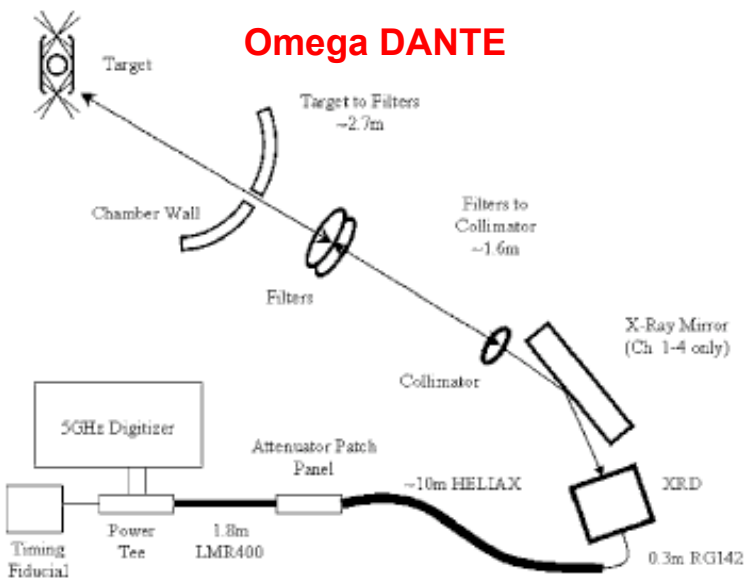
-The phosphor fluoresces and is recorded on film or a CCD

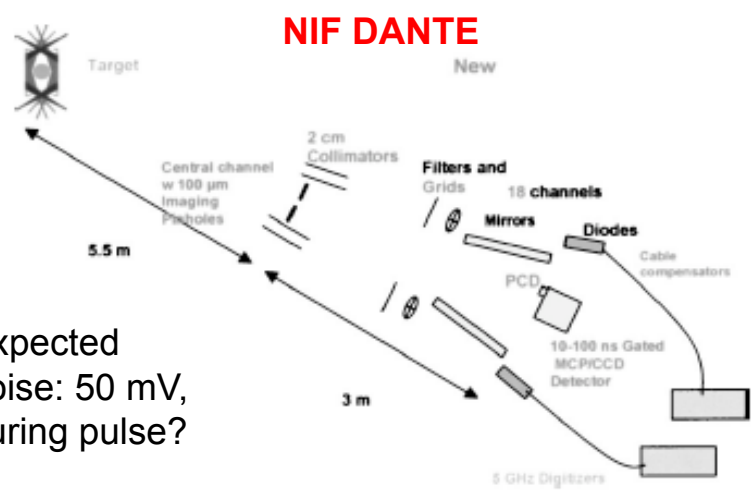
Dante may enable us to detect nuclear emission from long-lived isotopes (10s of ns)

Dante (50 eV-20 keV) x-ray diodes with filter packs for energy discrimination

Channels Requested (Select up to 10)

☐ Channel 1 (50-70 eV)	☑ Channel 10 (1600-1800 eV)
☑ Channel 2 (150-180 eV)	☑ Channel 11 (2000-5000 eV)
☑ Channel 3 (250-280 eV)	☑ Channel 12 (1800-2500 eV)
☑ Channel 4 (450-520 eV)	☑ Channel 13 (2540-3300 eV)
☑ Channel 5 (750-820 eV)	☑ Channel 14 (3170-4800 eV)
☑ Channel 6 (900-980 eV)	☐ Channel 15 (4300-6300 eV)
☑ Channel 7 (980-1050 eV)	☐ Channel 16 (5300-7000 eV)
☑ Channel 8 (1200-1300 eV)	☐ Channel 17 (7300-9500 eV)
☑ Channel 9 (1300-1500 eV)	☐ Channel 18 (10000-20000 eV)



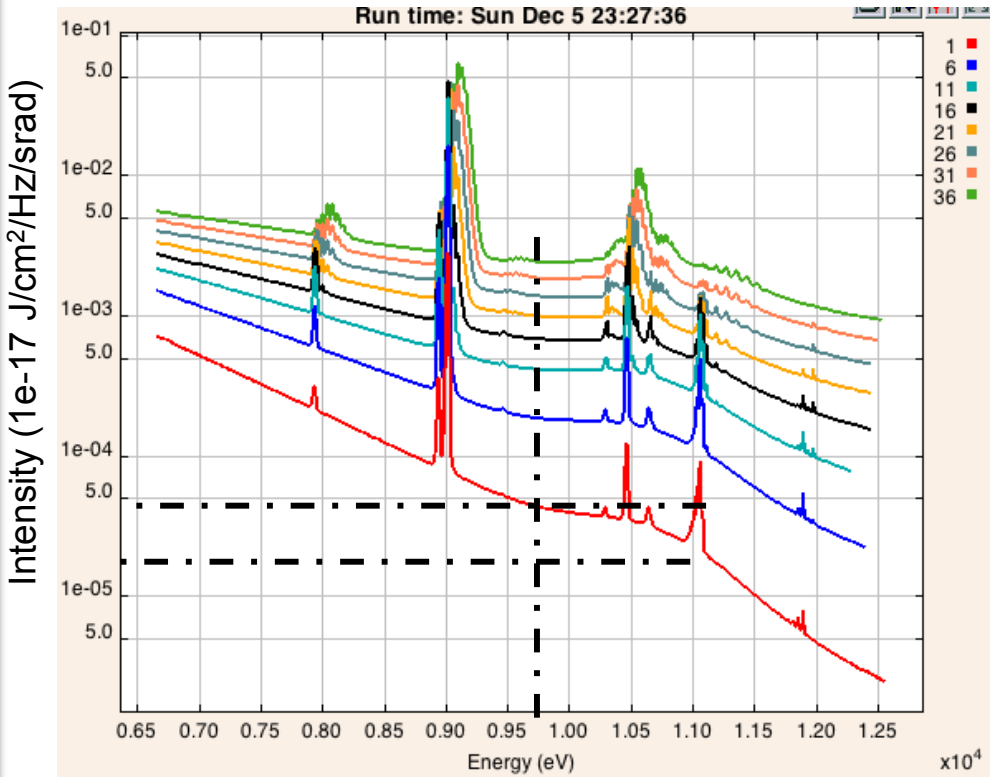


Expected noise: 50 mV, during pulse?

FIG. 2. Dante for NIF layout.

Atomic line emission may interfere with our NEET signal if the plasma gets to hot

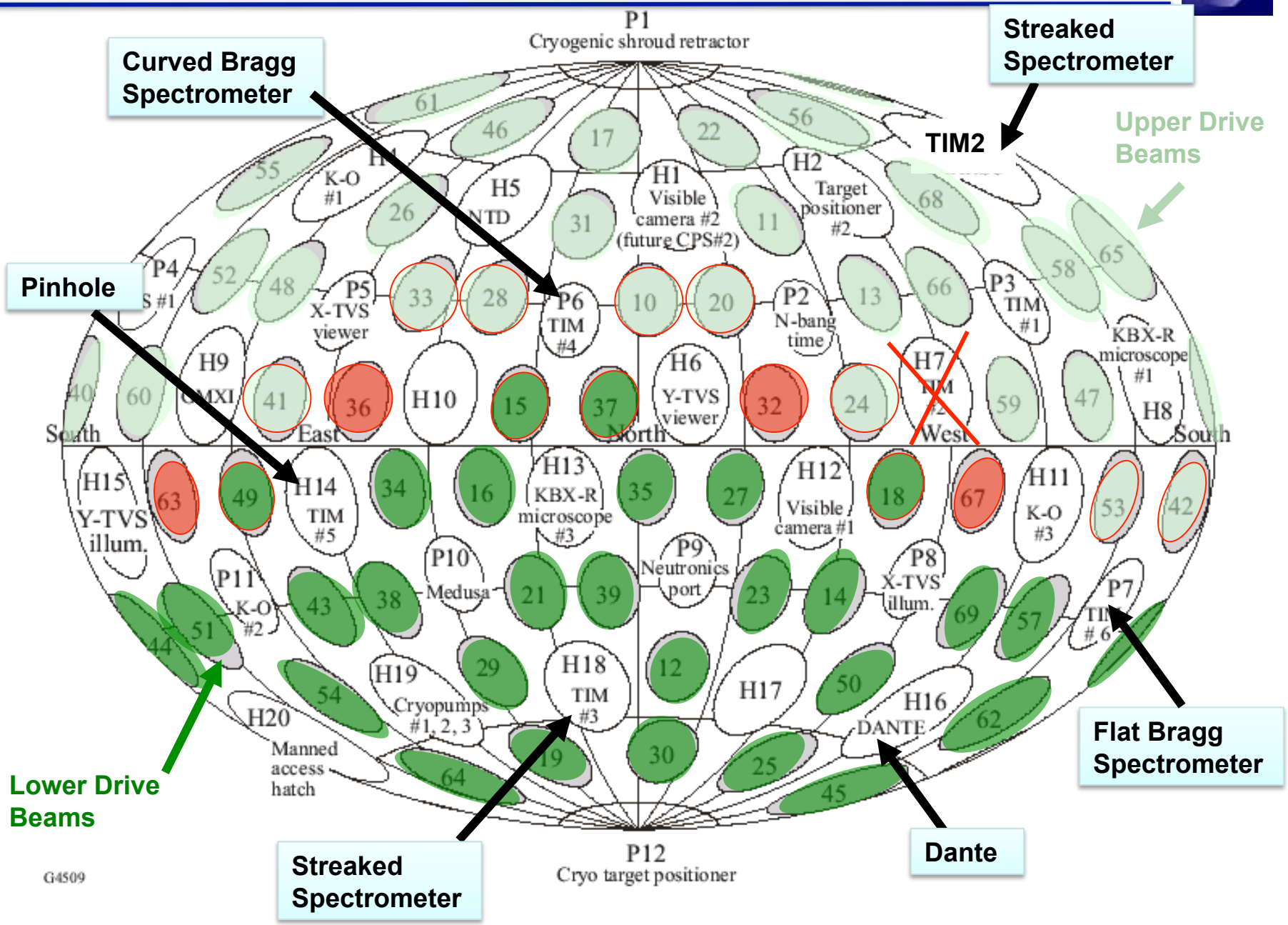
FLYCHK simulation of atomic line emission which is emitted within ~100 ps

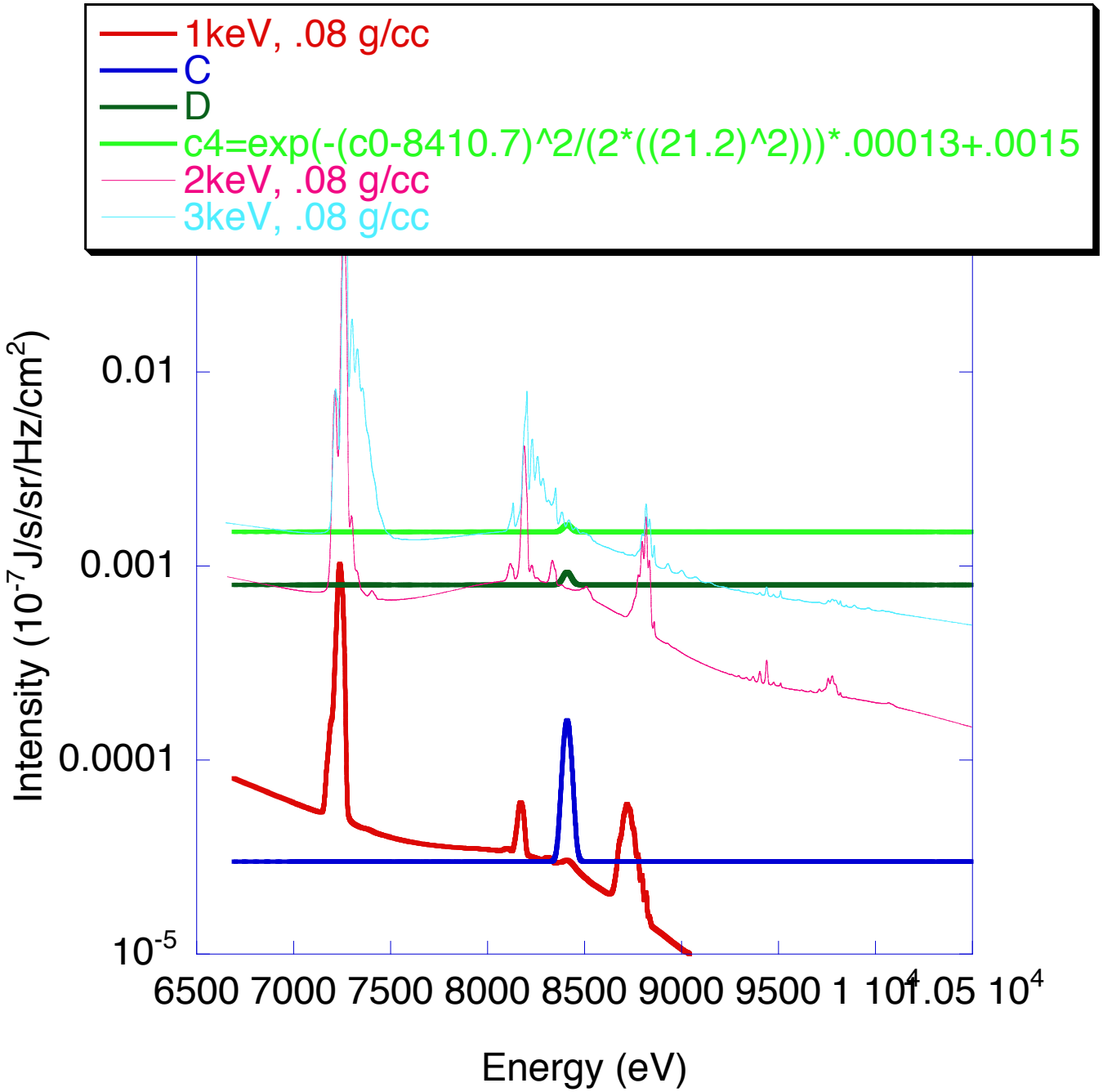


For Tm over the half-life time, the Intensity in units of (1e-19 J/cm^2/Hz/srad) is ~ 3.48x10^{-20}

-If the half life really shortens, we may be able to detect the nuclear decay emission above the atomic emission if the plasma is kept cool enough (<1keV)

Spectrometer and foil orientation in the Omega Chamber




1keV, .08 g/cc
C
D
c4=exp(-(c0-8410.7)^2/(2*((21.2)^2)))*.00013+.0015
2keV, .08 g/cc
3keV, .08 g/cc
Intensity (10^{-7} J/s/sr/Hz/cm^2)
0.01
0.001
0.0001
10^{-5}
6500 7000 7500 8000 8500 9000 9500 1 10^4 1.05 10^4
Energy (eV)

