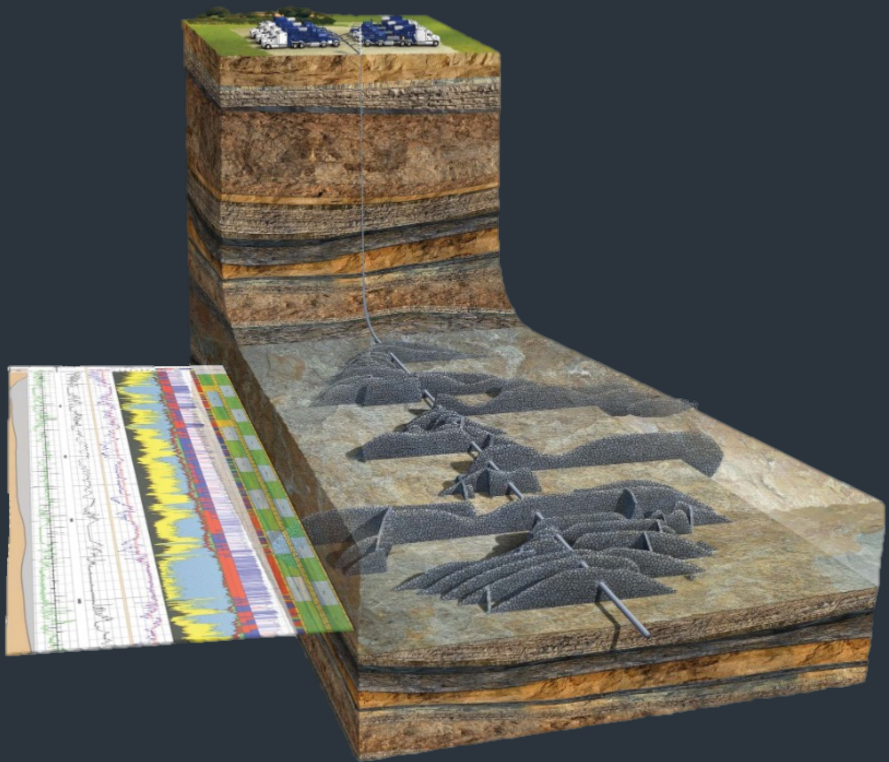
Missing Secondary Gamma Ray Lines in ENDF/B-VIII.0 Library and Impact on Oil Exploration



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Who is Schlumberger?

Founded by a physicist and an engineer in 1927 to conduct the first geophysical measurements of rock formations

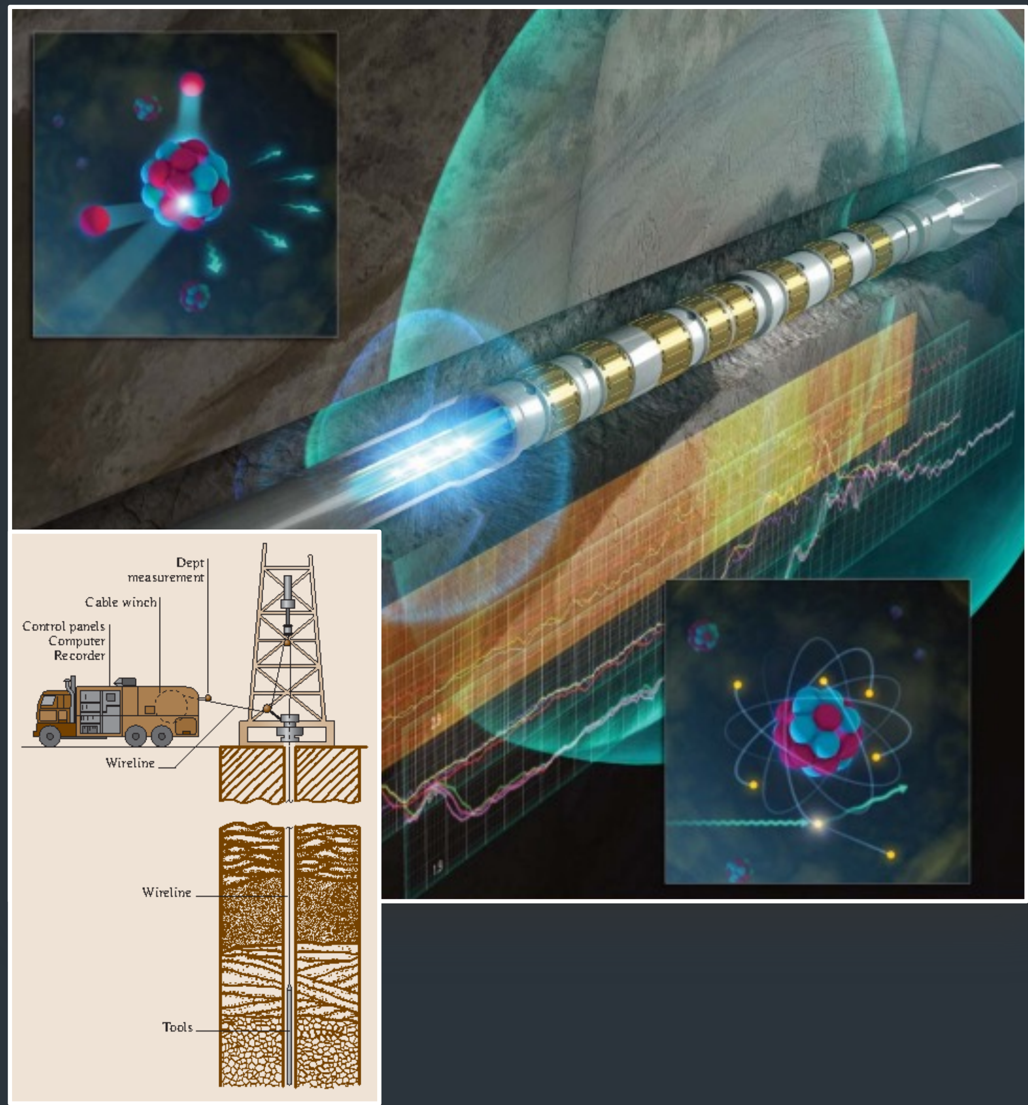
Now consists of:

- 90,000+ employees
  - 170 nationalities working in 120 countries
- 90 research and engineering centers worldwide

What We Do?

- We develop tools and provide hydrocarbon exploration measurements and data.
  - Where are the hydrocarbons?
  - What kind—oil or gas?
  - How much can be extracted?

- Use nuclear physics methods to measure
  - Natural radioactivity
  - Rock density
  - Hydrogen index, porosity
  - Rock matrix and pore fluid composition
  - Wellbore diameter
  - Etc.
- Provide full characterization of the reservoir



Rocks Are Composed of What?

Formation Rock = Matrix + Pores

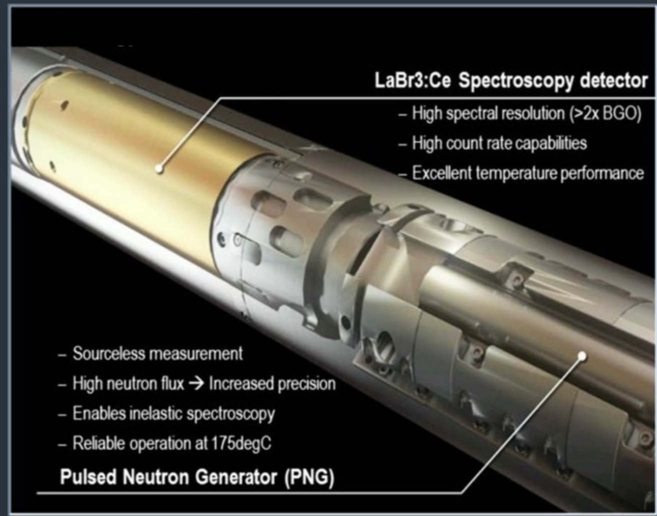
- Typical matrix materials
  - In the reservoir — sandstone (SiO_2), limestone ($CaCO_3$), dolomite ($CaMg(CO_3)_2$)
  - Everywhere else — “shale” (e.g., aluminosilicates)
- Typical pore fluids
  - Saltwater (NaCl brine)
  - Hydrocarbons (oil or gas, C_nH_m)

Tool Example—Spectroscopy Measurements

- Diameter: 4½ in. (11.5 cm)
- Length: 9 ft (3 m)
- Mass: 300 lbm (130 kg)
- Ratings: 350°F (175°C), 20,000 psi (1456 kPa)

- Uses LaBr3: Ce spectroscopy detector
- Pulsed neutron generator, 3.6 × 108 neutron/s nominal output

