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Thulium and Bismuth as Reaction-In-Flight Diagnostics and the New Clover System at LLNL

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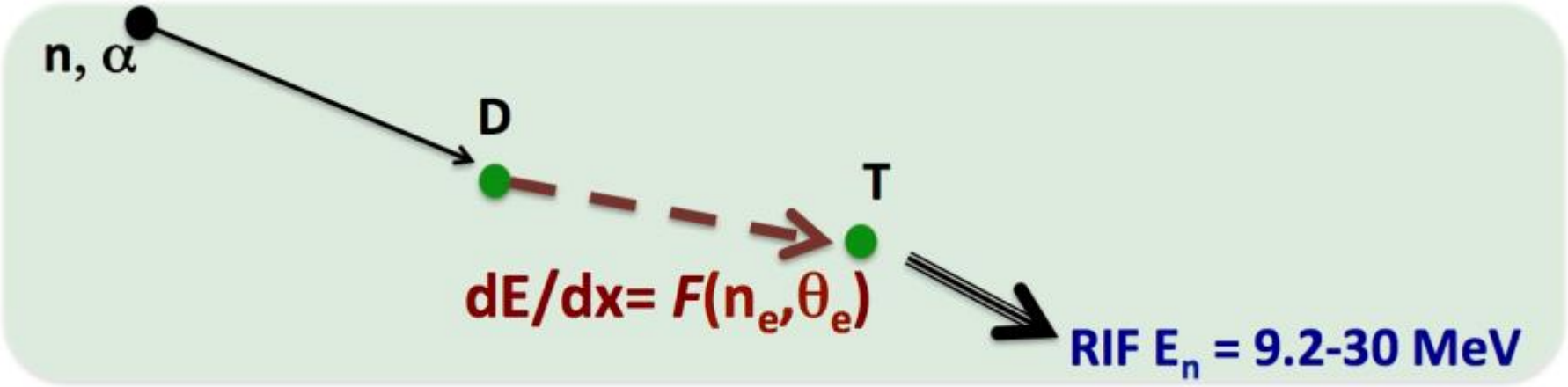
Outline

- RIF Physics
- Activation diagnostic
- Novel LANL assay capability
- NIF RIF data
- Summary

RIF neutrons are fusion products from in-flight fuel ions scattered by primary n's/α's



- Knock-on ions produce DT reactions out of equilibrium
- For low ion temperature (~ few keV) RIFs are the only significant source of neutrons above 15 MeV

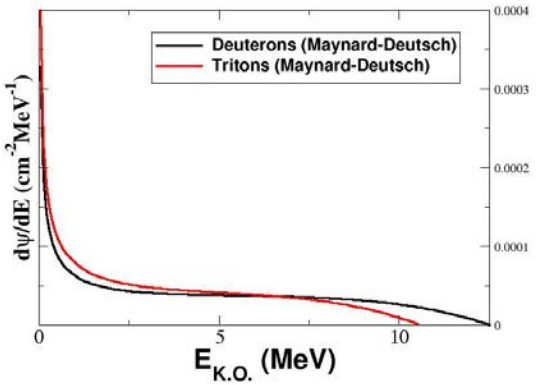
RIF neutrons probe charged particle stopping in the fuel assembly ➔ direct probe of mix

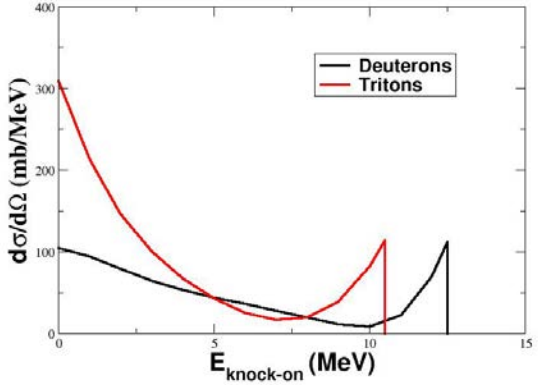
$$\frac{d\Gamma_{RIF}}{dVdE_{RIF}} = n_{fuel}\int \frac{d\psi_{ko}}{dE_{ko}}\sigma_{dt}\frac{1}{2m_n v_n v_{cm}}dE_{ko}$$

$$\frac{d\psi_{ko}}{dE}(E_f) = \frac{\psi_{14} n_{dt}\sigma_{k.o.}}{\left|de/dx(E_f)\right|}\int_{E_f}^{E_{0\max}} dE_0 q_0(E_0)$$