Estimation of the maximum signal from NEEC and NEET if plasma conditions are optimized

Target Isotope	# of Target nuclei	Avg Rate	# NEET/ shot	Plasma gen time	Conv Coeff	Photon E (keV)	Flat x-tal sigma	Curved x-tal sigma	Dante Sigma	Photons Flat x-tal	Photons Curved x-tal	Photons Dante	Half-Life	NEET or NEEC
169Tm	1.54E+17	6.00E+06	9.24E+14	1.00E-09	263.50	8.41	1.50E-05	9.50E-05	7.00E-06	5.26E+07	3.33E+08	6.47E+09	4.10E-09	NEET
57Fe	8.86E+17	3.33E+02	2.95E+11	1.00E-09	8.56	14.41	1.50E-05	9.50E-05	7.00E-06	5.18E+05	3.28E+06	2.07E+06	9.83E-08	NEEC
73Ge	3.40E+17	3.33E+00	1.13E+09	1.00E-09	1120.00	13.28	1.50E-05	9.50E-05	7.00E-06	1.52E+01	9.61E+01	7.93E+03	2.92E-06	NEEC
187Os	1.59E+17	3.33E+04	5.31E+12	1.00E-09	280.00	9.76	1.50E-05	9.50E-05	7.00E-06	2.84E+05	1.80E+06	3.71E+07	2.38E-09	NEEC
201Hg	1.14E+15	3.33E+04	3.79E+10	1.00E-09	47000.00	1.56	1.50E-05	9.50E-05	7.00E-06	1.21E+01	7.66E+01	2.65E+05	8.10E-08	NEET

Assume: We can heat the thickness of attn length to desired plasma temps with 2 kJ, for 1ns, with a 300um spot. ($N_{L,\ Omega}$=7.5 and $N_{L,NIF}$=250)

$$N = \frac{\rho N_A}{A} L_A F_L N_L$$

L_A = Self attenuation Length for detected gamma

F_L = Laser Focus (300 um)

N_L = Number of laser spots on a foil at Omega or NIF

Summary of candidates for observing NEEC/ NEET in a laser-produced plasma

Target Isotope	# of Target nuclei	Avg Rate	# NEET/ shot	Plasma gen time	Conv Coeff	Photon E (keV)	Flat x-tal sigma	Curved x-tal sigma	Dante Sigma	Photons Flat x-tal	Photons Curved x-tal	Photons Dante	Half-Life	NEET or NEEC
169Tm	1.54E+17	6.00E+06	9.24E+14	1.00E-09	263.50	8.41	1.50E-05	9.50E-05	7.00E-06	5.26E+07	3.33E+08	6.47E+09	4.10E-09	NEET
57Fe	8.86E+17	3.33E+02	2.95E+11	1.00E-09	8.56	14.41	1.50E-05	9.50E-05	7.00E-06	5.18E+05	3.28E+06	2.07E+06	9.83E-08	NEEC
73Ge	3.40E+17	3.33E+00	1.13E+09	1.00E-09	1120.00	13.28	1.50E-05	9.50E-05	7.00E-06	1.52E+01	9.61E+01	7.93E+03	2.92E-06	NEEC
187Os	1.59E+17	3.33E+04	5.31E+12	1.00E-09	280.00	9.76	1.50E-05	9.50E-05	7.00E-06	2.84E+05	1.80E+06	3.71E+07	2.38E-09	NEEC
201Hg	1.14E+15	3.33E+04	3.79E+10	1.00E-09	47000.00	1.56	1.50E-05	9.50E-05	7.00E-06	1.21E+01	7.66E+01	2.65E+05	8.10E-08	NEET

Summary of possible issues:

Target Isotope	*Photon Energy*	*Signal*	*Spectral Response (plasma expansion)*	*Background*	*Radiative Ex Interference?*
169Tm	8.4 keV	**3E+08**	**Ok**	**? (*"short lifetime"?*, may be atomic emission interference)**	**No**
57Fe	14 keV	**3E+06**	**? (long lifetime, may blurr Bragg spec response, other det options?)**	**Ok**	**? (Waiting for CEA calcs)**
73Ge	13.28 keV	**1.E+02**	**? (long lifetime, may blurr Bragg spec response, other det options?)**	**Ok**	**No**
187Os	9.76 keV	**1.8E+06**	**Ok**	**? (*"short lifetime"?*, may be atomic emission interference)**	**No**
201Hg	1.56 keV	**7.6E+02**	**? (long lifetime, may blurr Bragg spec response, other det options?)**	**Ok**	**No**

-All rates need to be finalized for non-LTE plasma and for correct blow off density…

Post-processing of 2D Hydra simulations are done to estimate the NEEC'd signal for 57Fe

Detailed estimate of # of excited Fe:
Matlab file to post-process HYDRA results:

$$N_{NEEC} = \frac{\rho}{A} N_A V_{ol} * 360\,\mathrm{deg} * R_{NEEC}$$

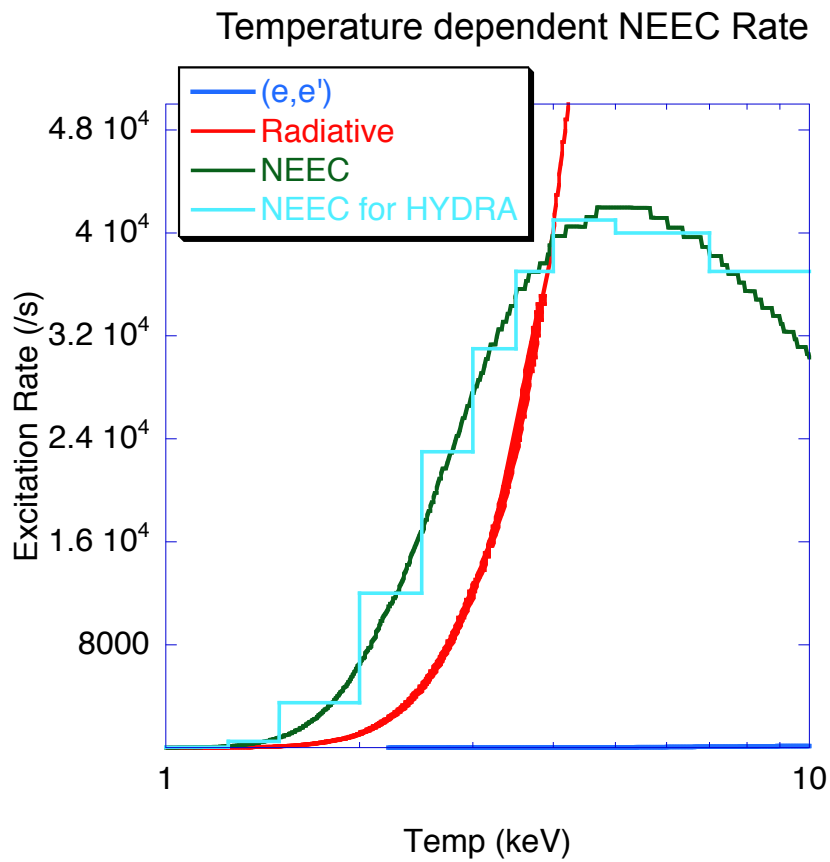
$$V_{ol} = Vol\ of\ Cell$$

$$R_{NEEC} = Neec\ Rate\,(T)$$

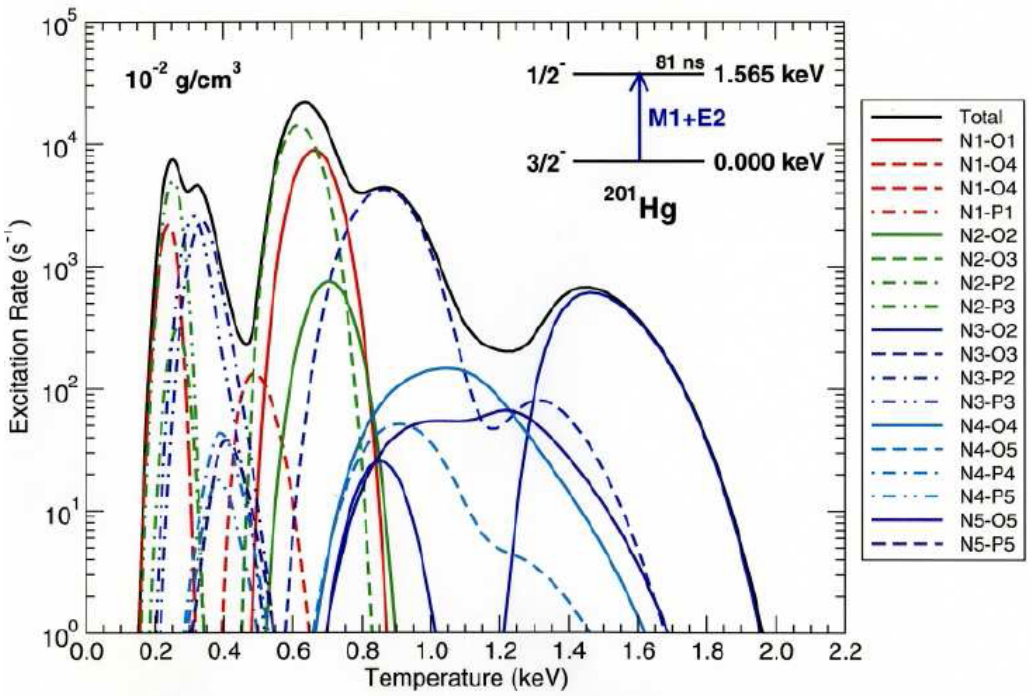
$$N_{NEEC} = Number\ NEEC'd\ nuclei$$

Done for each cell and summed over all.

Then, total NEEC'd number would be *15 because we can have 15 spots at 1 kJ



-For these laser conditions the total number of NEEC'd 57Fe nuclei is: 5e11 nuclei, 5e9 with density corr (prev estimate, 3e11 with den corr)