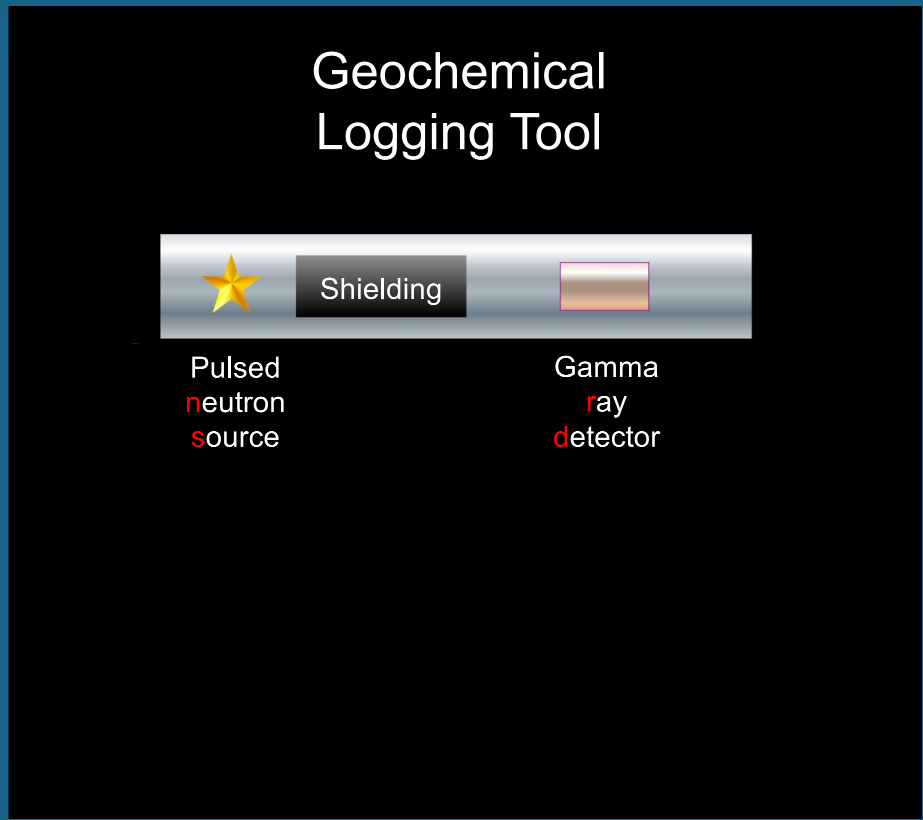
- First (in the industry) in-situ measurement of total organic carbon (TOC)
- Tool used in this study



Principles of Spectroscopy Measurement

Spectral Acquisition

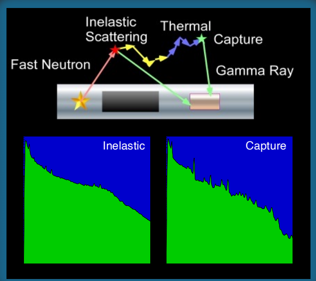
- Inelastic
- Capture

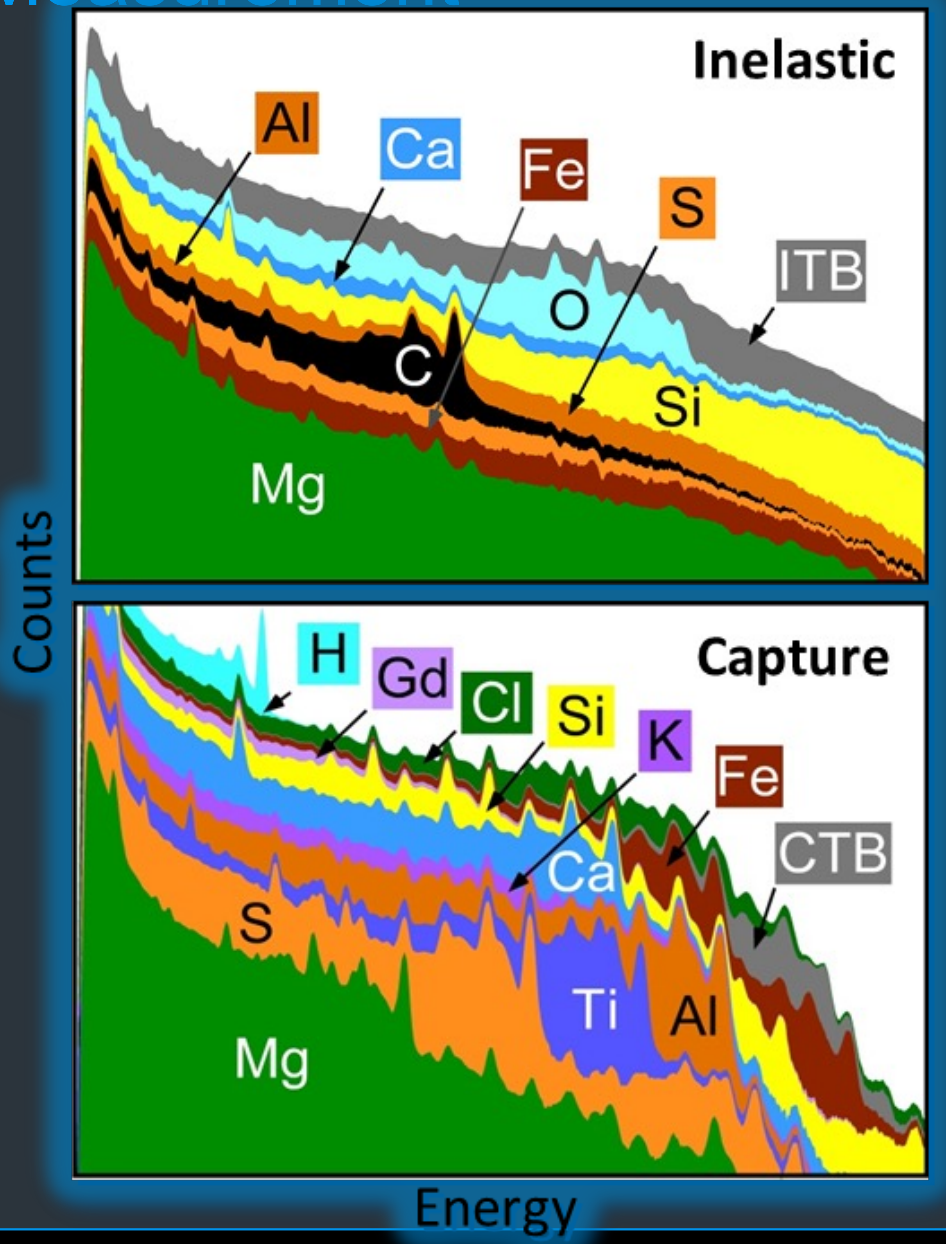


Principles of Spectroscopy Measurement

Spectral Acquisition
- Inelastic
- Capture

Spectral Stripping
- Elemental yields





Principles of Spectroscopy Measurement

Spectral Acquisition
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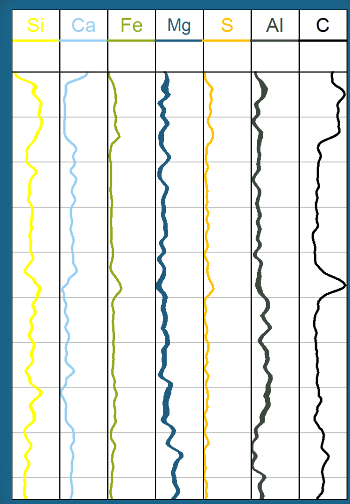
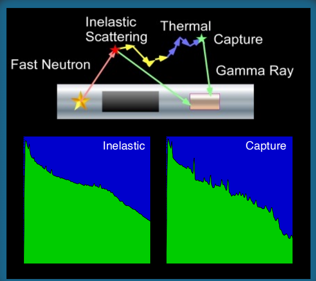
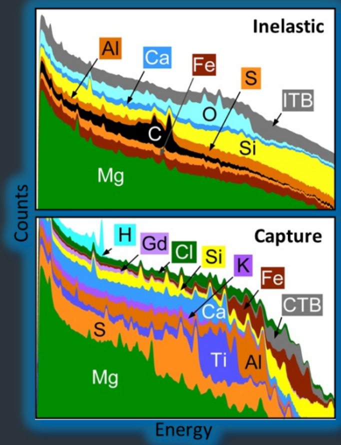
- Capture

Spectral Stripping
- Elemental yields

Composition
- Elemental weight fractions







Principles of Spectroscopy Measurement

Spectral Acquisition
- Inelastic
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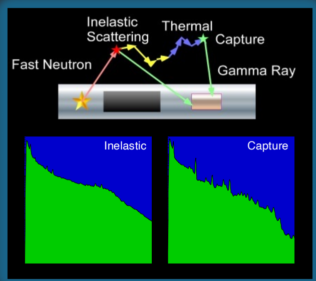
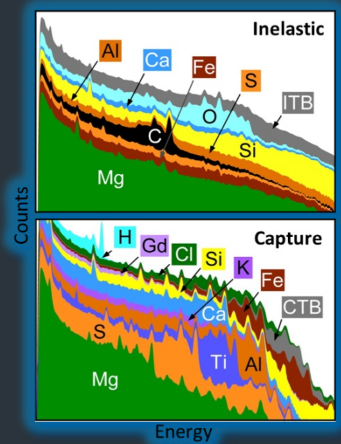
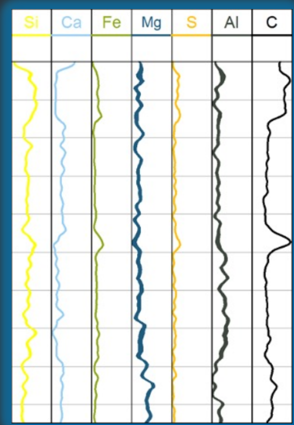
Spectral Stripping
- Elemental yields

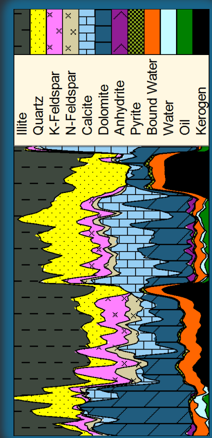
Composition
- Elemental weight fractions