After stopping

Birth spectrum



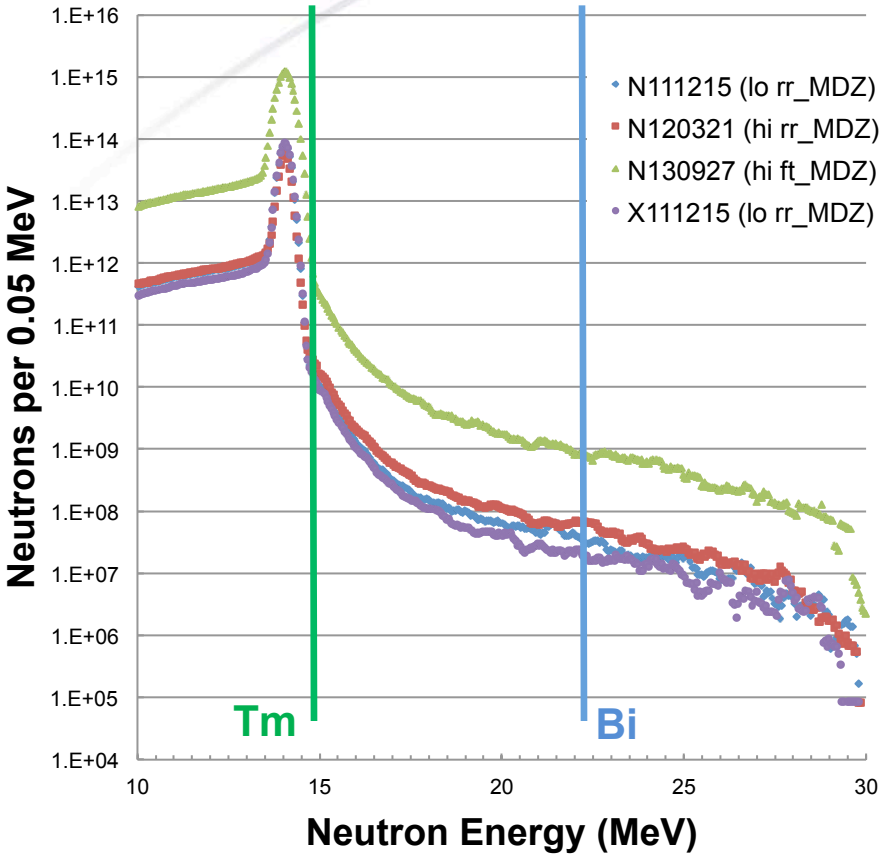


RIF Neutron Activation Diagnostic

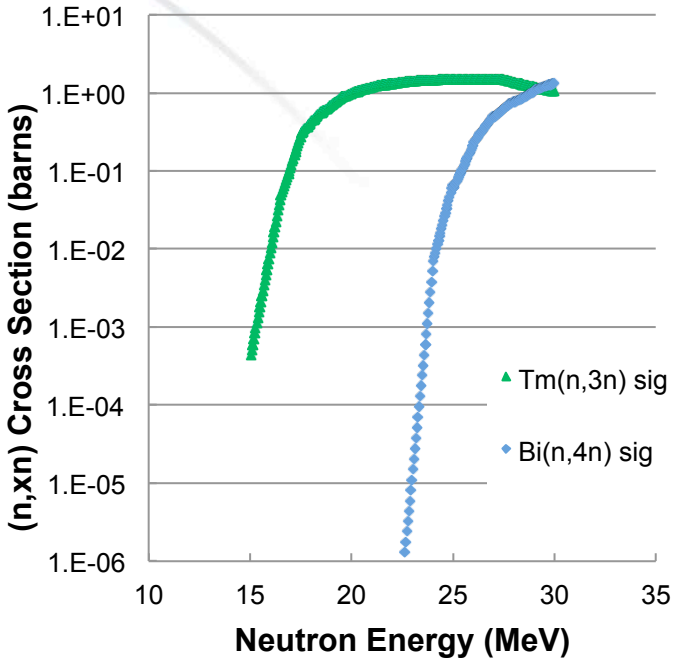
- *Neutron activation*
  - Advantages
    - Good solid angle and dynamic range
  - Disadvantages
    - Threshold measurements, i.e. no spectral information
    - Delayed data stream