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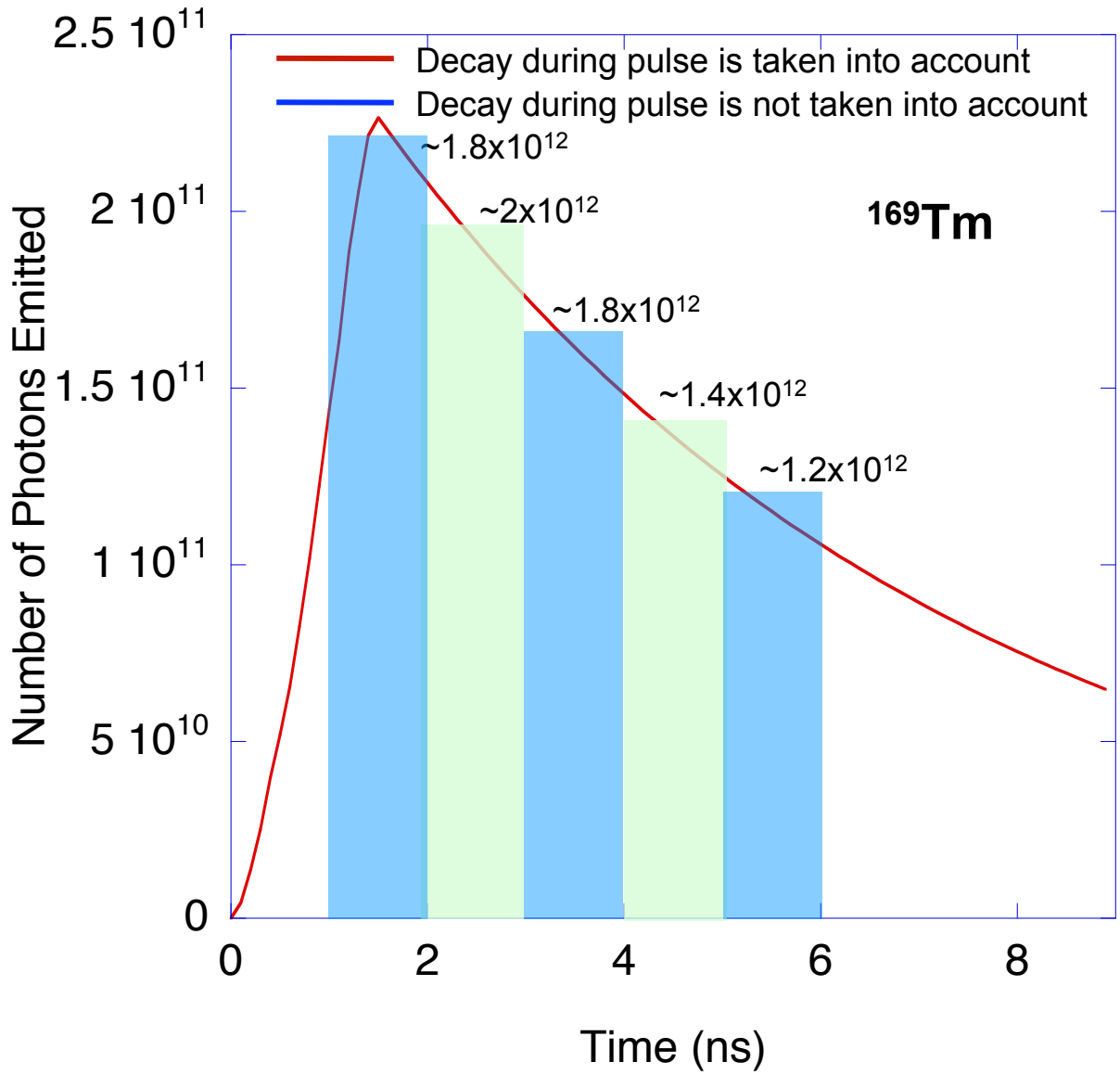
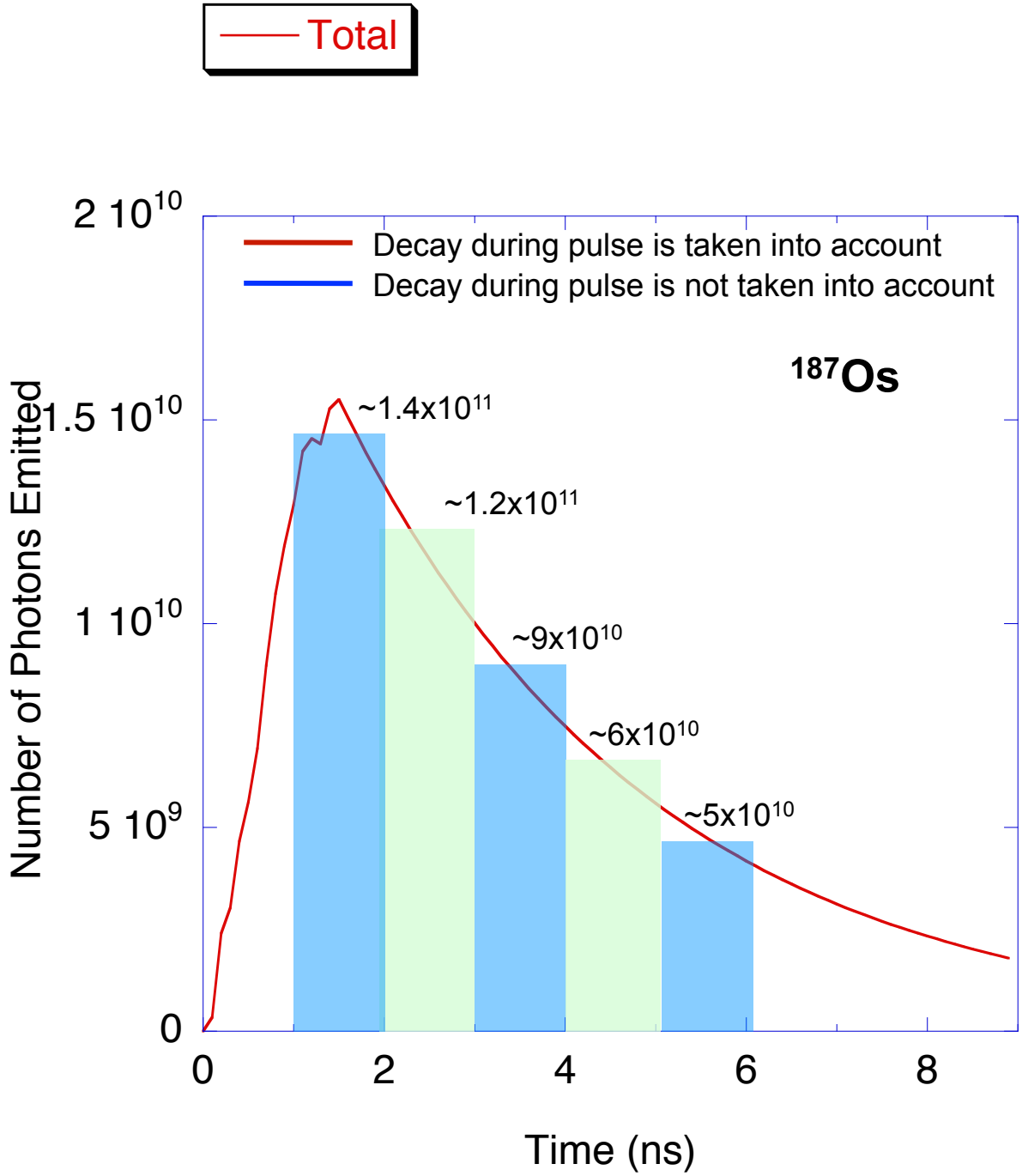
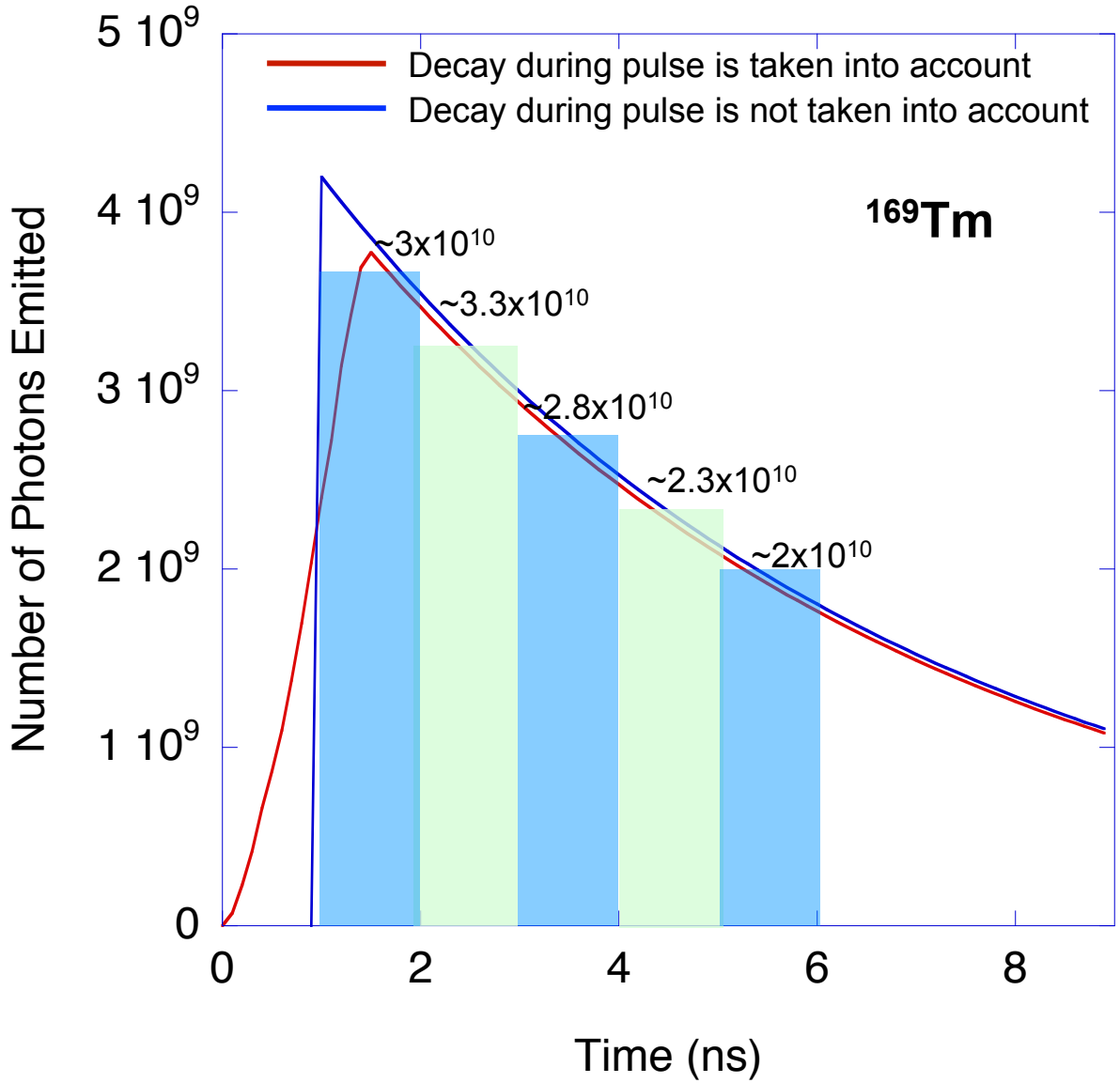
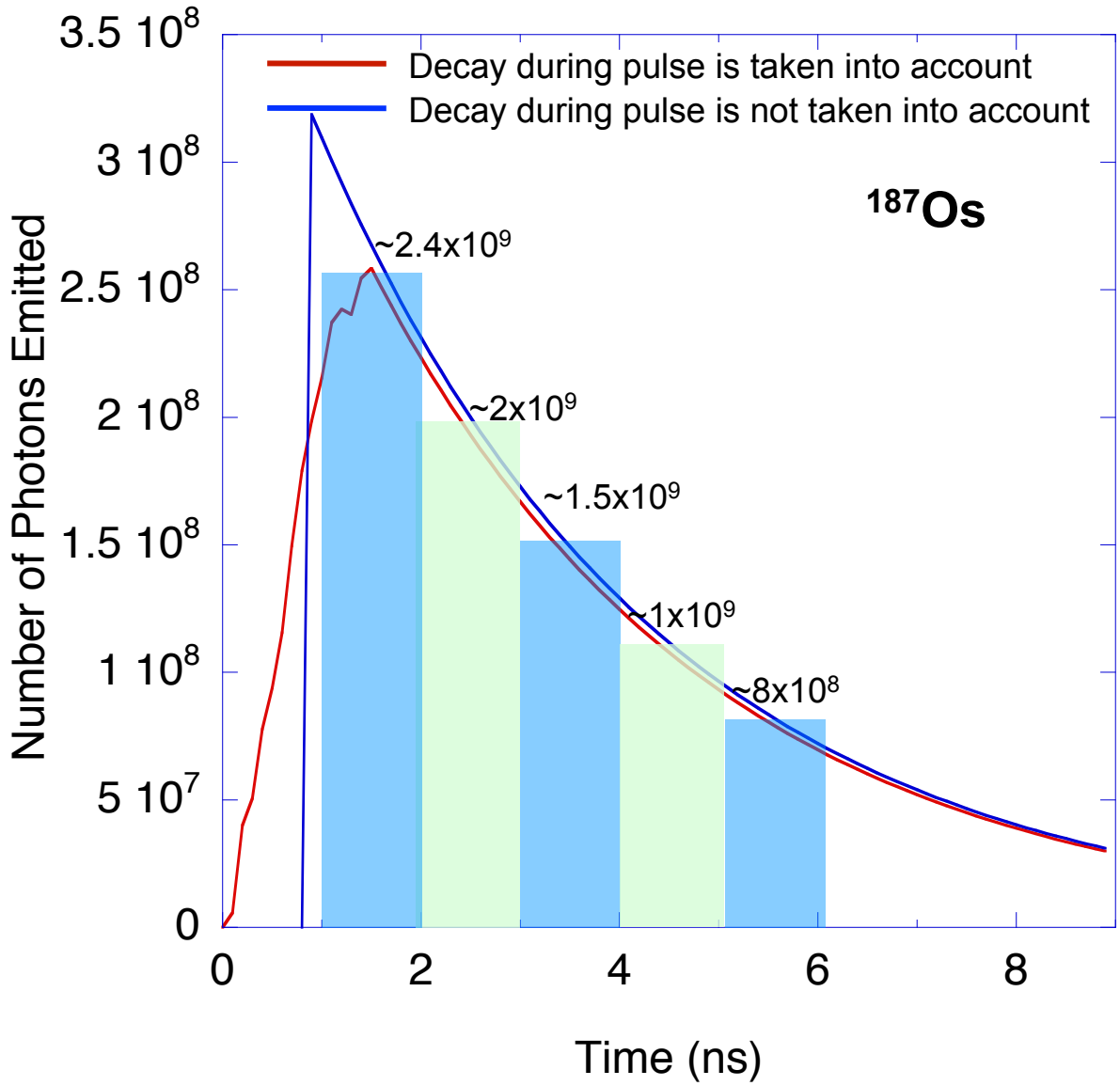
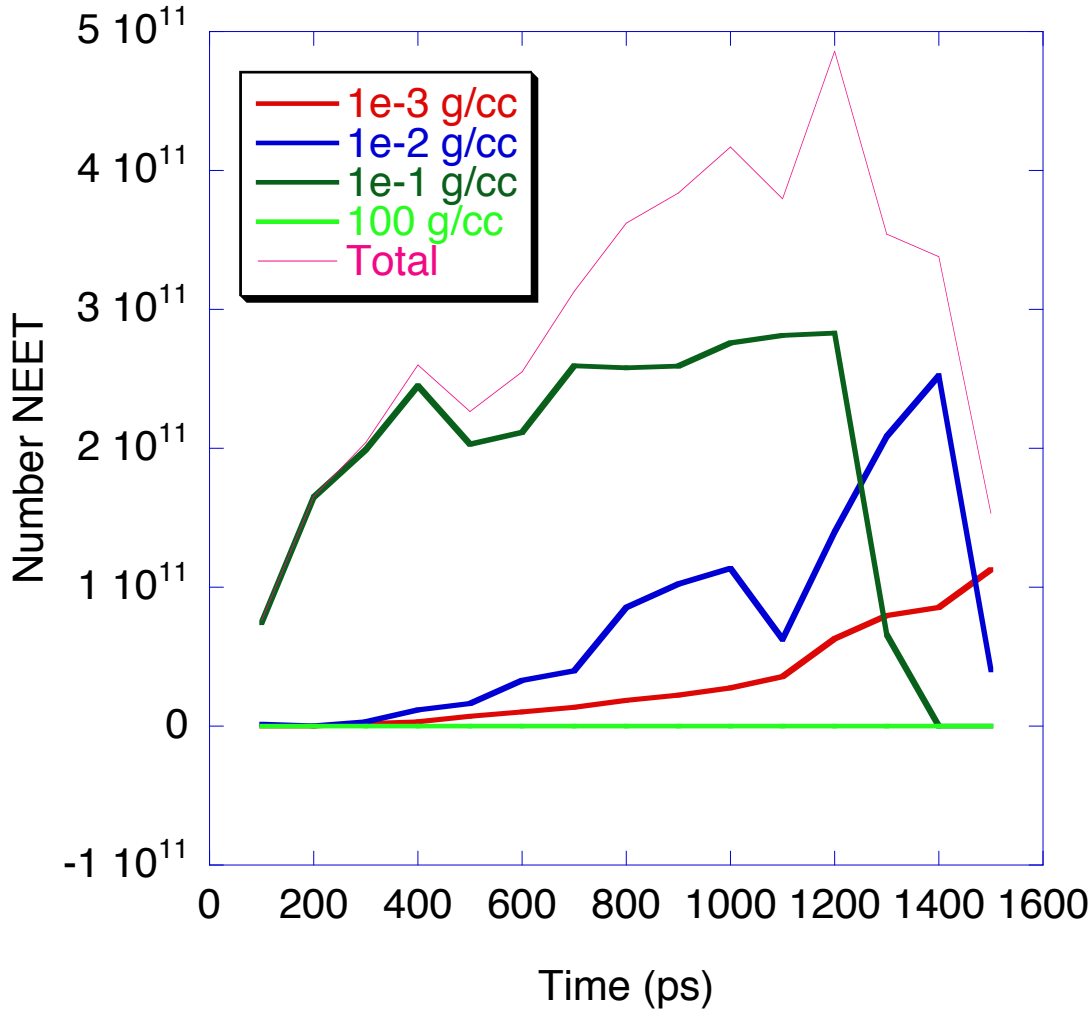

Decay during pulse is taken into account
Decay during pulse is not taken into account
~1.8x10^12
~2x10^12
~1.8x10^12
~1.4x10^12
~1.2x10^12
169Tm
Number of Photons Emitted
2.5 10^11
2 10^11
1.5 10^11
1 10^11
5 10^10
0
0
2
4
6
8
Time (ns)


Total
Decay during pulse is taken into account
Decay during pulse is not taken into account
187Os
~1.4x10^11
~1.2x10^11
~9x10^10
~6x10^10
~5x10^10
Number of Photons Emitted
2 10^10
1.5 10^10
1 10^10
5 10^9
0
0
2
4
6
8
Time (ns)