Mineralogy
- Lithology
- Pore fluid



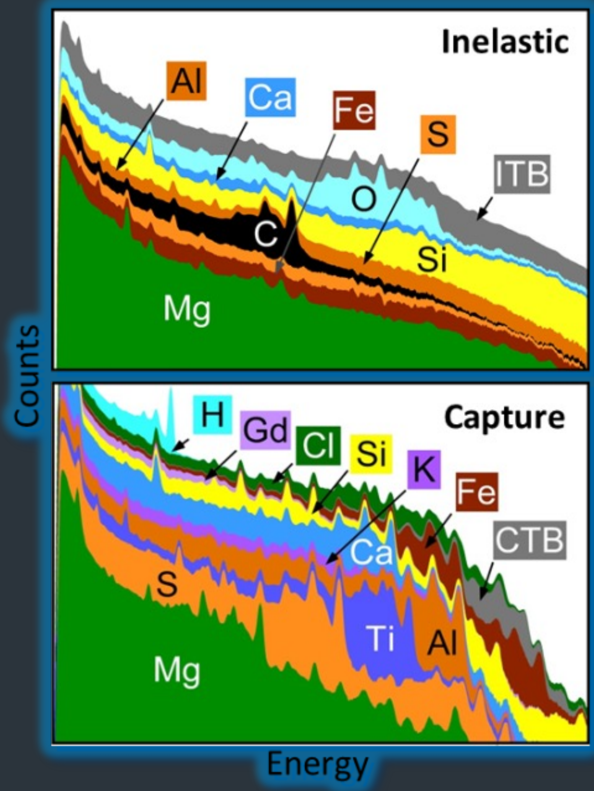






From Measurements to Elemental Standards

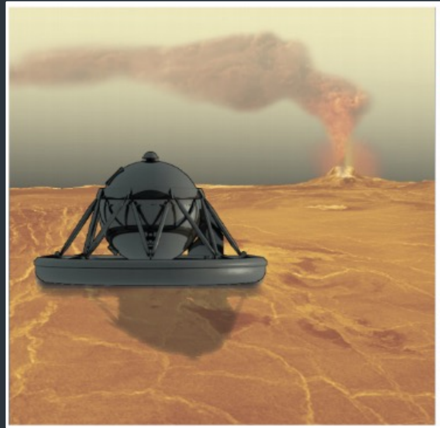
- Focus on
  - Si, Ca, Mg, Al, Fe, K, S, Na to identify rock matrix
  - H, C, O, Cl to identify pore fluid
- Extract the spectral signatures of the different elements
  - Acquire high-precision spectra in variety of environments
  - Combine measured spectra to isolate specific contributions
  - Guide this process through modeling

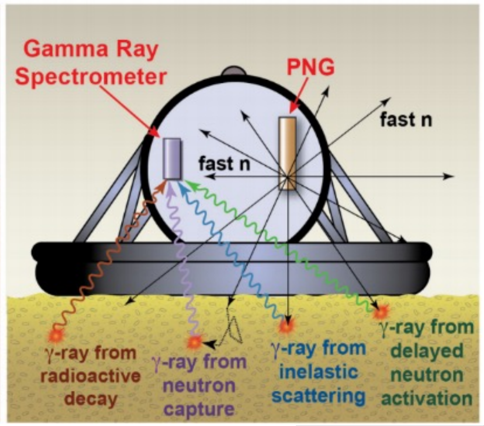


High-quality elemental standards enable accurate spectral analysis, from which all tool answers are derived—elemental weight fractions, mineralogy, and total organic carbon.

Hardware Not Only for Oilfield— SLB-NASA Engagements — BECA

- Spectroscopy on Venus Lander to analyze its crust and search for water
- Venus surface: P = 92 atm; T = 462ºC
- Operational lifetime: 2-4 h max.
- First test performed at NASA Goddard Space Flight Center with an actual tool.
- Very good results with only minor tool modifications





Maturation of Neutron-Gamma Instrumentation for Venus Surface Geochemistry Studies

PI: Ann M. Parsons, *NASA Goddard Space Flight Center, Greenbelt, MD*
Co-Investigators: David Lawrence, Patrick Peplowski, and John Goldsten, *Johns Hopkins, Applied Physics Laboratory*
Richard D. Starr, *Catholic University of America and NASA/GSFC*
Luke Perkins, Jeffrey Miles, *Schlumberger Technology Corporation*
Jeffrey Schweitzer, Jim Grau, *Schweitzer Consulting*
M. Darby Dyar, *Planetary Science Institute*

Submitted to NASA ROSES NNH16DA001N-MATISSE

Schlumberger Space Engagements — Dragonfly

- In collaboration with Johns Hopkins Applied Physics Laboratory
- Explore Titan (Saturn's largest moon) with an instrumented, radioisotope-powered dual-quadcopter
- Provide pulsed neutron generator and expertise on gamma ray spectroscopy (capture and inelastic) to analyze the composition of the shallow subsurface

Why Do We Need (accurate) Cross Sections?

- Nuclear modeling is fundamental to well logging tool development.
  - Explore design choices quickly
  - Balance mechanics, electronics, and physics without costly experimentation
  - Complement and extend characterization measurements

- Accurate modeling relies on accurate cross sections.
  - Adequate for gamma rays and neutrons transport
  - Improvement needed for neutron-induced gamma rays

- For spectroscopy, better cross sections would
  - Improve standards derivation and interpretation algorithms
  - Might allow for defining elemental standards directly from modeling

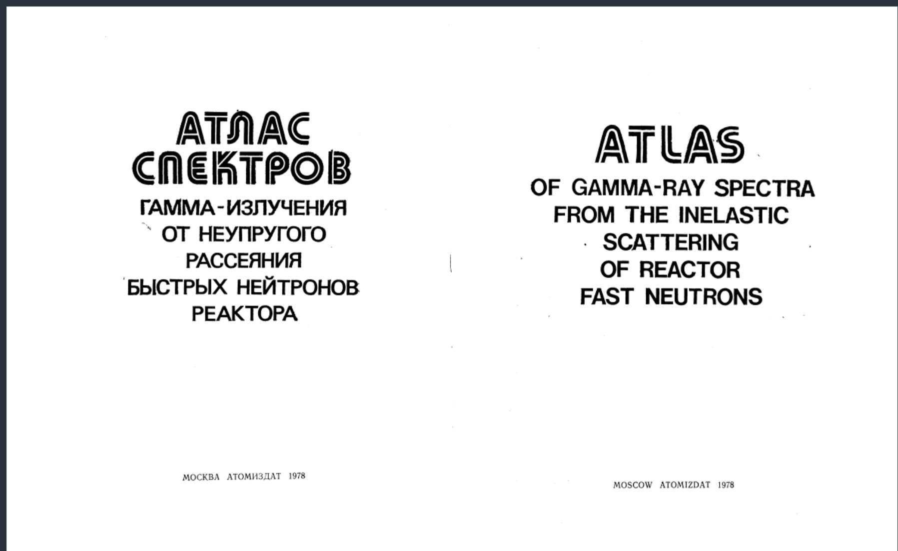
Tool Response Experiments

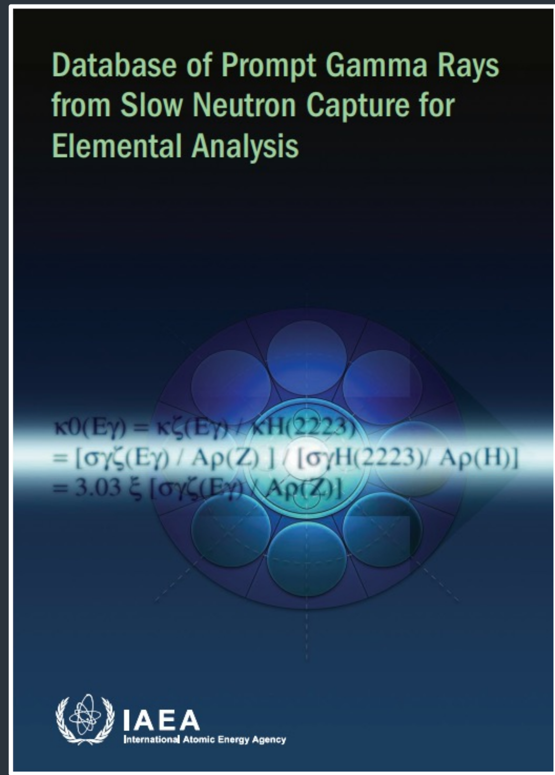
Experiments were performed to measure the tool response to some elements

- Experiments were not designed to benchmark modeling
- Benchmark limited to different ENDF library versions
- Focus on secondary emission of gamma ray, no absolute measurement

Emission Line Experiment Comparison

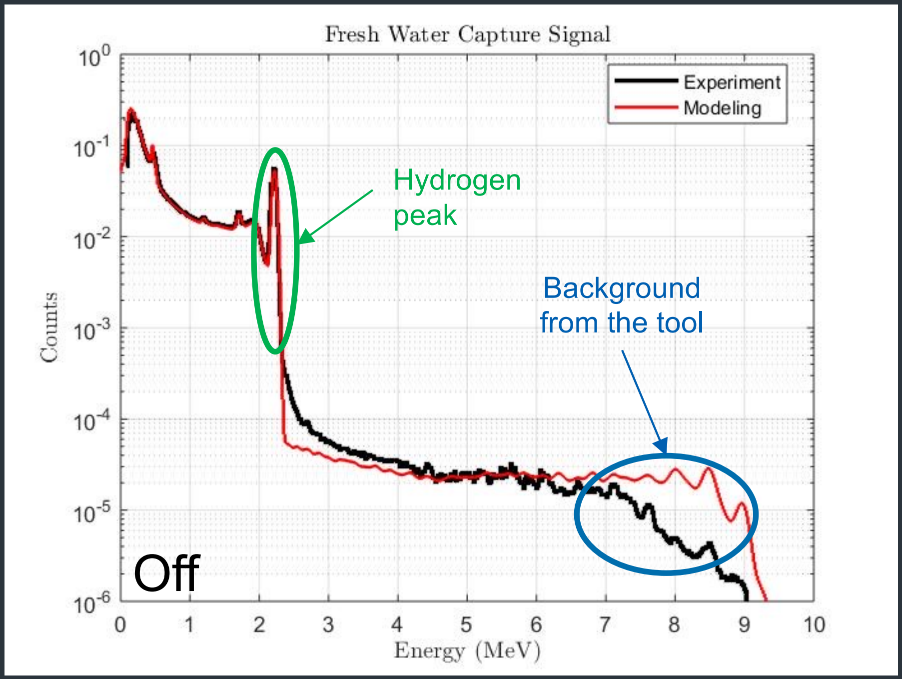
- Emission lines for comparison come from:
  - Capture—“Database of prompt gamma rays from slow neutron capture for elemental analysis” — Vienna : International Atomic Energy Agency, 2006
  - Inelastic—“Atlas of Gamma-Ray Spectra from the Inelastic Scattering of Reactor Fast Neutrons”, Nuclear Research Institute, Baghdad, Iraq (Moscow, Atomizdat 1978). No data above 5 MeV

