Beta-Delayed Gamma Emission by Combining the Statistical Model with Nuclear Structure Data

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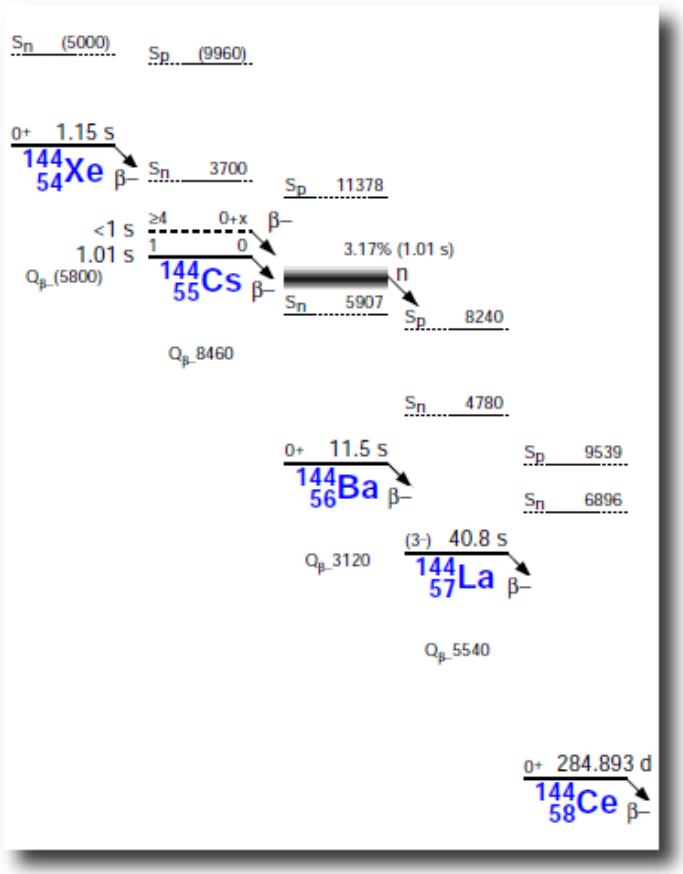
Introduction

Complicated β-Decay Chain in Fission



- Nuclear fission yields two fission fragments (FF) that emit prompt neutrons and γ-rays, and they de-excite to their ground state.
- Emission of delayed neutrons takes place when the final-state energy of β-decay is higher than the neutron separation energy.
- A detailed knowledge of each of the individual precursors and fragment yields is needed to fully characterize the delayed neutrons.
- The statistical model for the particle emission process should be combined with nuclear structure information.

Macroscopic observables (total delayed-neutron yields, six-group constants, and aggregate energy spectra) can be derived from each individual precursor.

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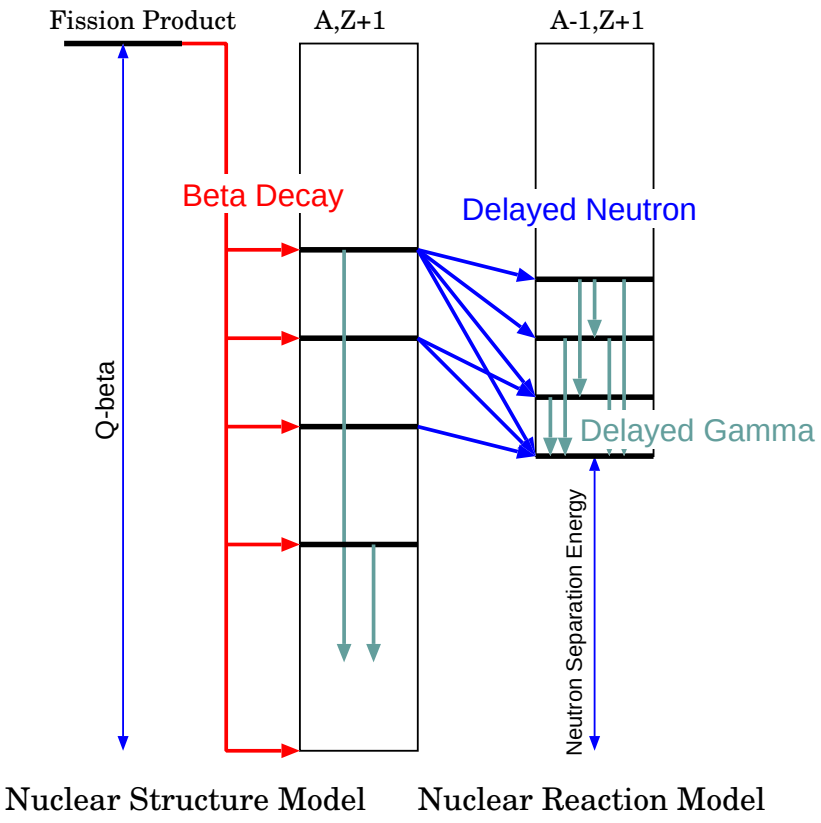
Theory Developed for Beta-Delayed Neutrons



Nuclear Structure

- β-decay rate
  - Q_β from Möller mass model (FRDM)
  - decay matrix element $\langle f|\beta_{GT}|i\rangle$ from (Möller) QRPA model
- Low-lying discrete state data are taken from ENSDF

Nuclear De-excitation

- Neutron and γ emission rate
  - statistical Hauser-Feshbach model
  - all possible transitions from $(A, Z+1)$ to $(A-1, Z+1)$ are included.