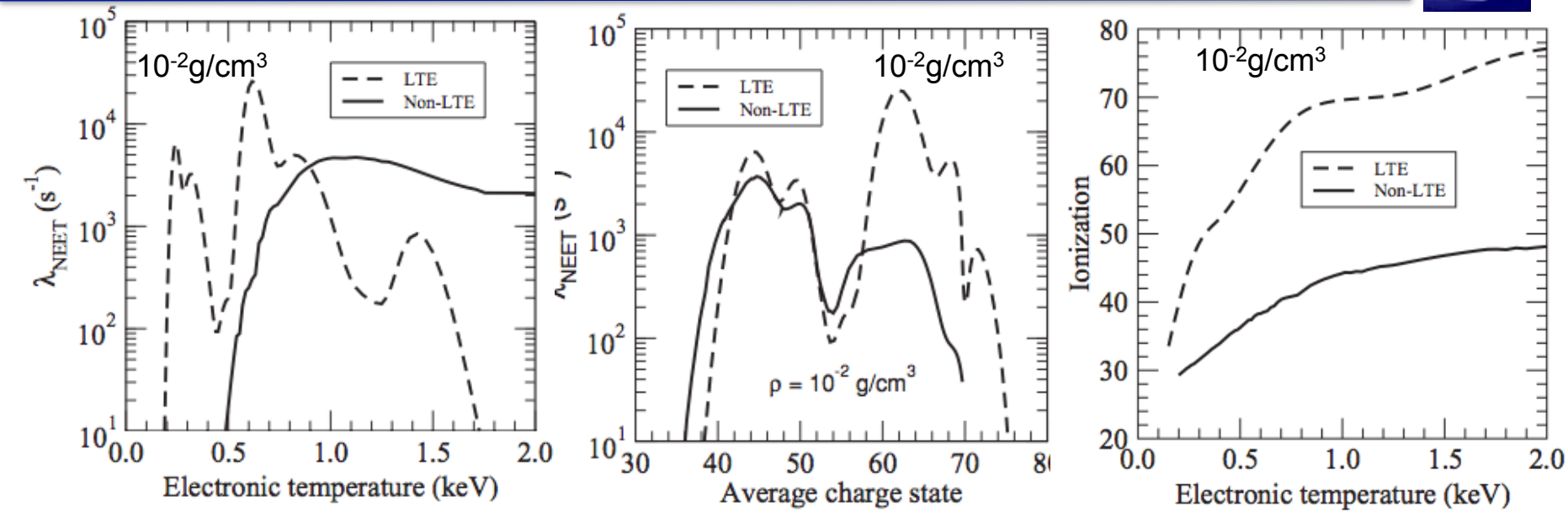

Decay during pulse is taken into account
Decay during pulse is not taken into account
169Tm
~3x10^10
~3.3x10^10
~2.8x10^10
~2.3x10^10
~2x10^10
Number of Photons Emitted
5 10^9
4 10^9
3 10^9
2 10^9
1 10^9
0
0
2
4
6
8
Time (ns)


Decay during pulse is taken into account
Decay during pulse is not taken into account
187Os
~2.4x10^9
~2x10^9
~1.5x10^9
~1x10^9
~8x10^8
Number of Photons Emitted
Time (ns)
3.5 10^8
3 10^8
2.5 10^8
2 10^8
1.5 10^8
1 10^8
5 10^7
0
0
2
4
6
8

169Tm


5 10^11
4 10^11
3 10^11
2 10^11
1 10^11
0
-1 10^11
Number NEET
0
200
400
600
800
1000
1200
1400
1600
Time (ps)
1e-3 g/cc
1e-2 g/cc
1e-1 g/cc
100 g/cc
Total

The NEET rate changes for a plasma in non-LTE, e.g. calculations have been done for ^{201}Hg



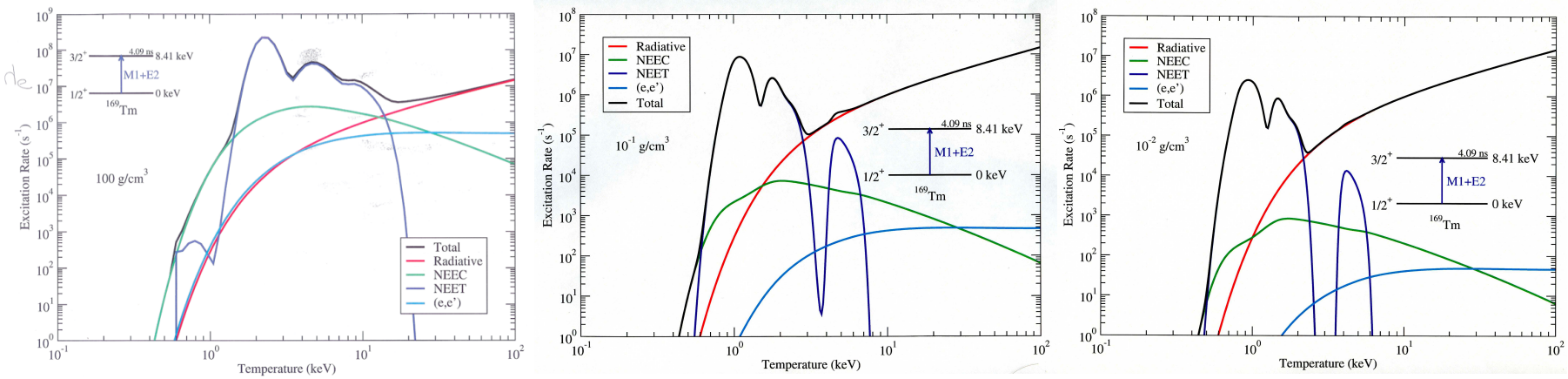
PHYSICAL REVIEW C **81**, 034609 (2010)

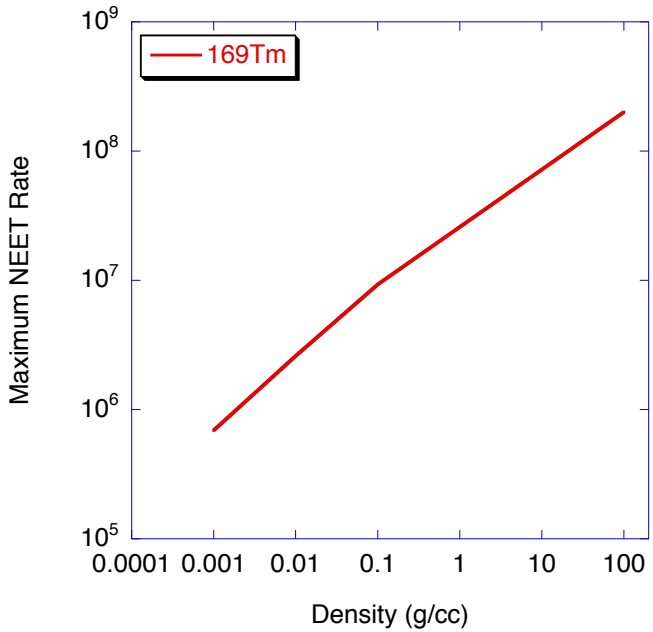
-The temperature of the resonance increases as a result of recombination and ionization non-balance in a non-LTE plasma

-To reach the same charge state in a non-LTE plasma, higher temperatures are required. Looking at the average Z from simulations is more relevant than Temp

-The peak NEET rate doesn't change much for lower charge states for LTE vs non-LTE, less than an order of magnitude

Tm NEET rate resonances are density dependent, we can scale from Tm example

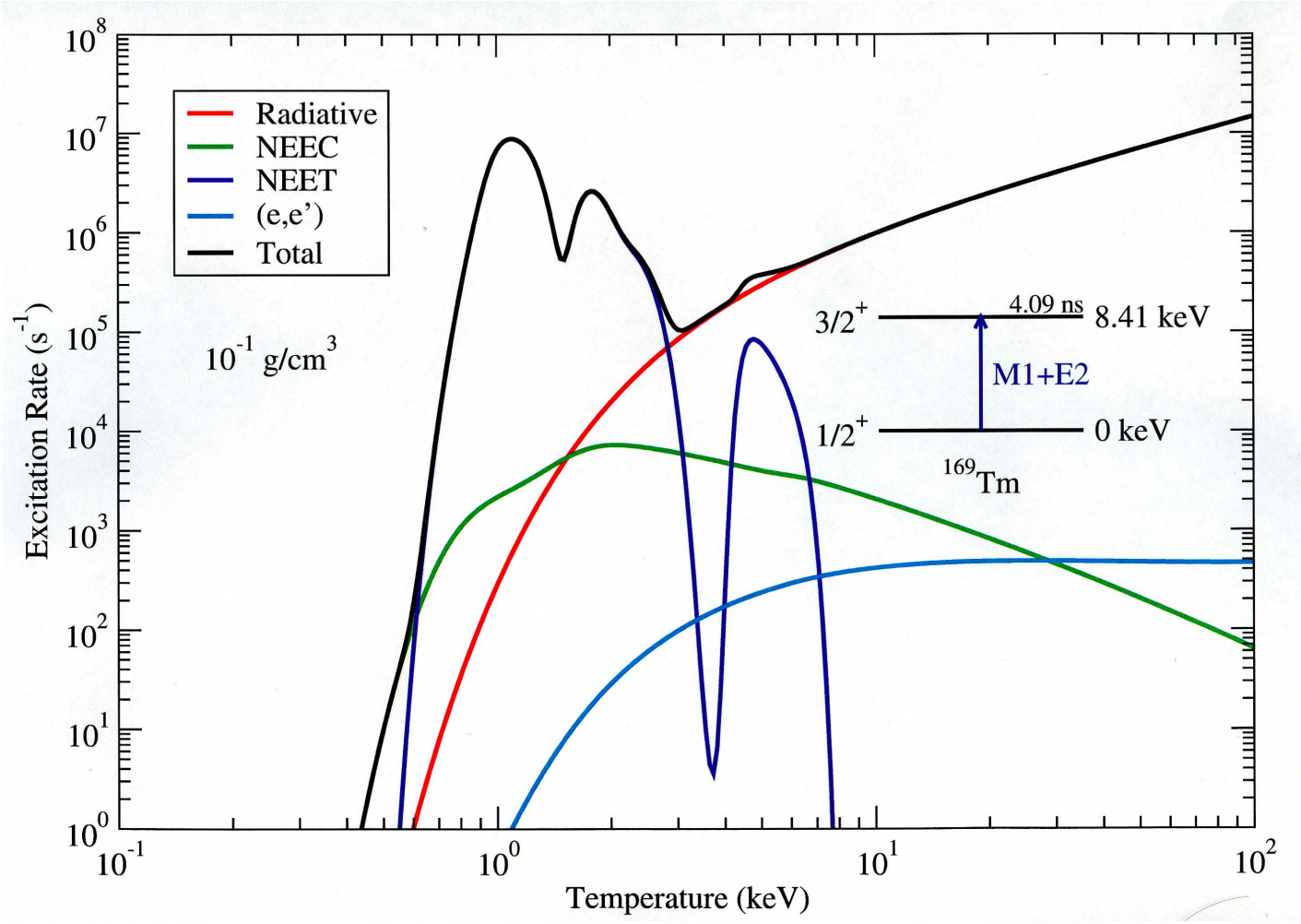




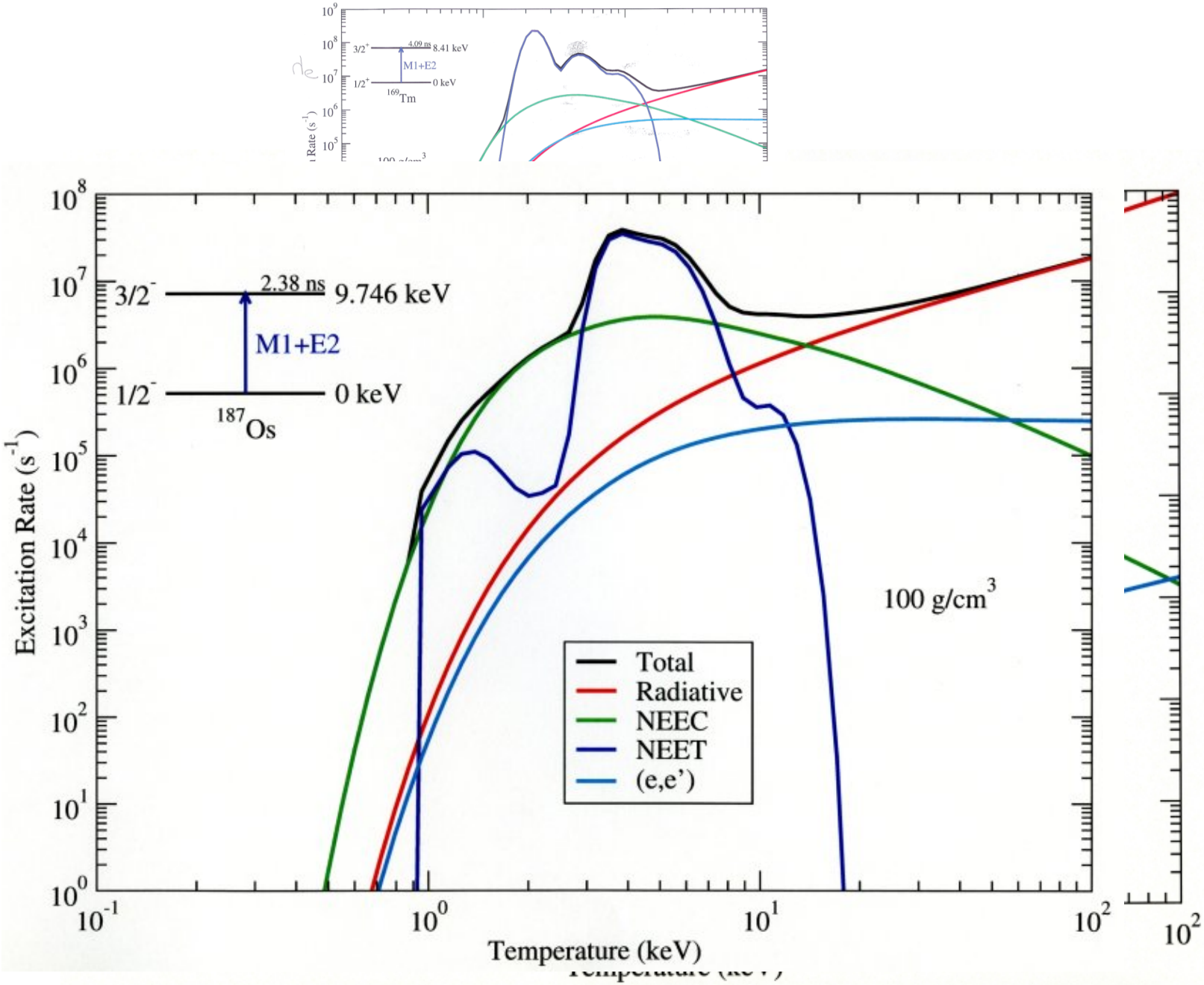
-The Rate doesn't change significantly with density because its dependent on energy matching of electronic shell transitions, so its mainly dependent on the ionization state (i.e. T)