- Currently ^{169}Tm is used as the main activation diagnostic
- ^{209}Bi has been suggested as a good **addition** to the neutron activation diagnostic

RIF Neutron Activation Diagnostic



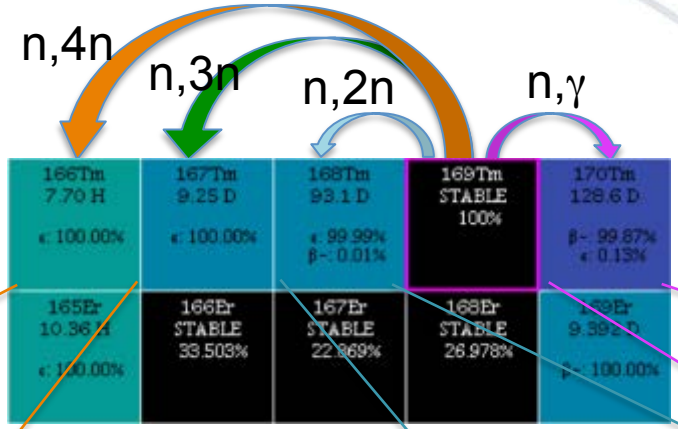
Neutron spectra from Cerjan; thresholds from NNDC



Cross section for Bi is an estimate from calculation (Kawano)

Cross section for Tm is from NNDC

Thulium is a good RIF activation target



^{169}Tm(n,4n)^{166}Tm
E_{th} = 23.7 MeV
$T_{1/2}$ = 7.7 h
E_γ = 2052 keV
I_γ = 17%

^{169}Tm(n,3n)^{167}Tm
E_{th} = 15.0 MeV
$T_{1/2}$ = 9.2 d
E_γ = 207.5 keV
I_γ = 41%

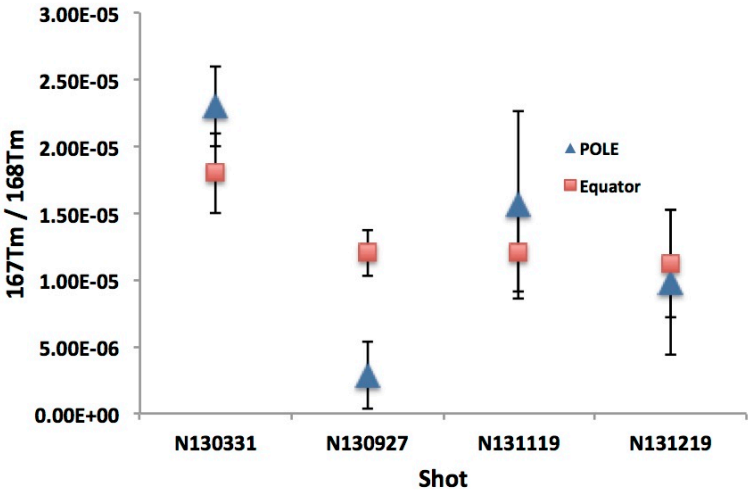
^{169}Tm(n,2n)^{168}Tm
E_{th} = 8.1 MeV
$T_{1/2}$ = 93 d
E_γ = 198, … keV
I_γ = 51%

^{169}Tm(n,γ)^{170}Tm
E_{th} = 0 MeV
$T_{1/2}$ = 128.6 d
E_γ = 84.2 keV
I_γ = 2.5 %

1. Unique decay characteristics after (n,2n), (n,3n), and (n,γ) reactions
2. Convenient post-shot half-lives
3. Strong gamma-ray transitions
4. Highest (n,3n) reaction yield
5. Known (measured) cross sections