We combine these two processes to calculate the energy distribution of emitted neutrons

TK, P. Moller, W.B. Wilson, Phys. Rev. C. **78**, 054601 (2008).

The same procedure can be applied to β-delayed γ emission.

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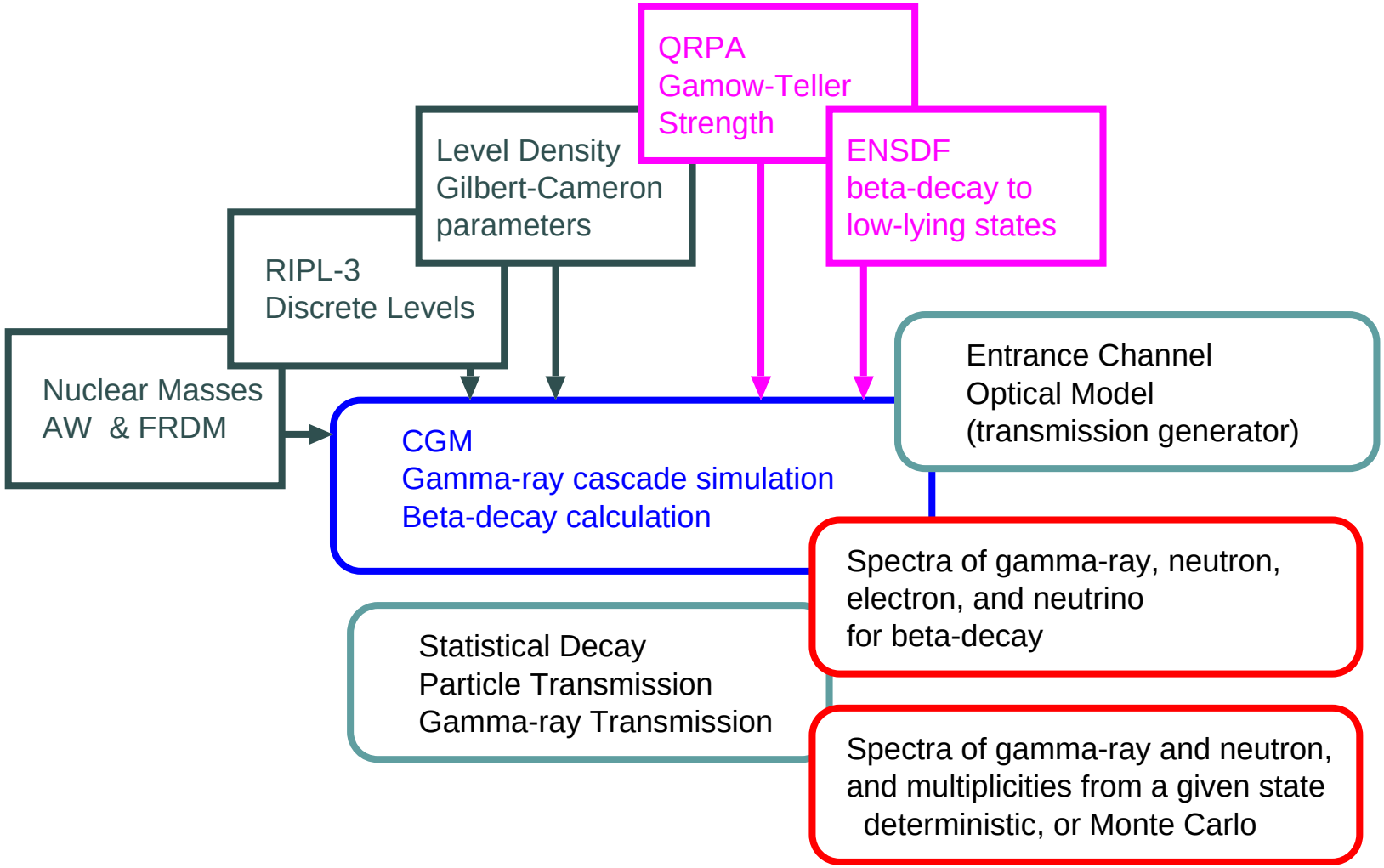
Neutron and Gamma Decay Code, CGM