-The rate decreases by about 70-80% for each order of magnitude (Also Roughly for Hg)

-This is used as a scaling for Fe and Os (we only have 100g/cc calculations)



-The NEET rate has resonant temperatures due to atomic transition resonances


3/2⁻
2.38 ns
9.746 keV
M1+E2
1/2⁻
0 keV
187Os
100 g/cm3
Total
Radiative
NEEC
NEET
(e,e')
Excitation Rate (s-1)
Temperature (keV)

Additional Diagnostics

Omega:

1) Filtered (Ross Pairs) CCD/IP with or without XRFC

2) XRFC: 40, 80, 200, 300, 400, 500, 1000 ps resolution

3) Streaked filtered x-ray camera:
-Can be timed to w/in 25 ps
-Can be used w/x-ray imaging optics, pinhole, or bragg x-tal (1.35 keV to 13.5 keV)
-Some with CCD and some with Film
-Ultrafast streaked camera: 3ps resolution
- Spherically bent crystals for x-ray imaging or KB optics (2-9 keV)

More detailed information coming…

Estimation of the number of isotopes at NEEC and NEET resonant temperatures (first pass)

Stable nuclei with low lying first excited states:	Temp Range of NEEC/ NEET Resonance	L_A (um)	Omega: # detected NEET and NEEC resonant temps
169Tm	700eV-2keV	8.8	1.5×10^{17}
57Fe	1-3 keV	20	8.8×10^{17}
73Ge	1-3 keV	14.6	3×10^{17}
187Os	1-3 keV	4	1.6×10^{17}
201Hg	100eV-1keV (NEEC) and 1-3 keV (NEET)	.35	1.0×10^{15}

$$N = \frac{\rho N_A}{A} L_A F_L N_L$$

L_A = Self attenuation Length for detected gamma

F_L = Laser Focus (300 um)

N_L = Number of laser spots on a foil at Omega or NIF

Assume: We can heat the thickness of attn length to desired plasma temps with 2 kJ, for 1ns, with a 300um spot. ($N_{L,\ Omega}$=7.5 and $N_{L,NIF}$=250)

-This is a best-case estimate, assuming we can heat the entire attenuation length to the desired temperatures

-We can weed out options that won't work

Estimates of the number of detected photons, is high enough for current Omega detectors

An estimate for the NEET rate and detected photons at **Omega**

An estimate for the NEET rate is…

$$N_{NEET} = N_{^{169}Tm} R_{NEET} \tau_{capsule}$$
$$= 1.4\text{x}10^{15}\ NEET/shot$$

Number of ^{169}Tm Nuclei: $N_{^{169}Tm} = 2.3\text{x}10^{17}$

Avg NEET Rate: $R_{NEET} \sim 6\text{x}10^{6}$ Hz

Capsule confinement time: $\tau_{capsule} = 1$ ns

$$N_{Detected} = N_{NEET} \Omega_{\text{target}} \Omega_{\text{detector}} (1/\alpha)$$

X-rays at Dante $= 9.7\text{x}10^{9}\ photons$

ϒ at flat xtal $= 7.9\text{x}10^{7}\ photons$

ϒ at curved xtal $= 5.1\text{x}10^{8}\ photons$

Flat Crystal Solid Angle: $\Omega_{\text{detector}} = 1.5\text{x}10^{-5}$

Curved Crystal Solid Angle: $\Omega_{\text{detector}} = 9.5\text{x}10^{-5}$

Dante Solid Angle: $\Omega_{\text{detector}} = 7\text{x}10^{-6}$

Target Solid Angle: $\Omega_{\text{target}} = 1$

Conversion Coefficient: $\alpha = 263.5$

An estimate for the NEET rate and detected photons at **Omega**

An estimate for the NEET rate is…

$$N_{NEET} = N_{^{57}Fe} R_{NEET} \tau_{capsule}$$
$$= 3\text{x}10^{11}\ NEET/shot$$

Number of ^{169}Tm Nuclei: $N_{^{57}Fe} = 8.9\text{x}10^{17}$

Avg NEET Rate: $R_{NEET} \sim 3\text{x}10^{2}$ Hz

Capsule confinement time: $\tau_{capsule} = 1$ ns

$$N_{Detected} = N_{NEET} \Omega_{\text{target}} \Omega_{\text{detector}} (1/\alpha)$$

X-rays at Dante $= 2\text{x}10^{6}\ photons$

ϒ at flat xtal $= 3\text{x}10^{6}\ photons$

ϒ at curved xtal $= 5.1\text{x}10^{5}\ photons$

Flat Crystal Solid Angle: $\Omega_{\text{detector}} = 1.5\text{x}10^{-5}$

Curved Crystal Solid Angle: $\Omega_{\text{detector}} = 9.5\text{x}10^{-5}$

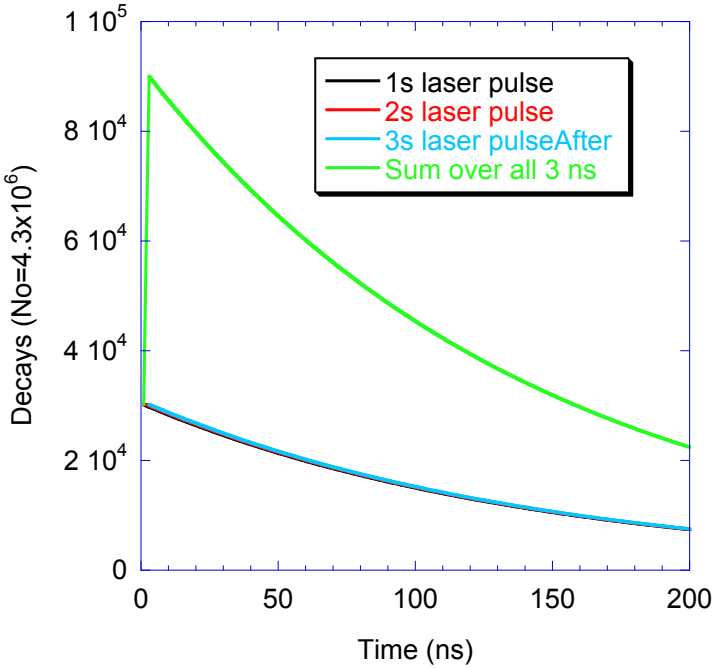
Dante Solid Angle: $\Omega_{\text{detector}} = 7\text{x}10^{-6}$

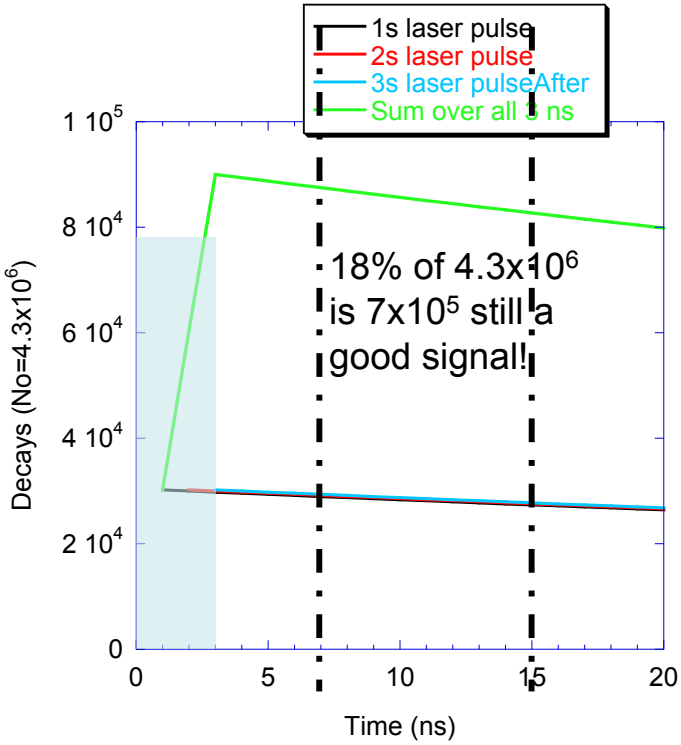
Target Solid Angle: $\Omega_{\text{target}} = 1$

Conversion Coefficient: $\alpha = 8.56$

-Target solid angle is 1 because N atoms is calc for ½ target

If we probe from 7-15 ns, the signal is still predicted to be high enough above the background for Fe





-Simulations indicate the ability to heat the blow-off plasma (for the Tm spatial configuration of the beams) to 2keV for 3ns.

-However, to be conservative, for a 3 ns pulse if we assume to only heat the entire blow-off plasma to 2keV for an average of 1ns, the signal would be ~$2x10^5$!

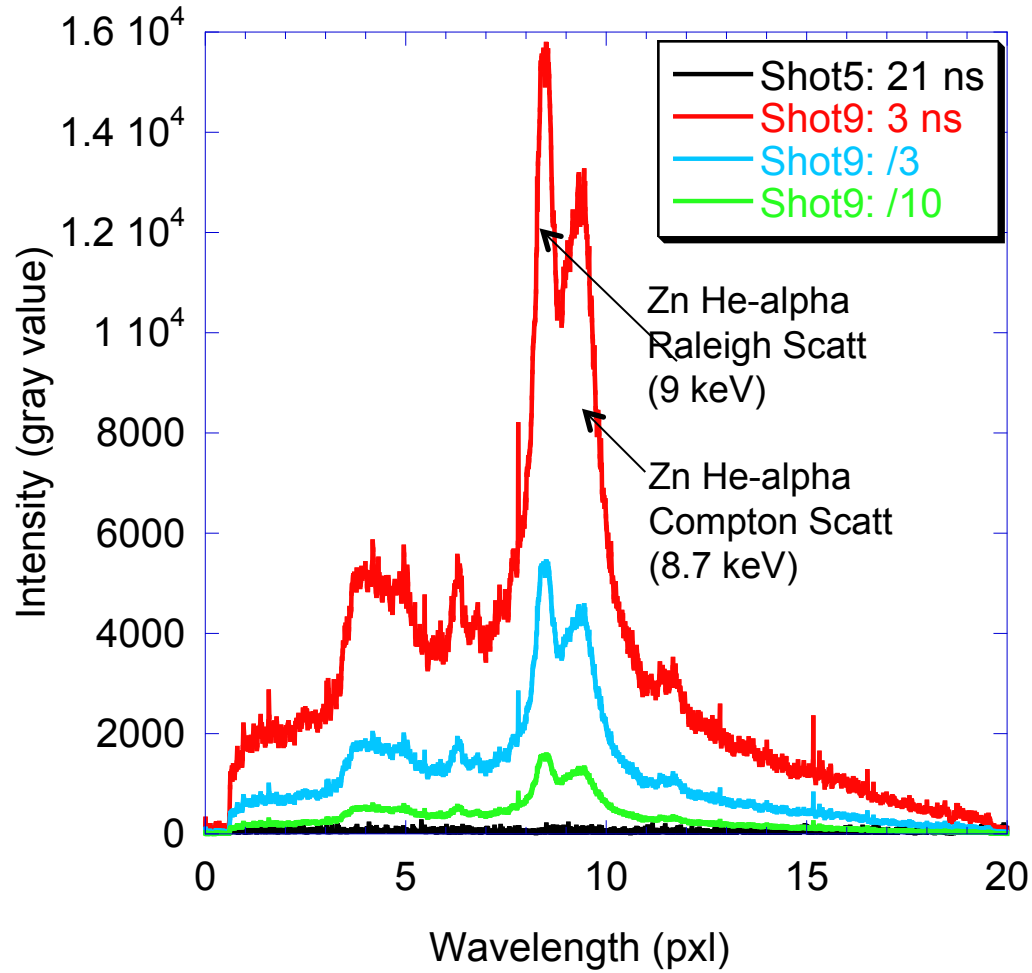
Measured background with HOPG at Omega, at ~20 ns after the end of the laser pulse

-$2x10^6$ Photons were detected in the Raleigh peak (red), corresponding to a signal to background ratio of ~ 5 at ~1 ns after the laser pulse ends.

-The broadening of this feature is partly due to the large scattering volume (~700um).

-The corresponding background for the same detector and filter settings is a factor of ~60 lower than at ~20 ns after the laser pulse ends (black).

-With Fe we will start looking after the laser pulse when atomic emission is low and before the plasma has expanded by too much (blue and green).



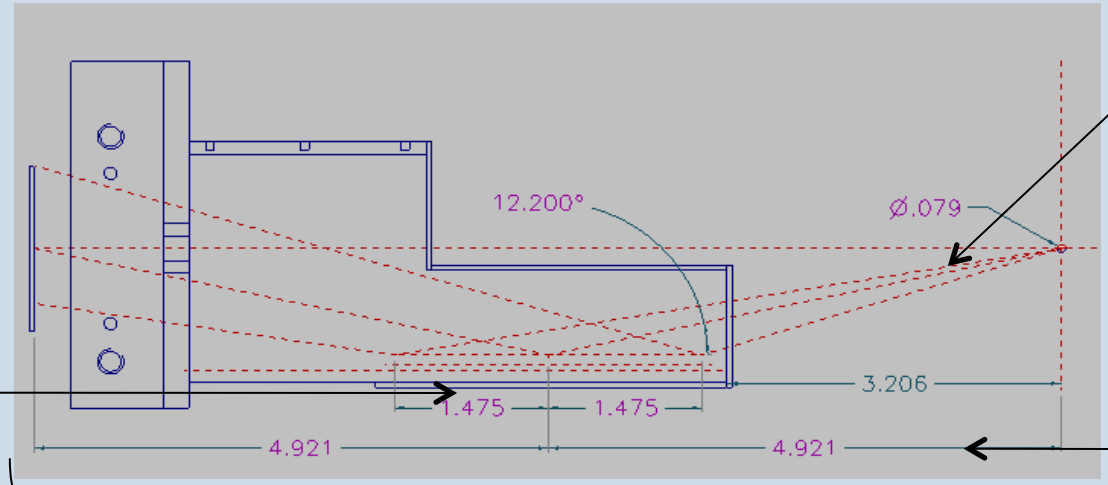
Atoms of Tm	Atoms of Tm	Atoms of Fe	Atoms of Fe	73Ge	187Os	201Hg
9.30E+00	9.30E+00	7.86	7.86	5.323	22.59	13.92
169	169	57	57	73	187	817.51
8.77E-04	8.77E-04	2.01E-03	2.01E-03	1.46E-03	4.13E-04	3.48E-05
10	250	10	250	10	10	10
0.007068583	0.176714587	0.007068583	0.176714587	0.007068583	0.007068583	0.007068583
2.05E+17	5.14E+18	1.18E+18	2.95E+19	4.53E+17	2.12E+17	1.51E+15
			Gamma	Gamma	Gamma	Gamma
			1.44E+01	13.2845	9.756	1.5648
			M1+E2	E2	M1(+E2)	M1+E2
			98.3 ns	2.92 us	2.38 ns	81 ns
	~30% transmission through 10 um		~60% transmission through 10 um	~50% transmission through 10 um	~10% transmission through 10um	10% transmission through 1um
8.77	8.77	20.1258	20.1258	14.5972	4.12752	0.348363