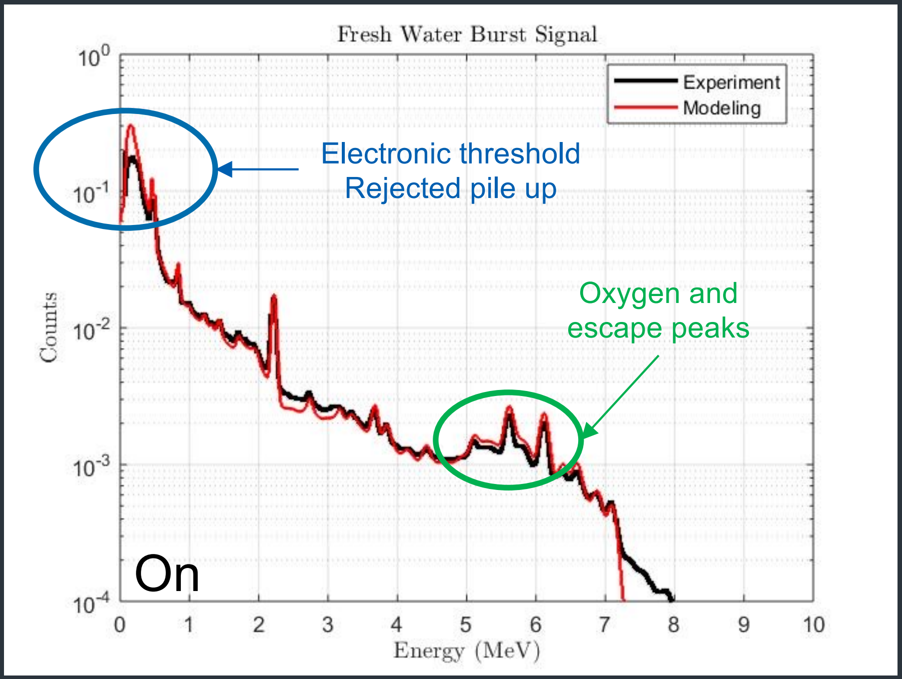




How Accurate Is Our Modeling?

- Compare modeling and experiment in the simplest environment; i.e., water
- Separate spectra acquired after the pulsed neutron generator is turned off (mainly capture reactions) and during the pulsed neutron generator burst (mainly inelastic reactions)

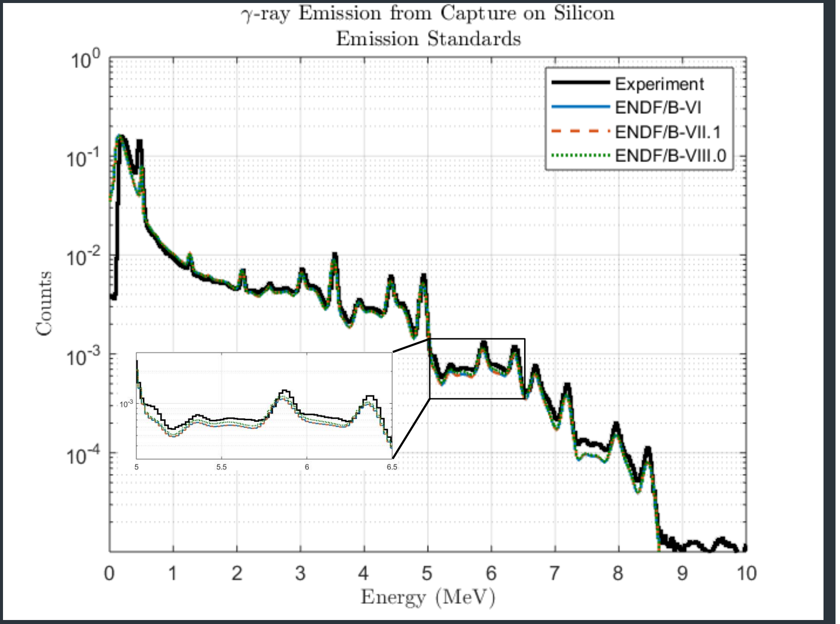


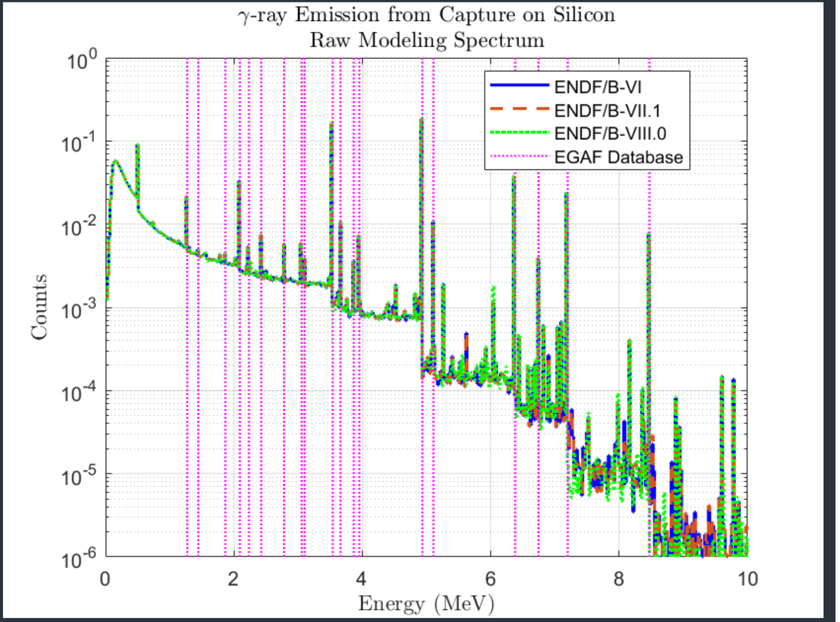


Silicon Capture Spectrum

- Focus on gamma rays emitted by silicon only
  - Very good reproduction of capture spectrum
  - Use of natural compound in ENDF/B-VI, Si-28 afterward
  - Slightly improved with ENDF/B-VIII.0 between 5 and 6.5 MeV

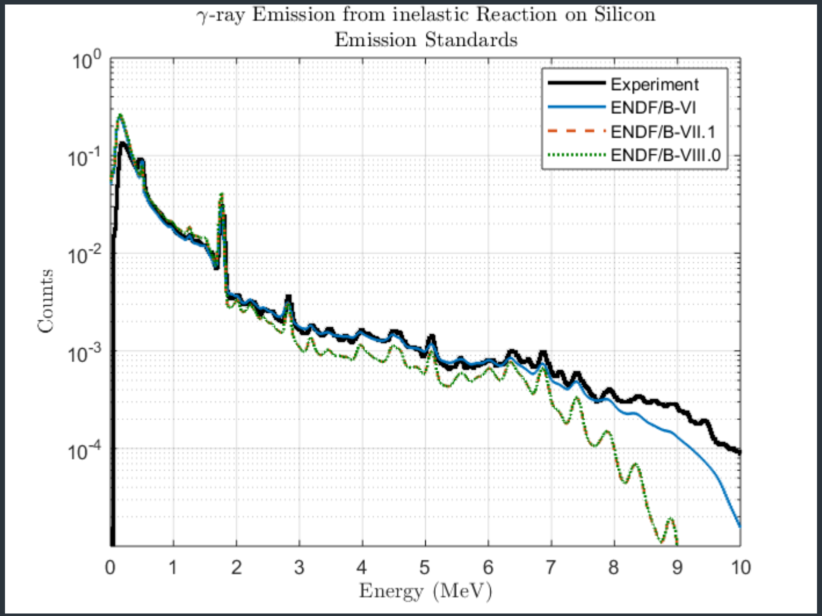
- Analyze modeling response without the detector response
  - Main lines from IAEA capture handbook above 1 MeV in dotted pink
  - Different versions of ENDF are very similar