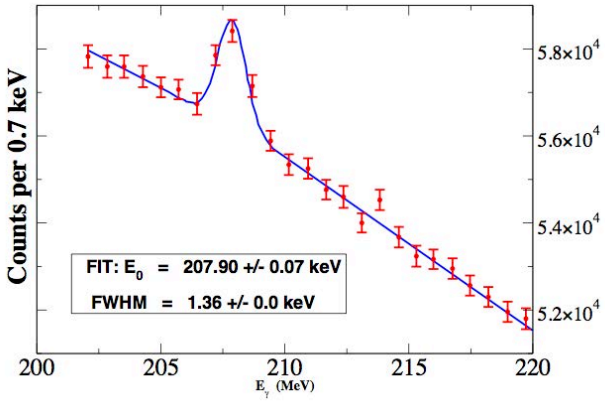
RIF Results With Thulium

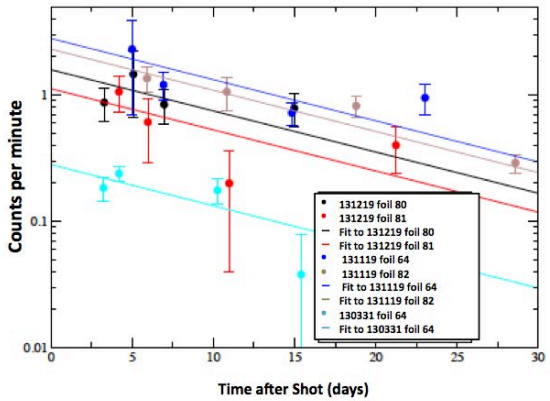
Previous



Best so far

- Shot N140306
  - Only 1 foil was used
- $^{167}Tm/^{168}Tm$ =
  $1.69 \pm 0.24 \times 10^{-5}$
- **2015 Measurements:**
  - $1.65 \pm 0.46 \times 10^{-5}$
  - $3.20 \pm 0.23 \times 10^{-5}$
  - $2.64 \pm 0.72 \times 10^{-5}$





- ^{167}Tm signal <u>not an artifact</u>
  - This is verified with a number of null results
  - N141008, N140520

^{209}Bi(n,4n) as a diagnostic

^{209}Bi(n,4n)^{206}Bi $T_{1/2}$ = 6.24 d
803γ (99%)

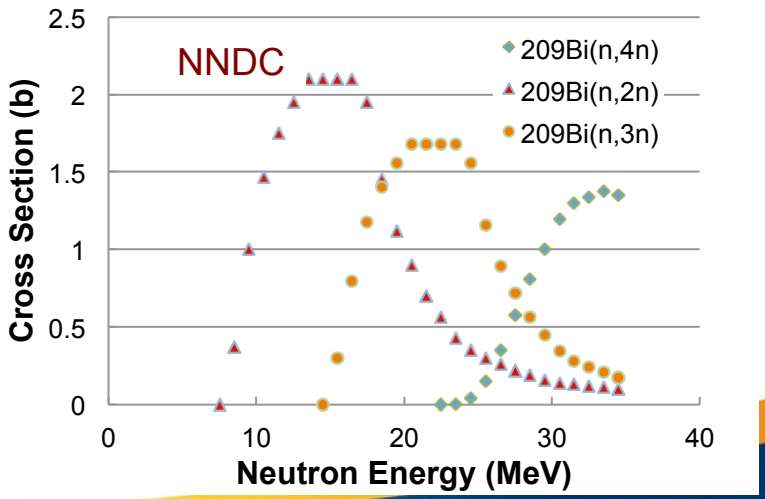
^{209}Bi(n,3n)^{207}Bi $T_{1/2}$ = 31 y; 1063γ (75%)
threshold ~ 14.5 MeV

^{209}Bi(n,2n)^{208}Bi $T_{1/2}$ 370,000 y; 2614γ (100%)
[RIF flux x 10^4]

^{209}Bi(n,γ)^{210}Bi $T_{1/2}$ = 5 d; no γs from β$^-$
^{210}Po $T_{1/2}$ = 138 d; 803γ (0.001%)
1.3x10^{-4} % alpha decay;
^{206}Tl β$^-$ 1021γ (69%)

^{209}Bi(n,p)^{209}Pb $T_{1/2}$ = 3.3 d; no γs [flux x10^4]

205Bi 15.31 D ε: 100.00%	206Bi 6.243 D ε: 100.00%	207Bi 31.55 Y ε: 100.00%	208Bi 3.68E+5 Y ε: 100.00%	209Bi STABLE 100%	210E 5.012 β-: 100 α: 1.3E
204Pb ≥1.4E+17 Y 1.4% α	205Pb 1.73E+7 Y ε: 100.00%	206Pb STABLE 24.1%	207Pb STABLE 22.1%	208Pb STABLE 52.4%	209P 3.253 β-: 100
203Tl STABLE 29.524%	204Tl 3.783 Y β-: 97.08% ε: 2.92%	205Tl STABLE 70.48%	206Tl 4.202 M β-: 100.00%	207Tl 4.77 M β-: 100.00%	208T 3.053 β-: 100