The high collection efficiency of the HOPG spectrometer enables the recording of high signal to noise data

Highly Oriented Pyrolytic Graphite (HOPG) crystal has an reflectivity of ~3 mrad and the spectrometer has a solid angle of ~10^{-5}

Direction of XRFC and CCD

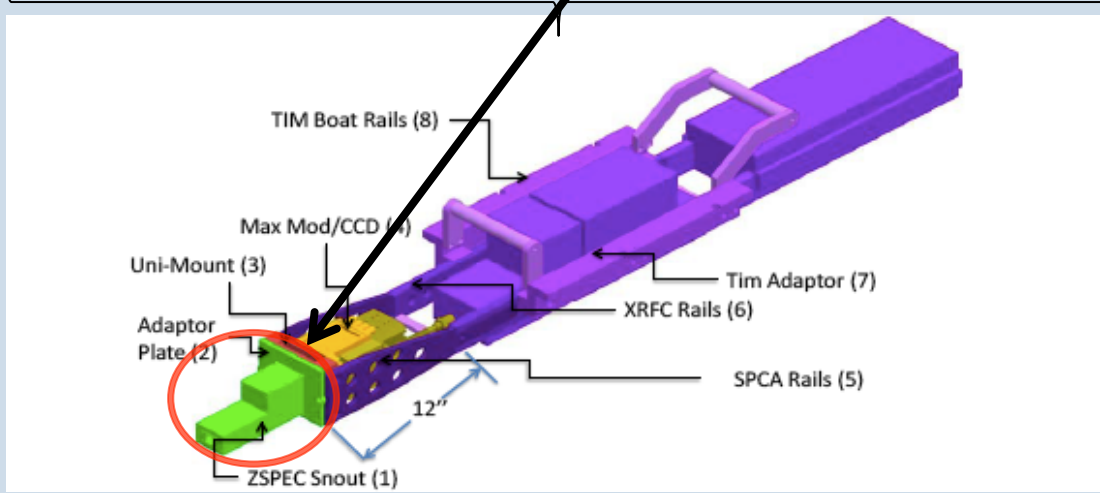
HOPG crystal (50x25 x2mm)



$\theta_{Bragg}=12^{o}$

Source

12.5 cm

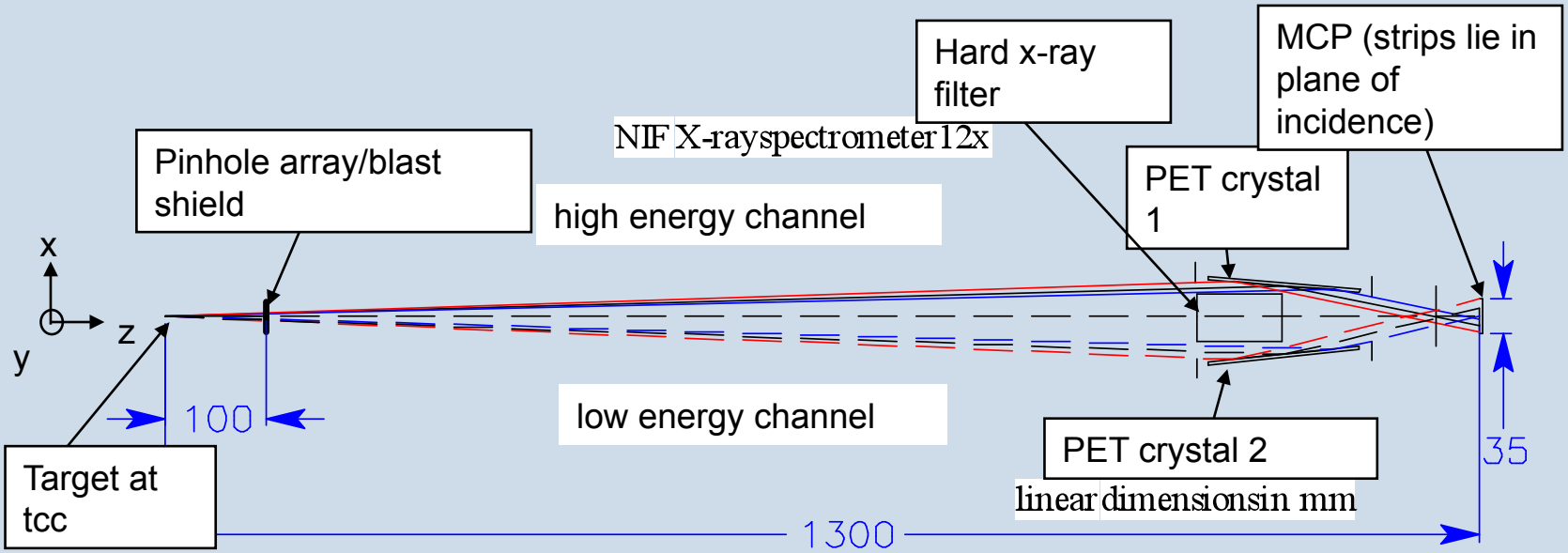


Dispersion for this geometry:

~3.3 eV/pxl
or
~180 eV/mm

Currently NIF has HSXRS with two Bragg crystals (5 cm x 15 cm) that are used to cover the Ge K-shell emission spectrum

The HSXRS Hot Spot X-Ray Spectrometer may be used to detect the emitted Tm or Fe gammas at NIF



Low energy channel
(9.98 keV < E < 10.9 keV)
High energy channel
(11.7 keV < E < 12.8 keV)

PET = pentaerythritol
2d = 8.740 Å
CE=1×10^{-4}

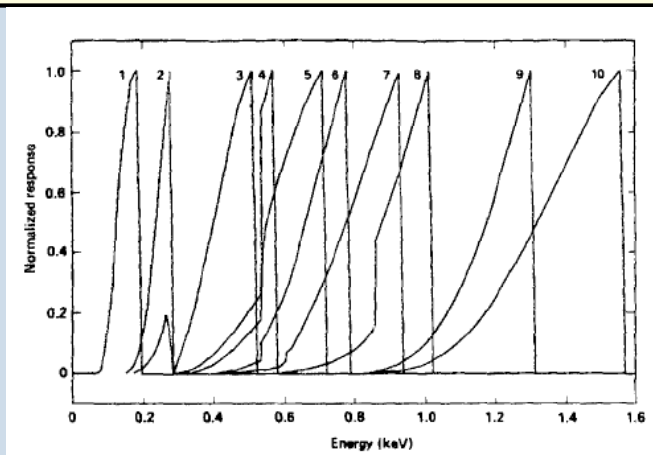
-Either a new NIF spectrometer will need to be designed for Fe and Tm experiments, or HSXRS will need to be modified

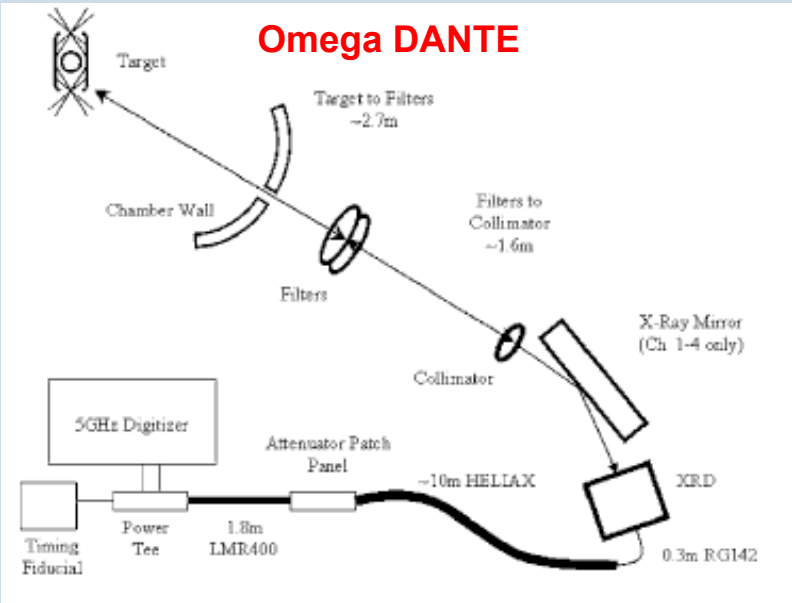
Dante may enable us to detect the low energy x-rays emitted when electrons transition to fill the vacancies after IC

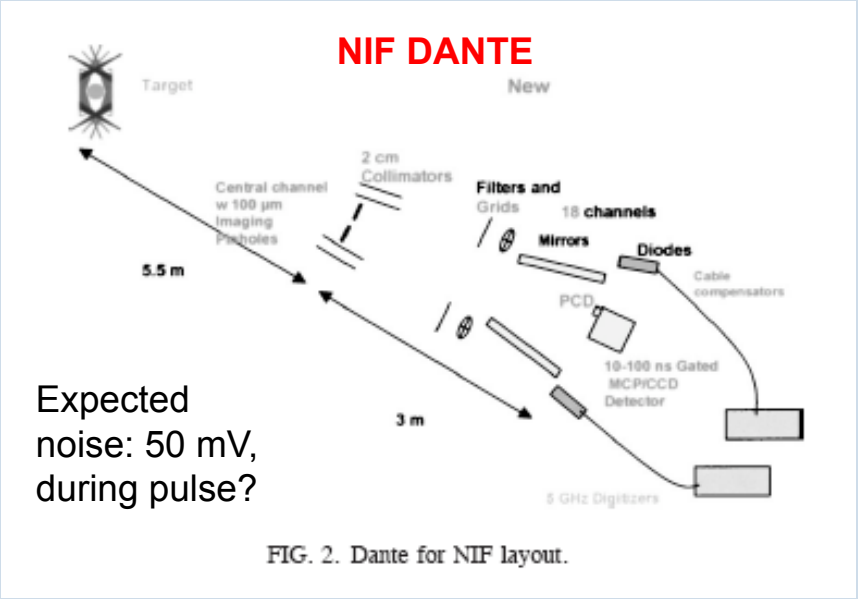
Dante (50 eV to 20 keV) is an array of x-ray diodes with filter packs that enable energy discrimination

Channels Requested (Select up to 10)

☐ Channel 1 (50-70 eV)	☑ Channel 10 (1600-1800 eV)
☑ Channel 2 (150-180 eV)	☑ Channel 11 (2000-5000 eV)
☑ Channel 3 (250-280 eV)	☑ Channel 12 (1800-2500 eV)
☑ Channel 4 (450-520 eV)	☑ Channel 13 (2540-3300 eV)
☑ Channel 5 (750-820 eV)	☑ Channel 14 (3170-4800 eV)
☑ Channel 6 (900-980 eV)	☐ Channel 15 (4300-6300 eV)
☑ Channel 7 (980-1050 eV)	☐ Channel 16 (5300-7000 eV)
☑ Channel 8 (1200-1300 eV)	☐ Channel 17 (7300-9500 eV)
☑ Channel 9 (1300-1500 eV)	☐ Channel 18 (10000-20000 eV)







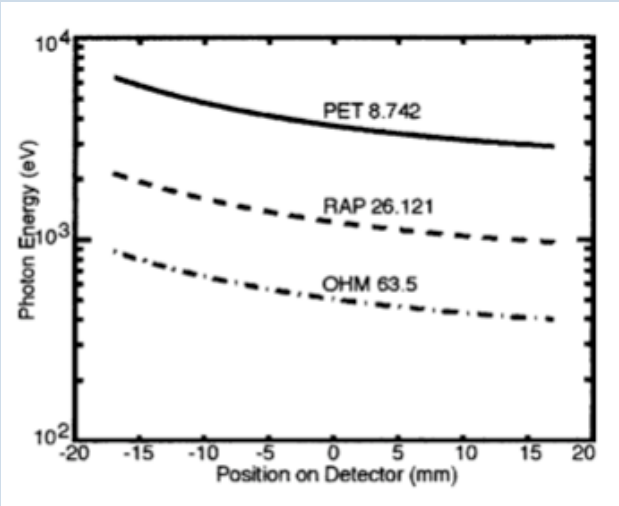
Expected noise: 50 mV, during pulse?

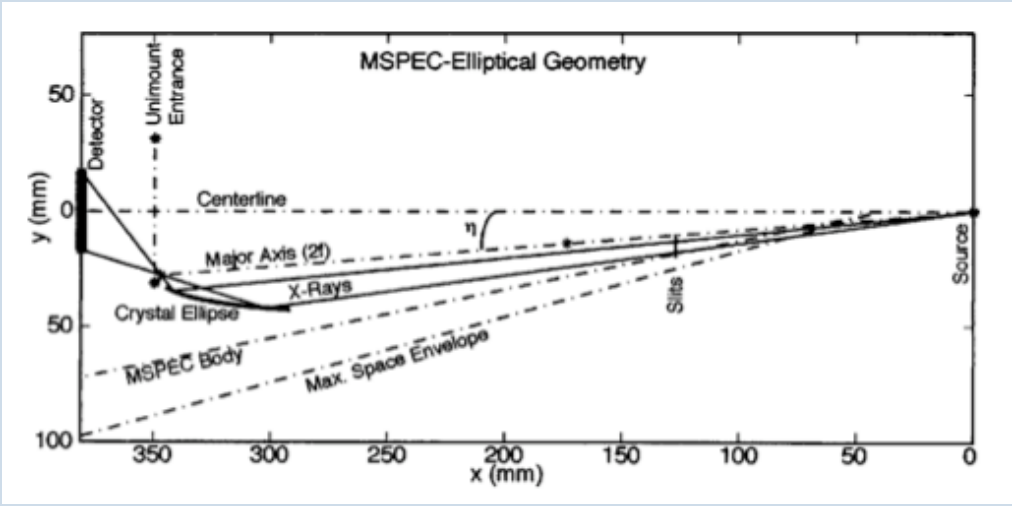
FIG. 2. Dante for NIF layout.