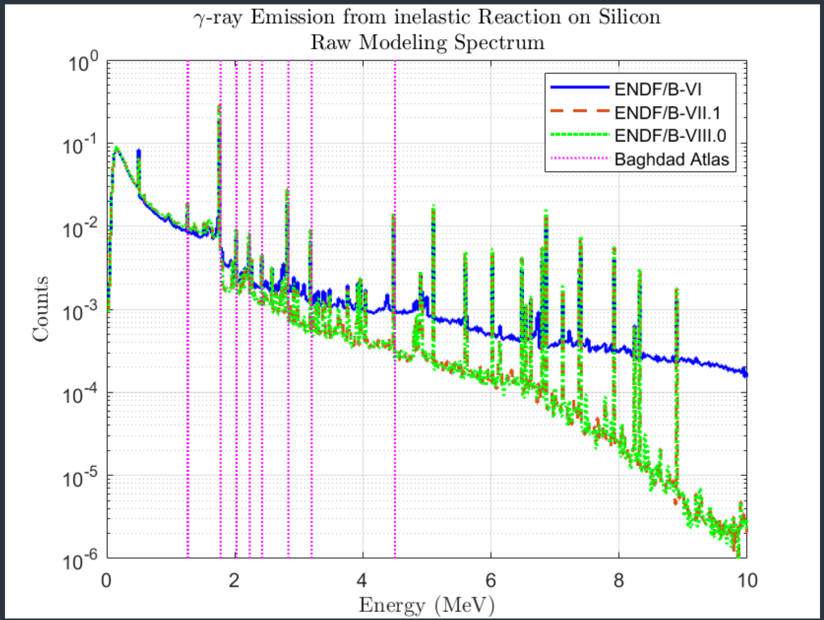




Silicon Inelastic Spectrum

- Use of natural compound in ENDF/B-VI, Si-28 afterward
- Totally different response between ENDF/B-VI and newer releases
- Emissions are better defined in latest versions.
- Continuum might be too low

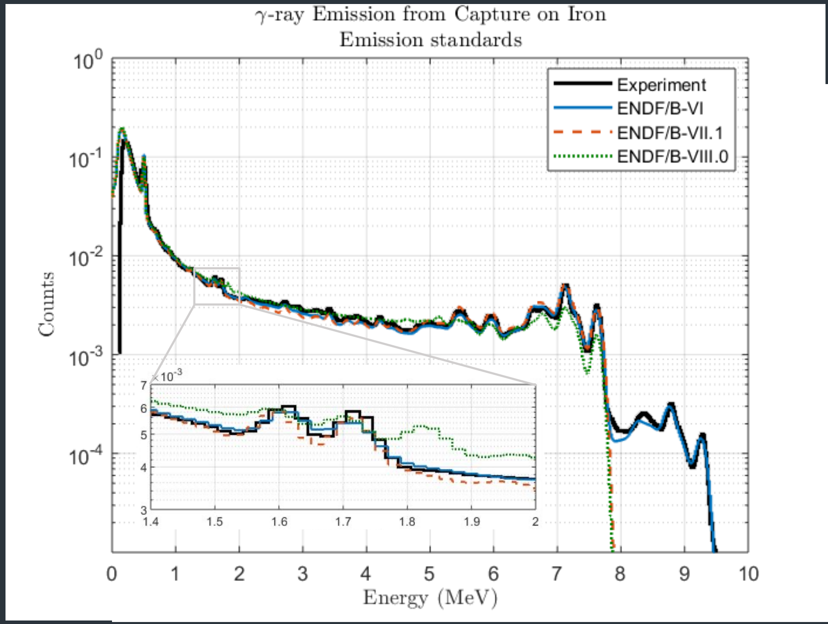


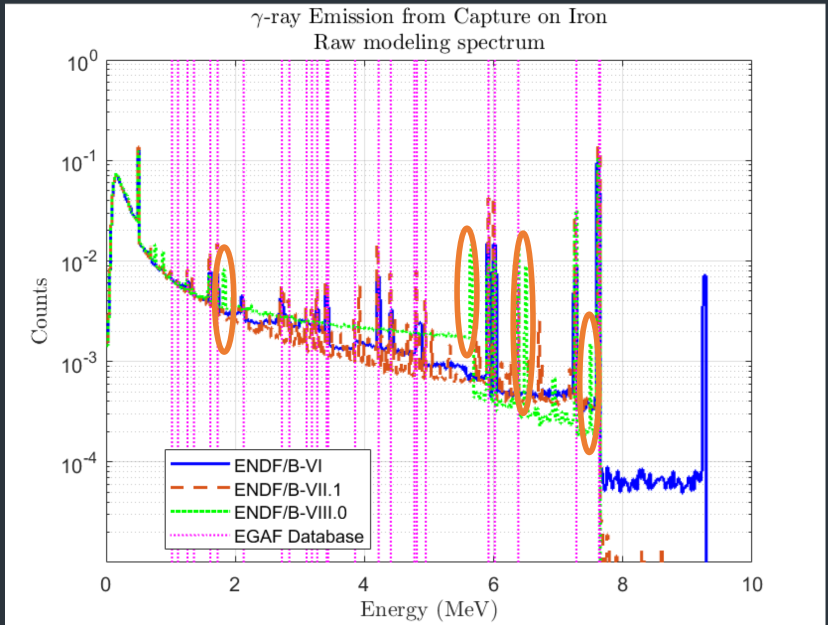


Iron Capture Spectrum

- Iron has been reevaluated through the CIELO collaboration
  - Focus on (n, g) cross section
  - Not on secondary gamma energy spectrum
  - Total count rate is of secondary interest to us.

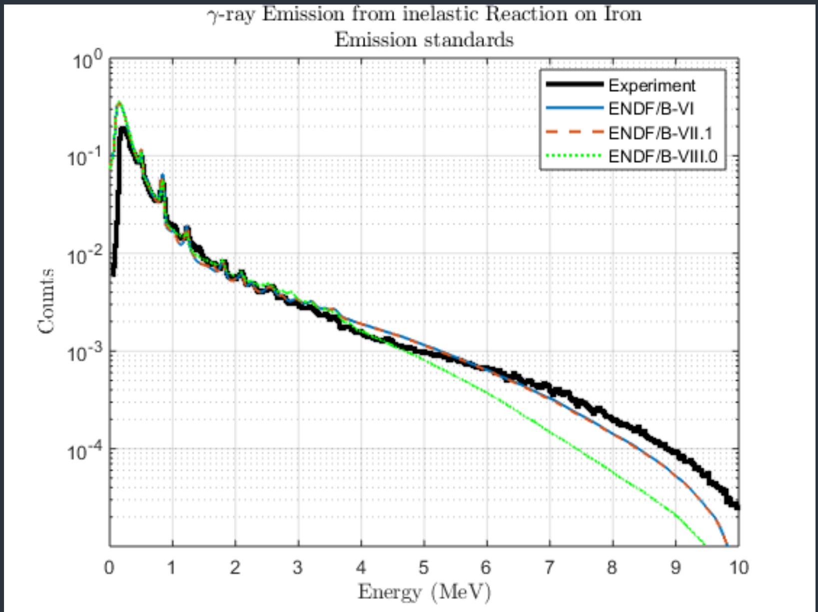
- Use of Fe-56 cross sections
- ENDF/B-VII.1 has the best match with experimental data and IAEA capture gamma-ray emission lines.
- ENDF/B-VIII.0 introduces new lines not observed experimentally nor reported in the literature.