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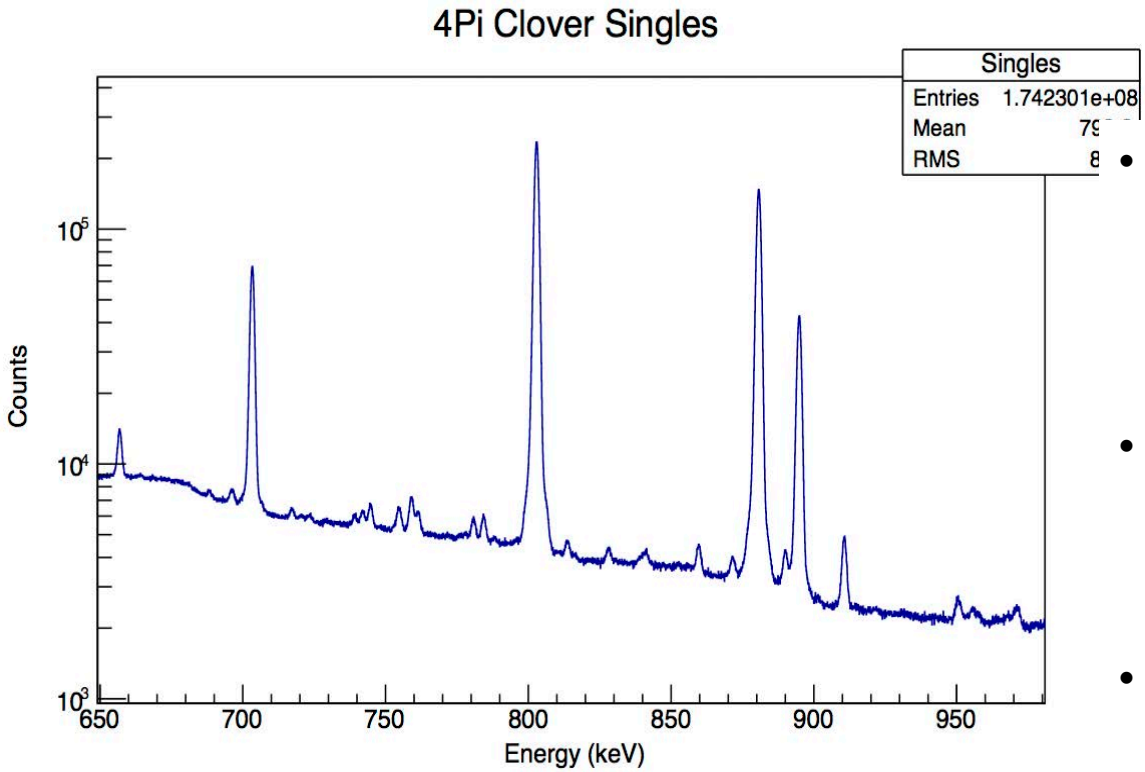
^{209}Bi(n,4n) as a diagnostic

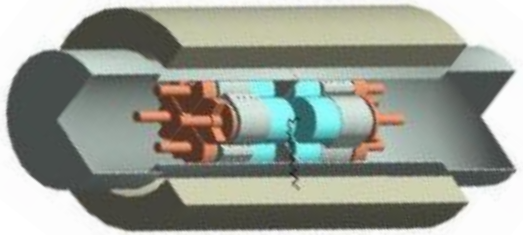


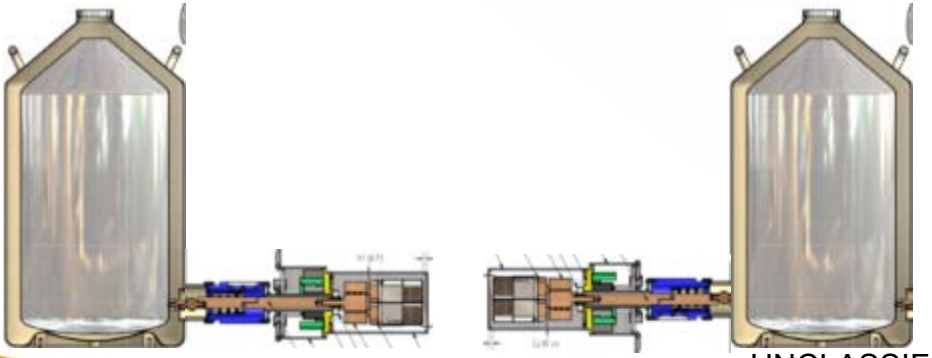
- Bismuth sample was irradiated at the 88” to study decay scheme with current Clover system
- Strongest line in ^{206}Bi is at 803 keV
  - Highly coincident decay scheme
- Sample is needed to calibrate the system due to geometry and complicated decay scheme