To achieve high spectral resolution of the emitted x-rays and gamma ray, we can use crystals with a large 2d spacing

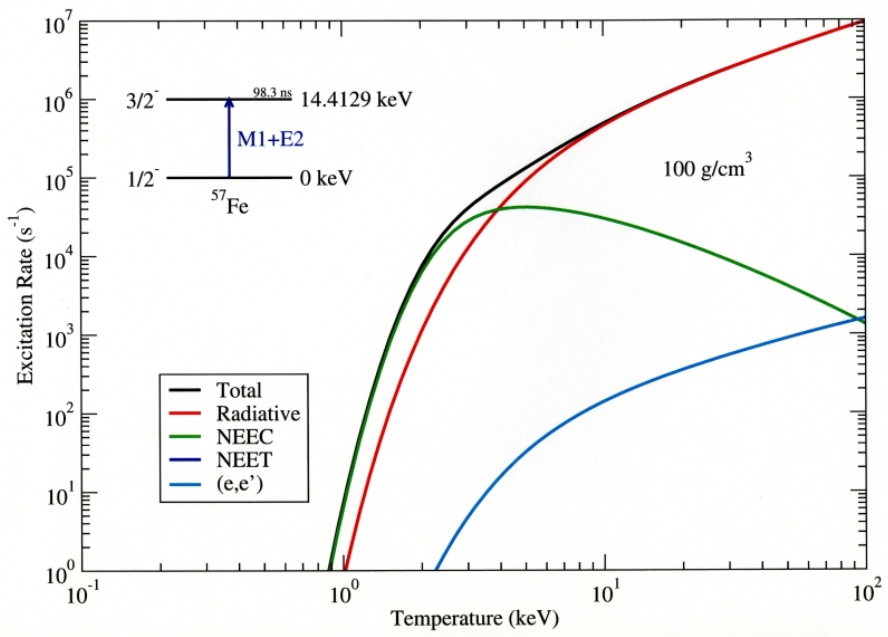
The Omega RAP and Beryl crystal can be used to record the low energy gammas from 201 Hg

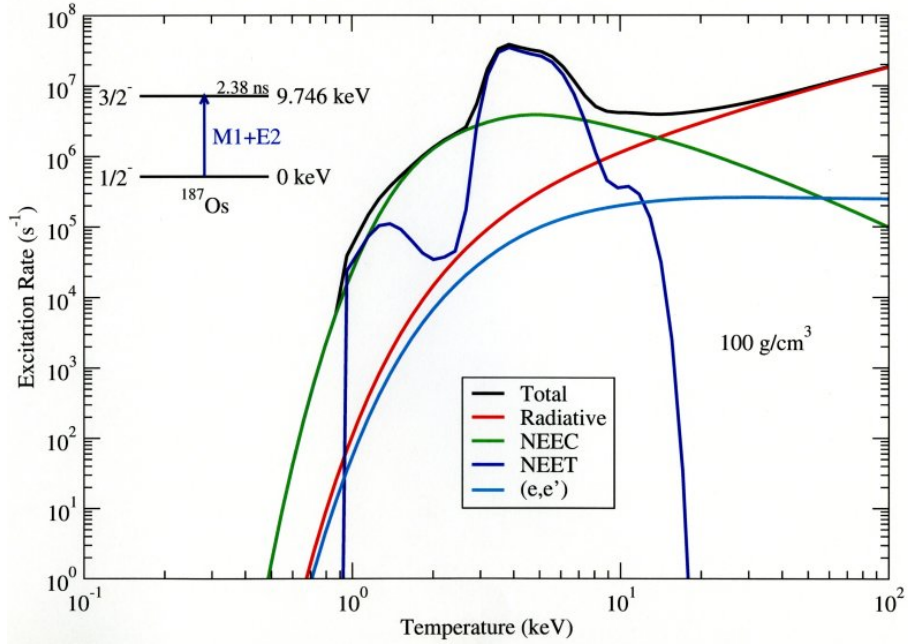
Crystal	Energy Range	ΔE/E	2D Ang	Int Refl Mrad	Bragg angle @1500 eV	Solid angle
Beryl (1010) $Al_2Be_3(Si_6O_{18})$	.8-2.8 keV	8e-4	15.9	4	31.3 deg	?
(Omega) MSPEC: RAP Elliptical	1.0-1.9 keV	2e-3	26.121	.1	18.5 deg	7.5e-7

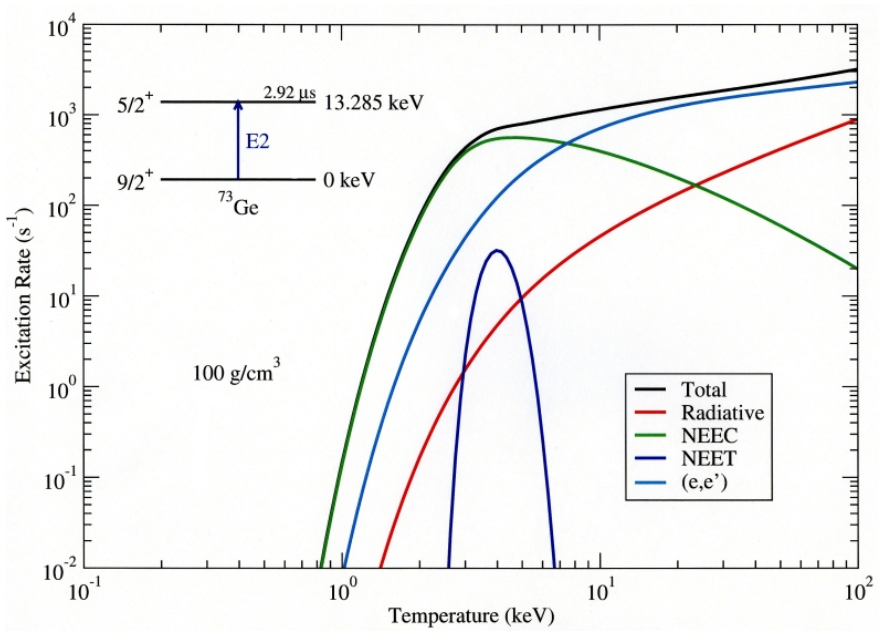


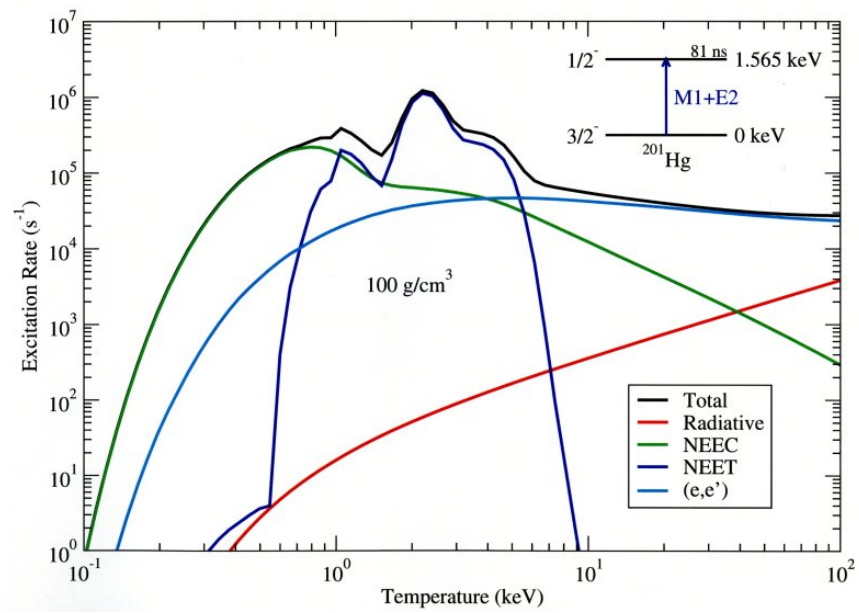


-Currently there is no MSPEC for NIF
-We could put the Beryl in an existing spectrometer with a similar Bragg angle?


3/2⁻
98.3 ns
14.4129 keV
M1+E2
1/2⁻
0 keV
57Fe
100 g/cm3
Total
Radiative
NEEC
NEET
(e,e')
Excitation Rate (s-1)
Temperature (keV)

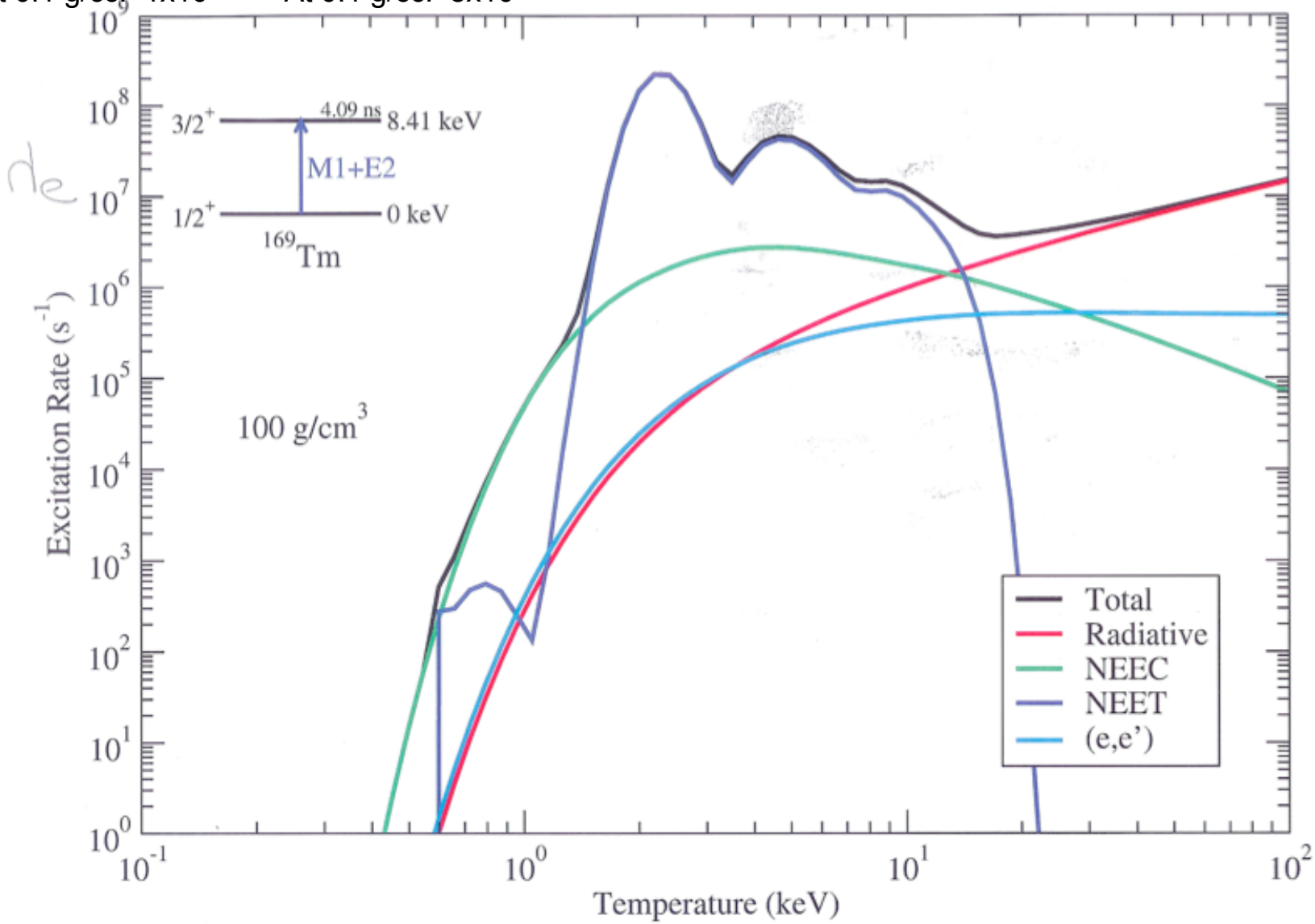

3/2⁻
2.38 ns
9.746 keV
M1+E2
1/2⁻
0 keV
187Os
100 g/cm3
Total
Radiative
NEEC
NEET
(e,e')
Excitation Rate (s-1)
Temperature (keV)


5/2+
2.92 μs
13.285 keV
E2
9/2+
0 keV
73Ge
100 g/cm3
Total
Radiative
NEEC
NEET
(e,e')
Excitation Rate (s-1)
Temperature (keV)


1/2⁻
81 ns
1.565 keV
M1+E2
3/2⁻
0 keV
201Hg
100 g/cm3
Total
Radiative
NEEC
NEET
(e,e')
Excitation Rate (s-1)
Temperature (keV)

NEET:
At 100 g/cc: 3×10^8
At 0.1 g/cc: 1×10^7

NEEC:
At 100 g/cc: 2×10^6
At 0.1 g/cc: 8×10^3



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ADOPTED LEVELS, GAMMAS for ^{169}Tm

Author: CORAL M. BAGLIN Citation: Nuclear Data Sheets 109, 2033 (20

Full ENSDF file

Q(β-)=-910 keV *4* S_n = 8033.6 keV *15* S_p = 5572.2 keV *11* Q_α = 1199.7

References:

A: ^{169}Er β- decay
B: ^{169}Yb ε decay (32.018 d)
C: ^{168}Er(p,p) IAR
D: ^{168}Er(^{3}He,d),(α,t)
E: ^{169}Tm(γ,γ):Mossbauer effect
F: ^{169}Tm(e,ep) IAR
G: Coulomb Excitation
H: ^{170}Er(p,γ2n),(d,γ3n)
I: ^{169}Tm(γ,γ')
J: ^{169}Tm(n,n'γ),(*polarized* n,n)
K: ^{169}Tm(^{3}He,^{3}He')
L: Muonic atom

E_{level}	E_γ [#]	I_γ [@]	Mult.[#]	δ[#]	α
8.41017	8.41017 *15*	100	M1+E2	0.0328 *5*	263 *5*
118.18945	109.77924[b] *3*	100.0 *4*	M1+E2	-0.139 *10*	2.37
	118.18940[b] *14*	10.78 *4*	E2		1.642
138.93315	20.752 *9*	1.73 *2*	M1+E2	0.0292 *16*	54.9 *9*

E_{level} (keV)	XREF	Jπ	$T_{1/2}$	E_γ (keV)	I_γ
0.0	AB DE GH J	1/2+	STABLE		
8.41017 *11*	AB DE GH J	3/2+	4.09 ns *5*	8.41017 *15*	100
118.18945 *11*	AB D GH J	5/2+	62 ps *3*	109.77924 *3*	100.0
				118.18940 *14*	10.78
138.93315 *12*	B D GH J	7/2+	302 ps *2*	20.752 *9*	1.73
				130.52293 *6*	100.0
316.14633 *11*	B D H J	7/2+	659.9 ns *23*	177.21307 *6*	62.01
				197.95675 *7*	100
				307.73586 *10*	27.96

Z (atomic number or symbol)
69
γ-energy (in keV)
8.41017 Uncertainty 15
Enter (optional) uncertainty in energy as **x** or **+x-y**
Multipolarity
M1+E2 δ .0328 Uncertainty 5
Enter (optional) uncertainty in δ as **x** or **+x-y**
Show Subshells ☐ **Data Set** BrIccFO
Calculate Reset