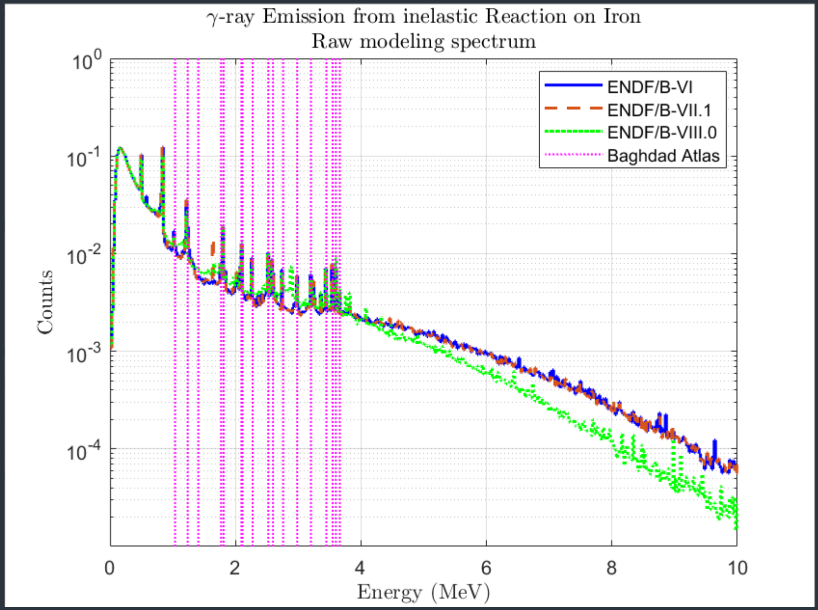




Iron Inelastic Spectrum

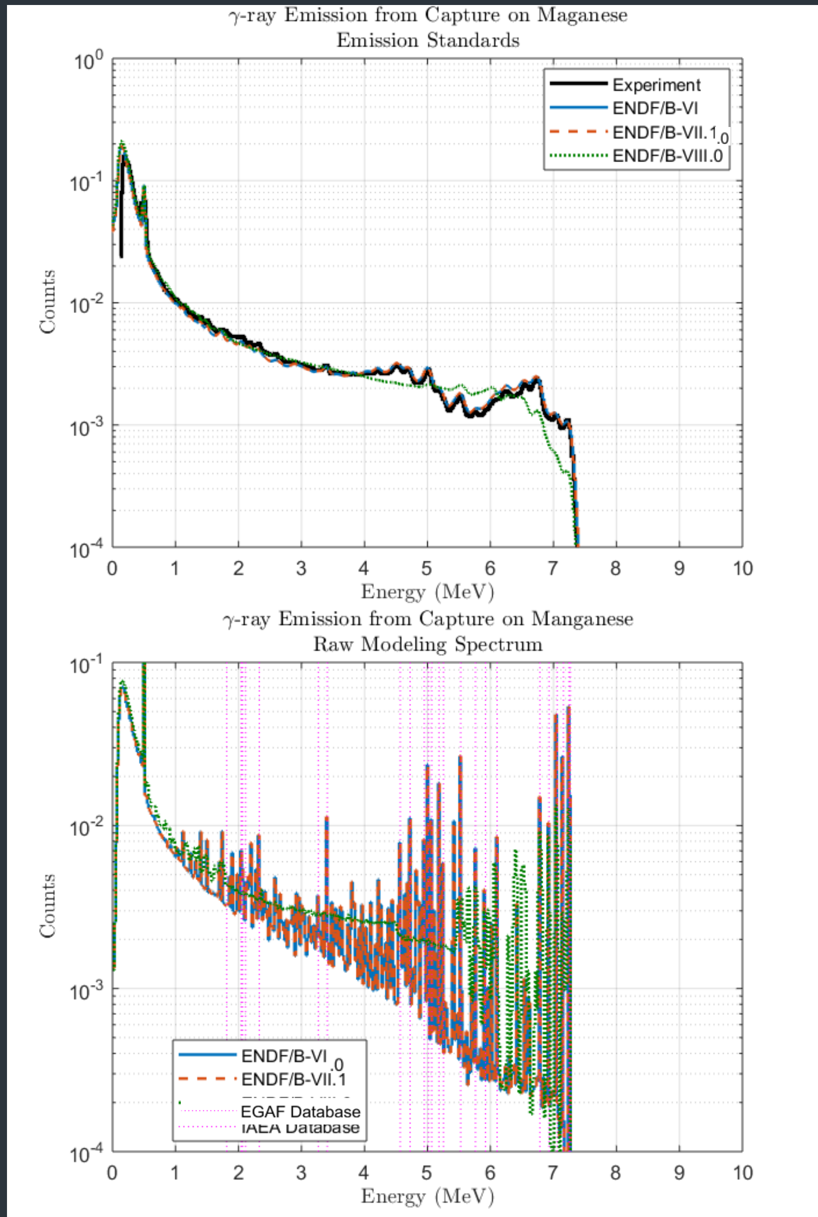
- Very limited number of features on our experimental data
- Mostly in agreement with Baghdad Atlas and among the different versions





Manganese Capture Spectrum

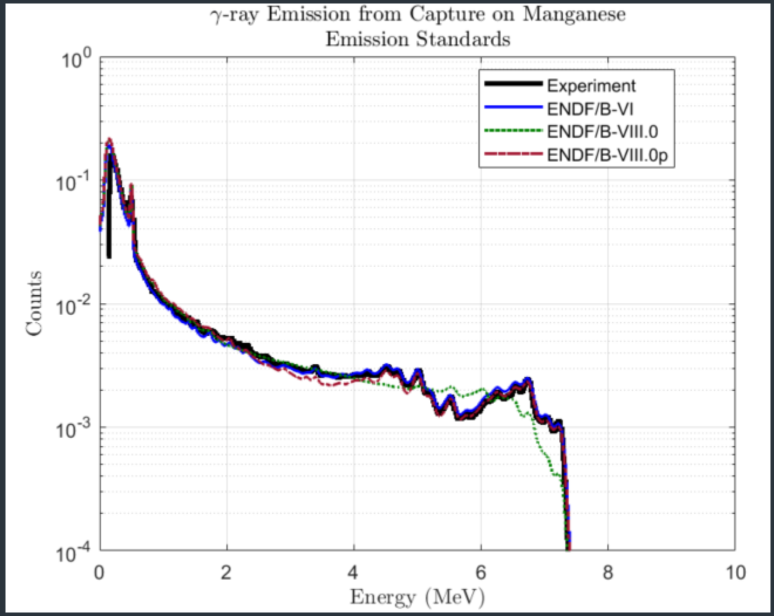
- Only one isotope found in natural manganese
  - Significantly of poorer quality in ENDF/B-VIII.0
  - ENDF/B-VI and ENDF/B-VII.0 data in better agreement with our experimental results and IAEA capture gamma ray emission lines

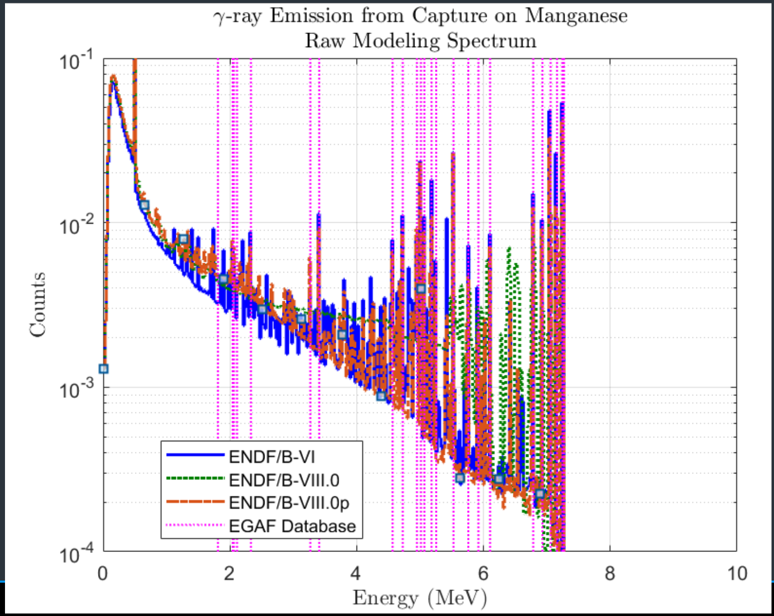


New Manganese Capture Cross Section

- Following the presentation of the results at CSEWG in 2019 an update of the cross sections have been made by R. Capote and A. Trkov (https://www-nds.iaea.org/publications/indc/indc-nds-0810.pdf) in orange.

- Significant improvement in the capture spectrum

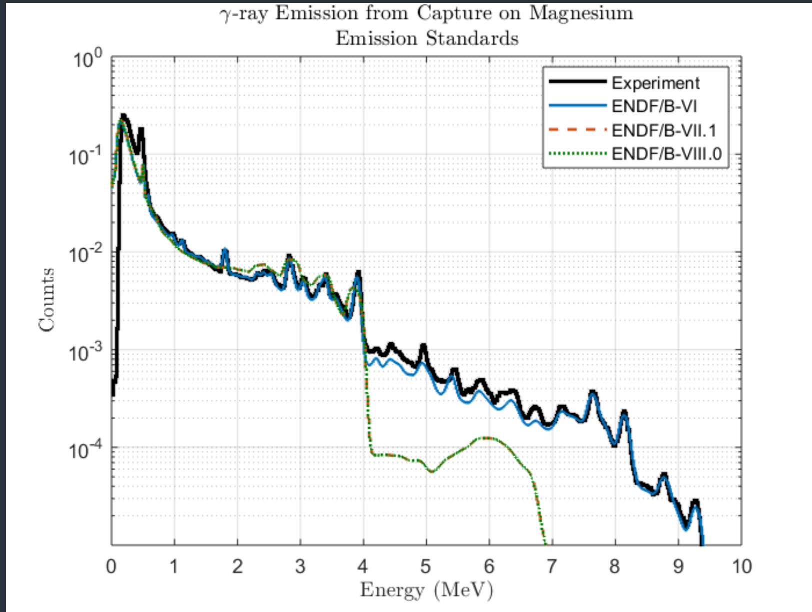


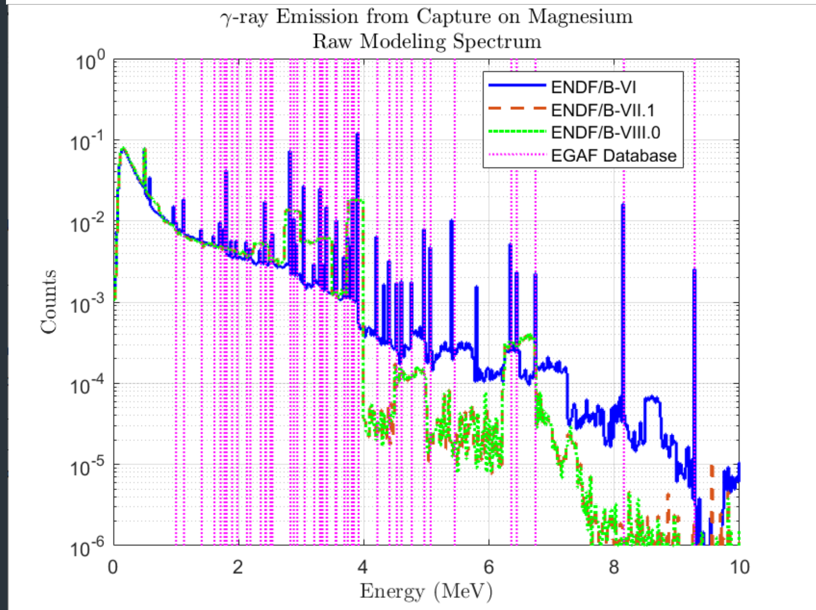


Magnesium Capture Spectrum

- Natural compound in ENDF/B-VI version break into isotopes afterward
- Significantly poorer quality in ENDF/BVII.1 and ENDF/B-VIII.0 versions
- Gamma ray emission energy is very coarse