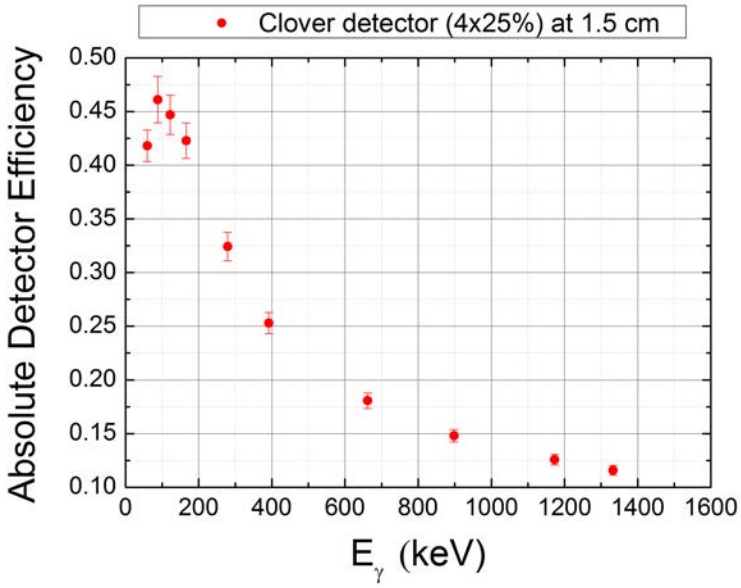
Activation decays are measured using LANL's HPGe 4π clover system…

State-of the Art Detection System:

Two 100% Clover HPGe detectors
Active 4π NaI(Tl) Compton Suppressor
Detector-target distance = 1.5 cm







The Los Alamos 4Pi Clover detector is a high precision tool providing 39% photopeak efficiency at 207 keV while suppressing gamma ray cascades.

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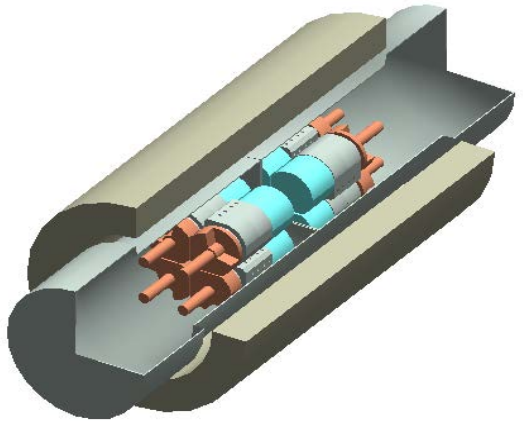
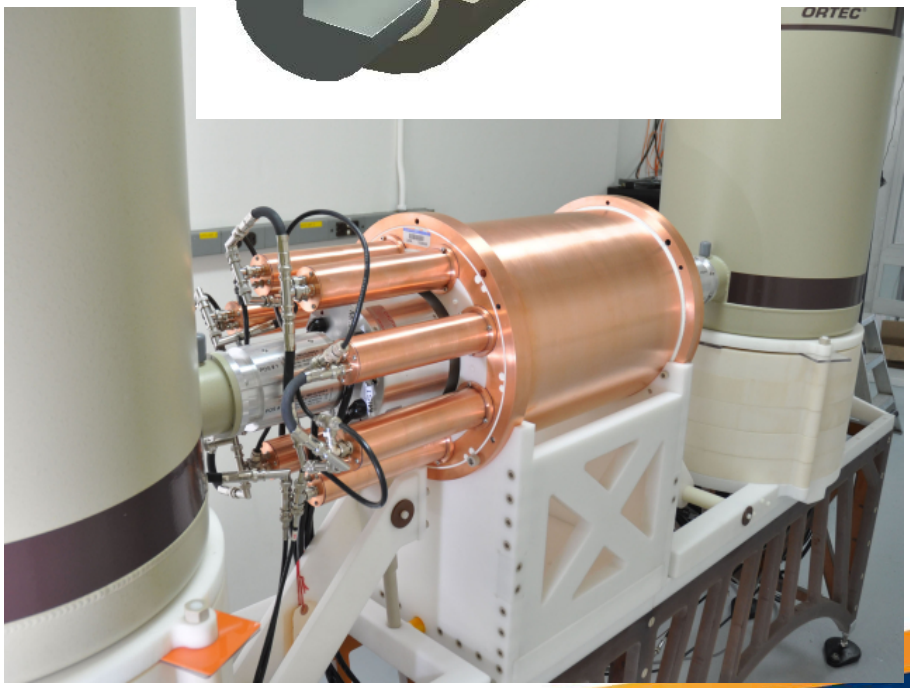
Detector Structure