BrIccS v2.2b (20-Jan-2009)
Z=69 (Tm, Thulium)
γ-energy: 8.41017 *(+15 -15)* keV
Mixing Ratio δ: .0328 *(+5 -5)*
Data Sets: BrIccFO

Shell	E(ce)	M1	E2	Mixed ICC
Tot		1.671E+02	8.965E+04	263 (5)
M-tot	6.25	1.316E+02	7.171E+04	209 (4)
N-tot	7.99	3.079E+01	1.612E+04	48.1 (9)
O-tot	8.36	4.406E+00	1.814E+03	6.35 (11)
P-tot	8.40	2.369E-01	7.469E-01	0.237 (4)

ADOPTED LEVELS, GAMMAS for ^{57}Fe

Author: M. R. BHAT Citation: Nuclear Data Sheets 85, 415 (1998)

Full ENSDF file

Q(β-)=-836.0 keV *4* S_n= 7646.03 keV *10* S_p= 10559.1 keV *4* Q_α= -732

References:

A: ^{57}Mn β- decay
B: ^{57}Co ε decay
C: ^{57}Fe(γ,γ): Mossbauer
D: ^{48}Ca(^{13}C,γ4n) E=25-65 MeV
E: ^{56}Fe(n,n'γ)
F: ^{54}Cr(α,γn),(*polarized* α,γn)
G: ^{55}Mn(t,γn),^{56}Fe(t,dγ):?
H: ^{55}Mn(α,γnp) E=25,28.6 MeV
I: ^{56}Fe(n,γ),(*polarized* n,γ) E=thermal
J: ^{56}Fe(n,γ) E=1151.5 eV res
K: ^{56}Fe(d,p),^{57}Fe(p,p')
L: ^{56}Fe(*polarized* d,p) E=10 MeV
M: ^{56}Fe(d,γp) E=6 MeV
N: Coulomb Excitation
O: ^{58}Fe(p,d),(d,t),(^{3}He,α)
P: ^{59}Co(μ-,γ2n),(π-,Xγ)
Q: ^{58}Ni(^{14}C,^{15}O) E=72 MeV
R: ^{60}Ni(p,Xγ),^{62}Ni(p,Xγ)

E_{level}	E_γ[#]	I_γ[#@]	Mult.[&]	δ[&]	α	Comments
14.4129	14.4129 *6*	100	M1+E2	0.00223 *18*	8.56 *26*	E_γ: from ε decay. **Mult.:** from Γ and adopted Jπ. See also 1984Pl05. **δ:** from $T_{1/2}$, B(E2)↑, Eγ, and α. α(K)=7.35 *19*; α(L)=0.779 *42*; α(M+..)=0.107 *10* **B(E2)(W.u.):** from adopted B(E2)↑ and J. B(M1)(W.u.)=0.0078 *3*; B(E2)(W.u.)=0.37 *7* Additional documentation [1]
136.4743	122.0614[b] *4*	100 *10*	M1+E2	+0.120 *1*	0.0240 *14*	α(K)=0.0214 *12*; α(L)=0.00224 *20*; α(M+..)=0.00037 *5* B(M1)(W.u.)=0.00118 *17*; B(E2)(W.u.)=2.3 *4* Additional documentation [2]
	136.4743[b] *5*	12.0 *12*	E2		0.137 *15*	α(K)=0.134; α(L)=0.0139 **Mult.:** Q from γ(θ,H,t) in ε decay and Coulomb excitation; E2 from RUL. B(E2)(W.u.)=10.9 *16*
366.759	230.29 *2*	9.2 *11*	(M1+E2)	+0.02 *8*		**Mult.:** D+Q from γ(θ) in Coul. ex. and ε decay; and ΔJπ. **δ:** weighted average of γ(θ) in Coul. ex. and ε. Other δ's excluded by comparison to B(M1)(W.u.)=0.0124 *25*; B(E2)(W.u.)=0.2 *+15-2*
	352.36 *1*	100 *11*	M1+E2	+0.025 *9*		B(M1)(W.u.)=0.038 *8*; B(E2)(W.u.)=0.4 *3*
	366.75 *1*	17.7 *20*	M1+E2	-0.45 *5*		**δ:** sign from Coul. ex. value from B(E2)↑ and $T_{1/2}$.
706.416	339.54 *18*	1.7 *3*	M1+E2	+0.083 *5*		**B(E2)(W.u.):** from B(E2)↑. B(M1)(W.u.)=0.0049 *10*; B(E2)(W.u.)=15 *4*
	569.92 *4*	11.0 *13*	M1+E2	+0.097 *8*		B(M1)(W.u.)=0.0020 *7*; B(E2)(W.u.)=0.23 *9*
	692.03 *2*	100 *11*	M1+E2	-0.465 *8*		B(M1)(W.u.)=0.0027 *9*; B(E2)(W.u.)=0.15 *6*
						B(M1)(W.u.)=0.011 *4*; B(E2)(W.u.)=10 *3*

E_{level} (keV)	XREF	Jπ	$T_{1/2}$	E_γ (keV)	I_γ
0.0	ABCDEFGHIJKLMNOPQR	1/2-	STABLE		
14.4129 *6*	ABCDEFGHIJKLMNOP R	3/2-	98.3 ns *3*	14.4129 *6*	100
136.4743 *5*	ABCDEFGHIJKLMNOPQR	5/2-	8.7 ns *3*	122.0614 *4*	100 *10*
				136.4743 *5*	12.0 *12*
366.759 *7*	AB DEFGHIJKLMNOPQR	3/2-	10.5 ps *14*	230.29 *2*	9.2 *11*
				352.36 *1*	100 *11*
				366.75 *1*	17.7 *20*
706.416 *16*	AB DEFGHIJK MNOP R	5/2-	4.1 ps *11*	339.54 *18*	1.7 *3*
				569.92 *4*	11.0 *13*
				692.03 *2*	100 *11*
				706.4 *2*	5.7 *24*
1007.13 *4*	A DEF HI K M	7/2-	0.13 ps *7*	640.20 *14*	4.7 *32*
				870.68 *5*	100.0 *16*
				992.68 *8*	51.6 *16*

Z (atomic number or symbol): 26

γ-energy (in keV): 14.4129 Uncertainty

Enter (optional) uncertainty in energy as **x** or **+x-y**

Multipolarity: M1+E2 δ .00223 Uncertainty

Enter (optional) uncertainty in δ as **x** or **+x-y**

Show Subshells ☐ **Data Set** BrIccFO

Calculate Reset

BrIccS v2.2b (20-Jan-2009)
Z=26 (Fe, Iron)
γ-energy: 14.4129 keV
Mixing Ratio δ: .00223
Data Sets: BrIccFO

Shell	E(ce)	M1	E2	Mixed ICC
Tot		8.544E+00	6.134E+02	8.55 (12)
K	7.30	7.646E+00	4.056E+02	7.65 (11)
L-tot	13.58	7.859E-01	1.837E+02	0.787 (11)
K/L		9.728E+00	2.208E+00	9.72 (20)
M-tot	14.32	1.080E-01	2.387E+01	0.1082 (16)
L/M		7.275E+00	7.695E+00	7.28 (15)
N-tot	14.41	4.704E-03	1.896E-01	0.00471 (7)
L/N		1.671E+02	9.692E+02	167 (4)

ADOPTED LEVELS, GAMMAS for ^{187}Os

Author: M. S. Basunia Citation: Nuclear Data Sheets 110, 999 (2009)

Full ENSDF file

Q(β-)=-1502 keV *6* S_n= 6290.0 keV *6* S_p= 6577.0 keV *10* Q_α= 2723.9 keV *12*

References:
A: ^{187}Re β- decay
B: ^{187}Re β- decay (32.9 y)
C: ^{187}Ir ε decay
D: ^{186}Os(n,γ)
E: ^{186}Os(d,p)
F: ^{187}Re(d,γ2n),^{187}Re(p,γn)
G: ^{187}Os(d,d')
H: Coulomb Excitation
I: ^{188}Os(d,t)
J: ^{189}Os(p,t)

E_{level} (keV)	XREF	Jπ	$T_{1/2}$	E_γ (keV)	I_γ	γ mult.		
0.0	ABCD FGH J	1/2-	STABLE					
9.756 *19*	BCD F H J	3/2-	2.38 ns *18*	9.75 *3*	100	M1(+E2)	0.0	1/2-
74.356 *21*	CDEFGHI	3/2-	37 ps *28*	64.59 *3*	36 *7*	M1+E2	9.756	3/2-
				74.30 *3*	100 *23*	M1+E2	0.0	1/2-
75.016 *22*	CDEFGHIJ	5/2-	2.16 ns *16*	65.31 *3*	100 *20*	E2+M1	9.756	3/2-
				75.03 *3*	84 *16*	E2	0.0	1/2-
100.45 *4*	CDE HIJ	7/2-	112 ns *6*	25.62 *5*	100 *50*	M1+E2	75.016	5/2-
				90.37 *10*	4.7 *17*	E2	9.756	3/2-
117 *2*	I							
187.42 *3*	CD FGH J	5/2-	107 ps *9*	87.62 *10*	1.8 *12*	(M1+E2)	100.45	7/2-
				112.35 *10*	1.53 *15*	E2	75.016	5/2-
				113.20 *10*	8.1 *5*	M1+E2	74.356	3/2-
				177.68 *7*	100 *4*	M1+E2	9.756	3/2-
				187.37 *7*	67.4 *23*	E2	0.0	1/2-
190.57 *6*	CD FG J	7/2-		115.67 *8*	26 *4*	M1+E2	75.016	5/2-
				180.83 *11*	100 *8*	E2	9.756	3/2-
257.10 *7*	C F J	11/2+	231 μs *2*	156.63 *7*	100	M2+E3	100.45	7/2-
263.07 *24*	F J	(9/2-)		162.4 *3*	100		100.45	7/2-
333.35 *5*	CDEFG IJ	(7/2-)		146.19 *9*	12.1 *12*		187.42	5/2-
				258.65 *7*	100 *19*	(E2)	74.356	3/2-
				323.11 *9* ?		(E2)	9.756	3/2-

E_{level}	E_γ #	I_γ #	Mult.#	δ#	α	Comm
9.756	9.75 *3*	100	M1(+E2)	<0.04	2.8×10^2 *7*	α(M)=2.2×10^2 *5*; α(N+..)=62 *14* α(N)=53 *12*; α(O)=8.8 *18*; α(P)=0.524 *9*
74.356	64.59 *3*	36 *7*	M1+E2	0.13 *2*	3.91 *15*	B(M1)(W.u.)>0.026; B(E2)(W.u.)<$3.0\times10^{+2}$ α(L)=3.01 *11*; α(M)=0.70 *3*; α(N+..)=0.201 *8* α(N)=0.170 *7*; α(O)=0.0288 *10*; α(P)=0.00191 *3*
	74.30 *3*	100 *23*	M1+E2	0.08 *3*	≈9.97	B(M1)(W.u.)=0.06 *5*; B(E2)(W.u.)=$1.0\times10^{+2}$ *9* α: From ^{187}Ir ε decay. Deduced by the evaluator from intensities in 1962Ha24. Eγ close to ^{187}Os K-shell bin using Bricc (2008Ki07) yields 2.4.
75.016	65.31 *3*	100 *20*	E2+M1	2.9 *3*	24.4 *7*	B(M1)(W.u.)=0.11 *10*; B(E2)(W.u.)=$5.\times10^{+1}$ *+6-5* α(L)=18.4 *5*; α(M)=4.70 *13*; α(N+..)=1.29 *4* α(N)=1.12 *3*; α(O)=0.165 *5*; α(P)=0.00043 *4*
	75.03 *3*	84 *16*	E2		14.62	B(M1)(W.u.)=0.00010 *4*; B(E2)(W.u.)=81 *22* α(K)=0.804 *12*; α(L)=10.42 *15*; α(M)=2.67 *4*; α(N+..) α(N)=0.638 *9*; α(O)=0.0937 *14*; α(P)=0.0001714 *24*
100.45	25.62 *5*	100 *50*	M1+E2	0.021 *8*	54.5 *14*	B(E2)(W.u.)=38 *10* α(L)=42.0 *11*; α(M)=9.68 *25*; α(N+..)=2.80 *7* α(N)=2.36 *6*; α(O)=0.406 *10*; α(P)=0.0295 *5* B(M1)(W.u.)=0.00021 *15*; B(E2)(W.u.)=0.06 *6*

Z (atomic number or symbol)
76

γ-energy (in keV)
9.756 Uncertainty

Enter (optional) uncertainty in energy as **x** or **+x-y**

Multipolarity
M1+E2 δ .04 Uncertainty

Enter (optional) uncertainty in δ as **x** or **+x-y**

Show Subshells ☐ **Data Set** BrIccFO

Calculate Reset

BrIccS v2.2b (20-Jan-2009)
Z=76 (Os, Osmium)
γ-energy: 9.756 keV
Mixing Ratio δ: .04
Data Sets: BrIccFO

Shell	E(ce)	M1	E2	Mixed ICC
Tot		2.157E+02	7.852E+04	341 (5)
M-tot	6.90	1.673E+02	6.173E+04	266 (4)
N-tot	9.17	4.084E+01	1.466E+04	64.2 (9)
O-tot	9.68	7.039E+00	2.134E+03	10.44 (15)
P-tot	9.75	5.222E-01	1.398E+00	0.524 (8)

Non-LTE NEET rate building (1)

- LTE calculation
  - accurate atomic transitions
  - corresponding charge state Q
- NOHEL (radial quantum number n only) :
  - non-LTE temperature relative to Q
  - Average number of electrons, degeneration, energy, in each atomic shell
  - Collisional, radiative and total rates and fluxes
- Population of each sub-shell assuming :
  - Maxwell Boltzmann statistics
  - Conservation number of electron
- Occupation probability :
  - Given by the Bernoulli law
    - occupation rate p of the sub-shell with k electrons for a degeneration n

$$P(N = k | D = n) = C_n^k p^k (1 - p)^{n-k} \text{ with } \sum_{k=0}^{n} P(N = k | D = n) = 1$$

Non-LTE NEET rate building (2)

- Distribution of electrons on the sub-shells with its own probability, for each atomic transition and charge state Q.
  - Core fully filled
  - Spectators sub-shells never occupied

- Distributions allowing NEET : corresponding transition
  - Dirac-Fock equation $\Rightarrow$ transition energy
  - Matrix element calculation
  - Atomic widths
  - Time-dependent NEET probability

Non-LTE NEET rate

Pascal MOREL, Gilbert GOSSELIN, Vincent MEOT, CEA/DAM/DIF