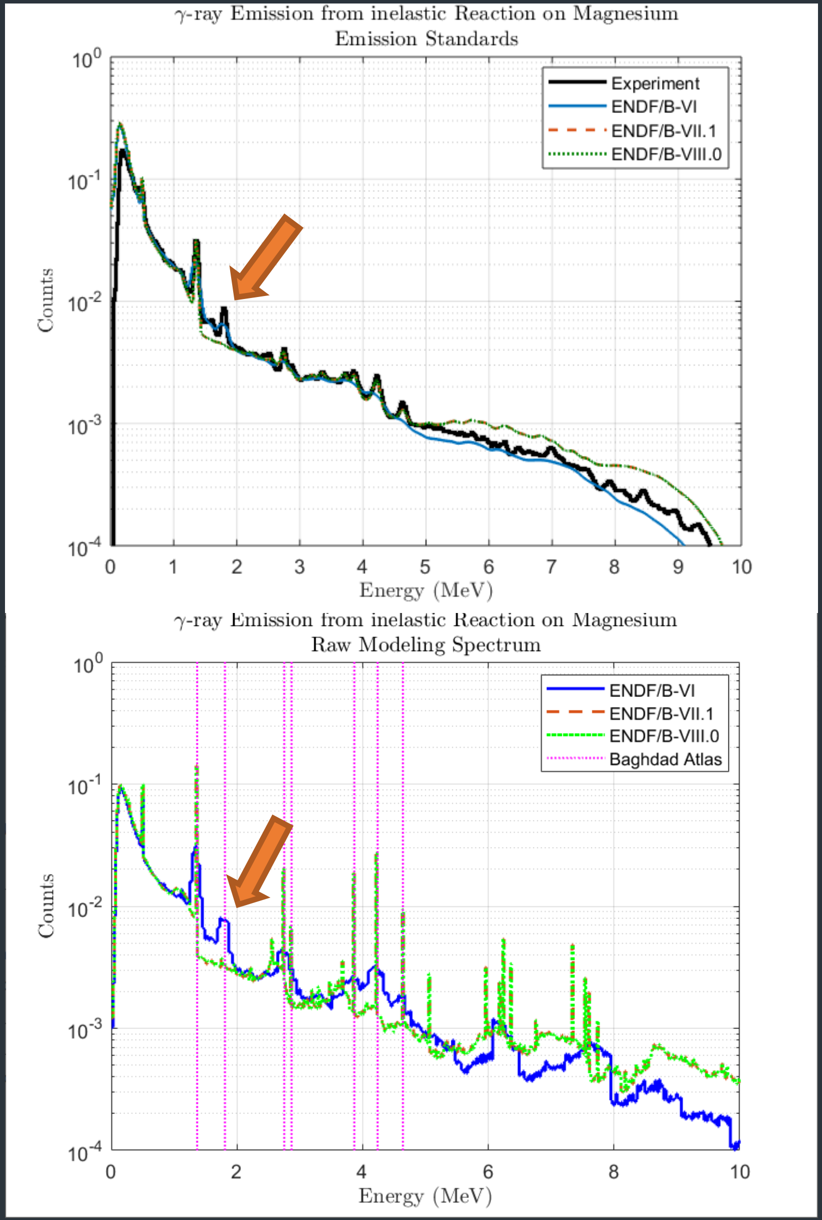
Conclusion—ENDF/B-VI version is much better for capture than ENDF/BVII.1 and ENDF/B-VIII.0 versions!





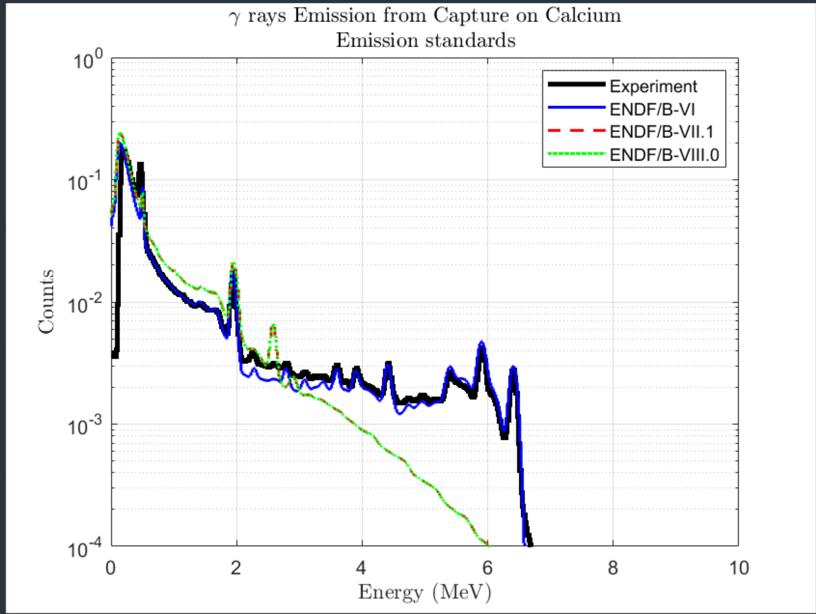
Magnesium Inelastic Spectrum

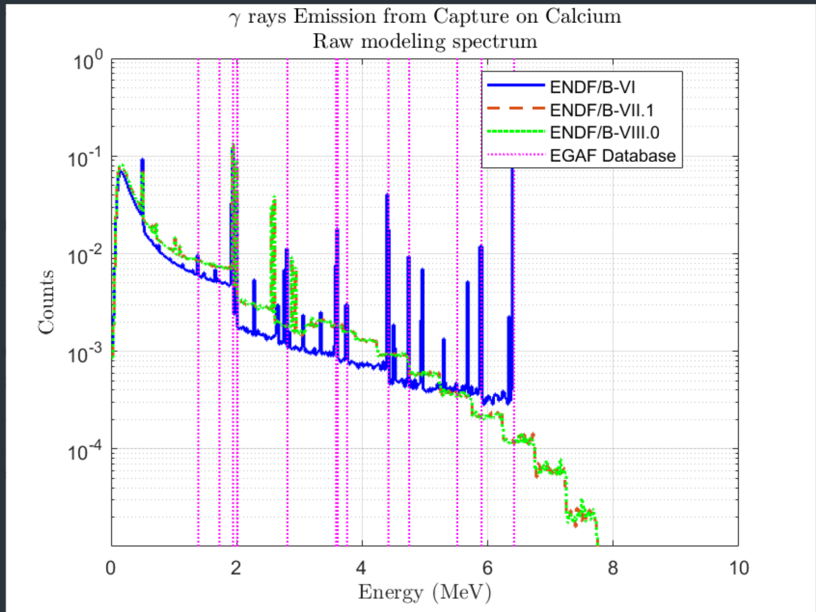
- ENDF/B-VI—Elemental cross sections
- ENDF/B-VII—Isotopic cross sections
  - Finer binning of gamma ray energies but limited impact due to our detector resolution
  - Missing line at ~1.8 MeV



Calcium Capture Spectrum

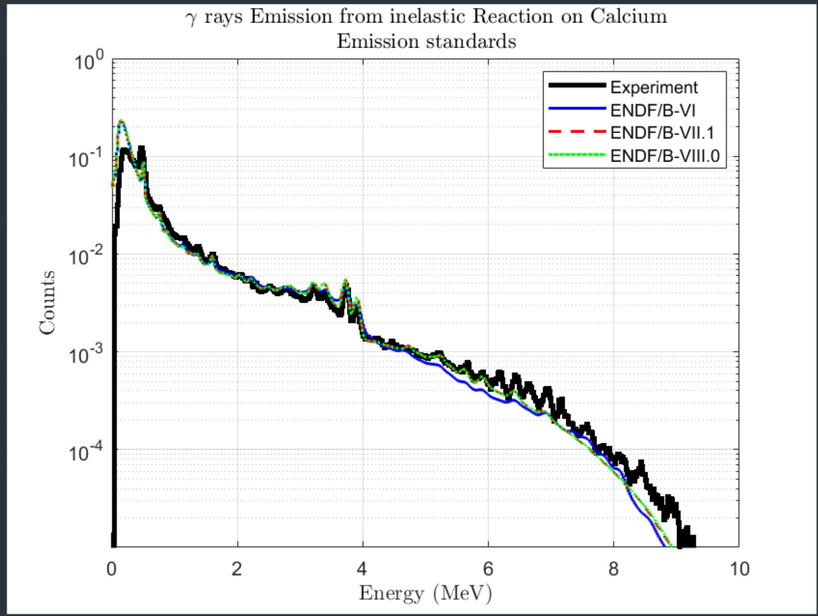
- Calcium is an important element for geology evaluation.
  - It was the first element for which we observed the regression
  - No gamma ray lines above 3 MeV, extra line near 2.5MeV with unusual continuum shape

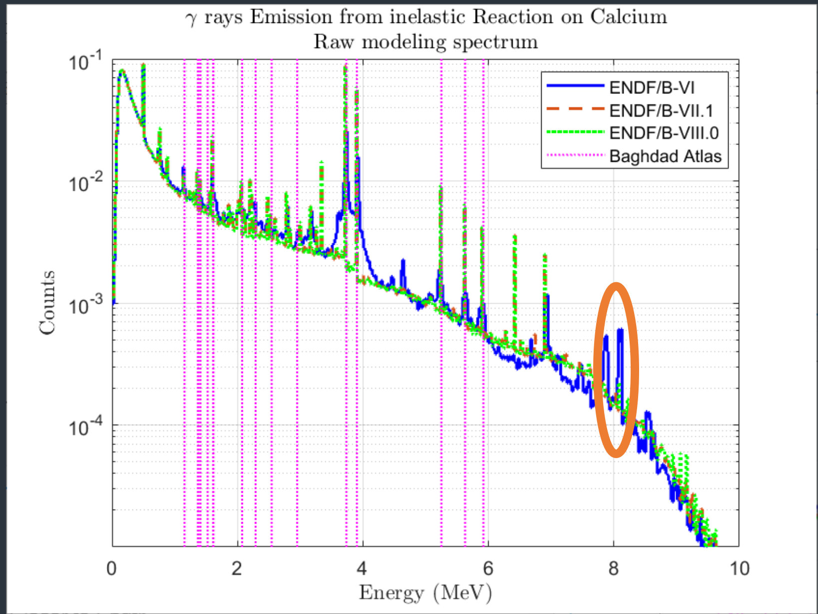




Calcium Inelastic Spectrum

- Calcium remains constant globally with some improvement in the sharpness of the peaks
- Two peaks near 8 MeV disappeared
  – No information at that energy