- **Clover Structure (2 sets of 4 crystals)**
  - Each crystal ~55 mm diameter x 70 mm long
  - Quantify gamma rays in cascades and utilize coincidence counting methods
  - Preserve high resolution while attaining a large volume and detector face area
    - Environmental samples can be quite large
    - Accommodate a wide range of sample sizes and shapes

Compton suppression

- **Modeled using GEANT prior to purchase**
- **Custom made NaI(Tl) detector**
  - 2” thick walls, 16” long
  - OFHC Copper outer jacket
  - Thin copper and plastic inner jacket
  - Reduced background ~ 10x



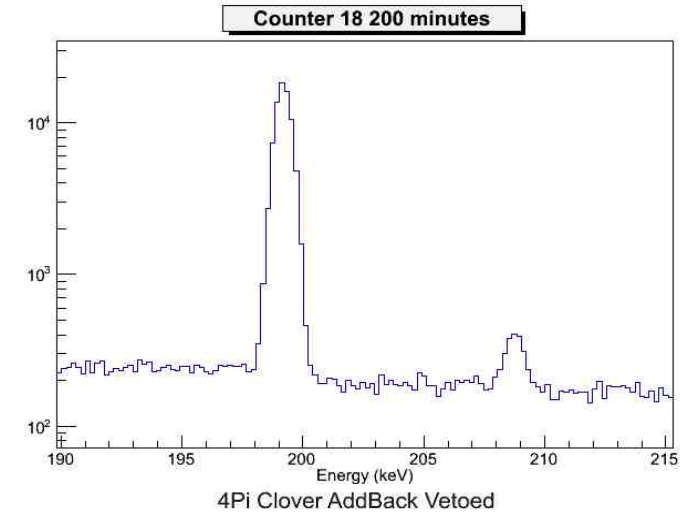


Comparison of Photo-peak Height in Clover to a Planar HPGe

- A thulium foil was irradiated with 15.8 MeV neutron at TUNL and shipped to Los Alamos for gamma ray spectrometry.

- Counter 18 is 50 mm diameter 19 millimeter deep ORTEC LOAX detector.

- The lower figure is the 4Pi Clover in Add Back mode with an anti-Compton Shield. The peak height of the 208 keV line from ^{167}Tm is clearly enhanced relative to 198 keV line from ^{168}Tm.



Future Clover System To Be Stationed at LLNL

- Why a new clover:
  - ^{167}Tm has a 9 day half life
  - Other Radchem options open up having a high-efficiency gamma spectrometer in place locally
    - Possibly Tm(n,4n) With a 7.5 hour half-life?

- Status of new clover:
  - All electronics, clover stand and 1 of 2 Clovers have arrived
  - Electronics are being upgraded to CAEN VME based system from the XIA cards used currently
  - Second clover detector expected from Ortec in the next 1-2 weeks

Future Work …

- Systematics studies to characterize uncertainties in ^{167}Tm measurements.
- Modeling of RIF neutron production and comparison with data using LANL's Eulerian Applications Project code suite.
- Acquisition of a second high resolution gamma spectrometer to locate at LLNL to eliminate transportation requirements and open up short half-life opportunities – To be completed 2015.

Summary

- The RIF neutron intensity can be measured well with thulium external activation foils.
- The Los Alamos 4π clover provides adequate sensitivity to measure the ^{169}Tm(n,3n)^{167}Tm reaction.
- Results indicate that for NIF implosions

$$\frac{Y_{E_n>15}}{Y_{E_n\approx14}} \approx 1\times10^{-4} \pm 30\%$$

- This ratio, which is consistent with stopping in a degenerate plasma, is in agreement with quantum mechanical stopping models.

A.C. Hayes, et.al.,"Reaction-in-Flight Neutrons as a Test of Stopping Power in Degenerate Plasmas". arXiv:1411.6971.