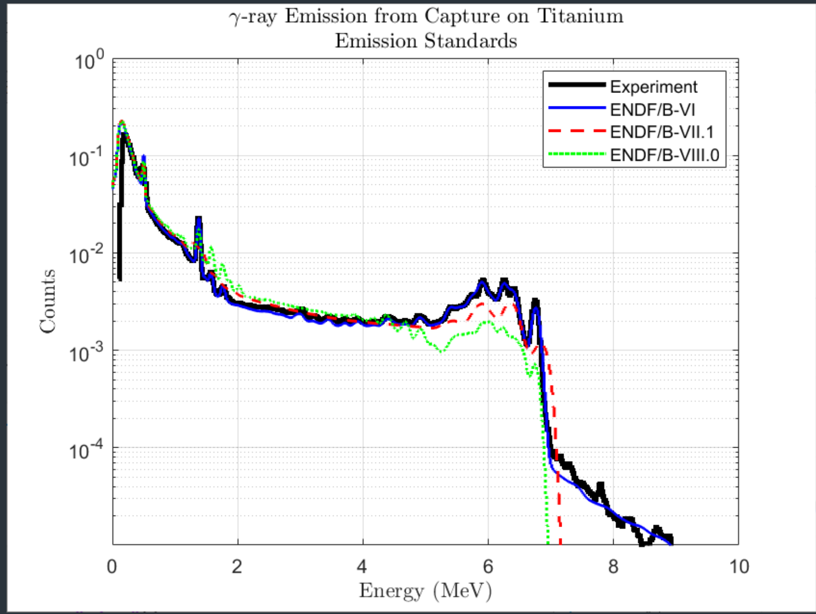


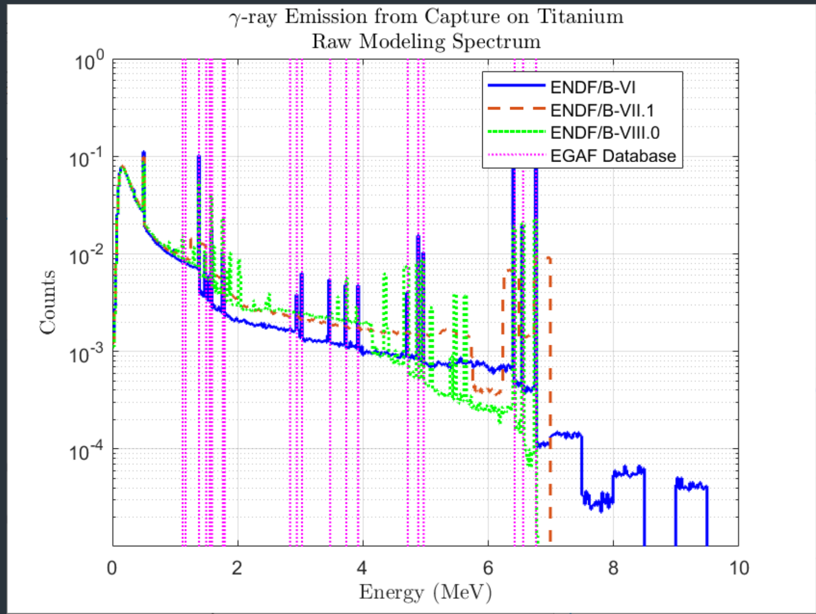


Titanium Capture Spectrum

- Some gamma ray lines are missing, and some were added that are not in the IAEA capture handbook.

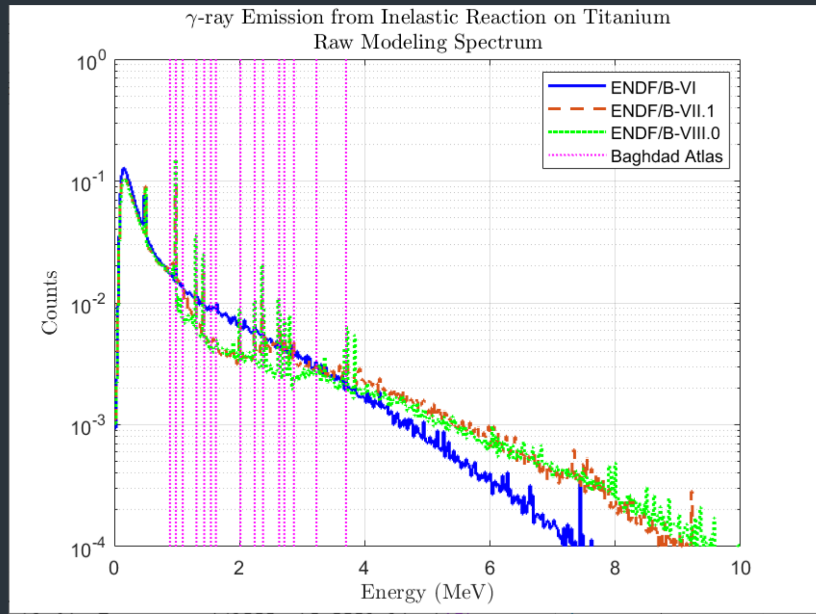
- ENDF/B-VIII.0 version shows improvements over ENDF/B-VII.1 version, but not at the level of the ENDF/B-VI version.





Titanium Inelastic Spectrum

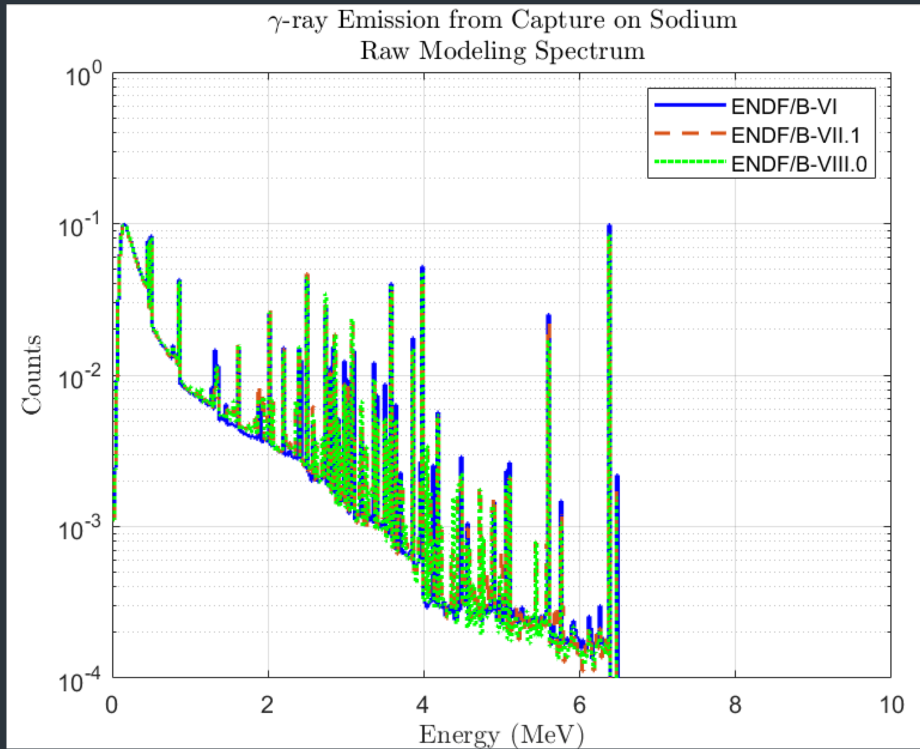
- Unfortunately, no experimental comparison
- Better agreement between the latest ENDF version and the Baghdad Atlas



Other Elements

We checked other elements, including:

- Aluminum
- Chlorine
- Oxygen
- Sodium
- Carbon



For these elements, we did not see major changes.

Most of the changes are on the peak intensity, not the energy.

Summary

Recommendations for capture gamma ray spectra are shown in this table.

- For inelastic reactions, the benchmark is generally poor.
- Changes in emission spectrum are relatively small.
- Experimental results might not be sufficiently accurate to choose one vs. another.

Element	ENDF-B/VI	ENDF/B-VII.1	ENDF/B-VIII.0
Hydrogen	✓	✓	✓
Silicon	✓	✓	✓
Calcium	✓	?	?
Iron	✓	✓	?
Manganese	✓	✓	?
Magnesium	✓	?	?
Titanium	✓	✓	?
Sodium	✓	✓	✓
Chlorine	✓	✓	✓
Aluminum	✓	✓	✓

? Questionable reproduction of direct measurement
✓ Good reproduction of direct measurement

Conclusions

- The oilfield industry focuses more and more on secondary gamma ray measurements.
- It is critical to have accurate gamma ray energy lines and related emission cross sections for both capture and inelastic reactions.

- In the last two major releases of the ENDF/B program, we have seen more degradations than improvement concerning this specific topic.

- This result is impacting other domains as well, including:
  - Space
  - Cargo inspection

- An equivalent study should be performed to verify results of other libraries.