T. Kawano and S. Holloway,CGM: Cascading Gamma and Multiplicity, Ver.3"

LA-CC-11-018



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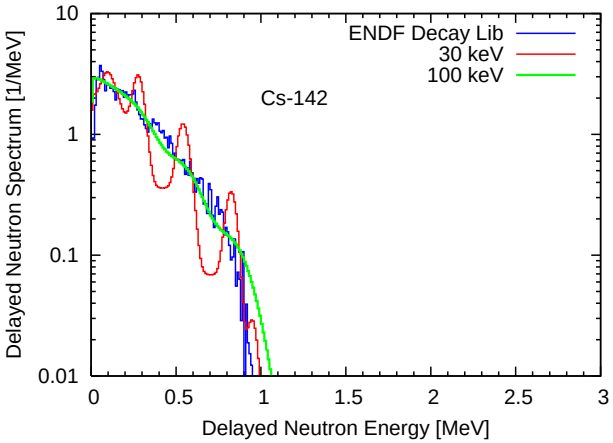
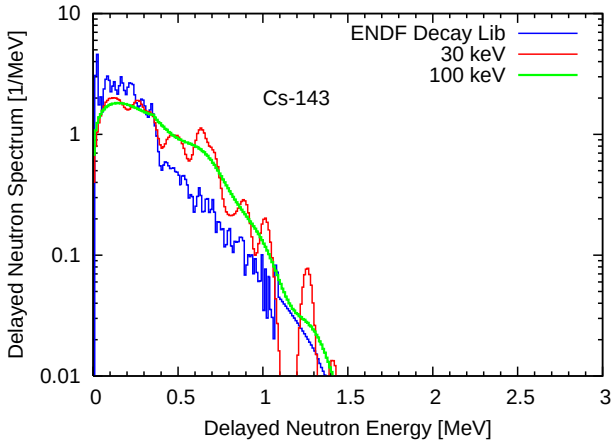
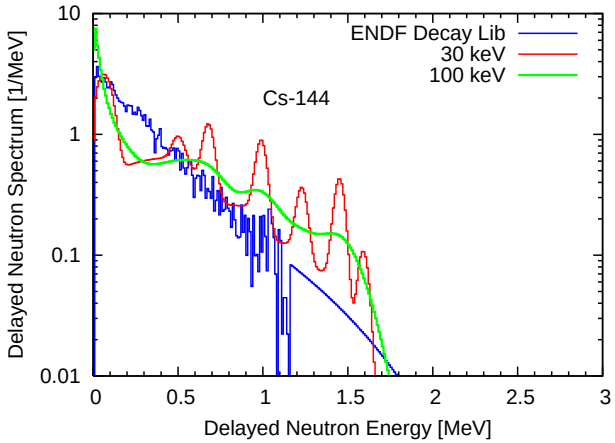
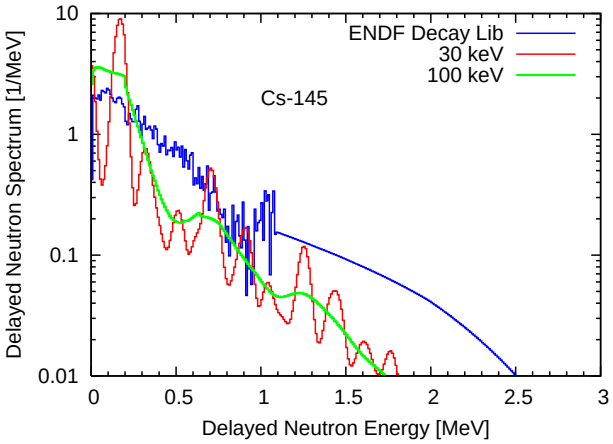
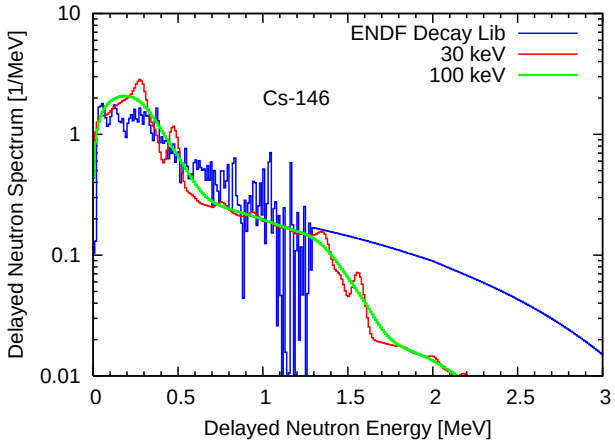
Delayed Neutron Spectra from Cs Isotopes

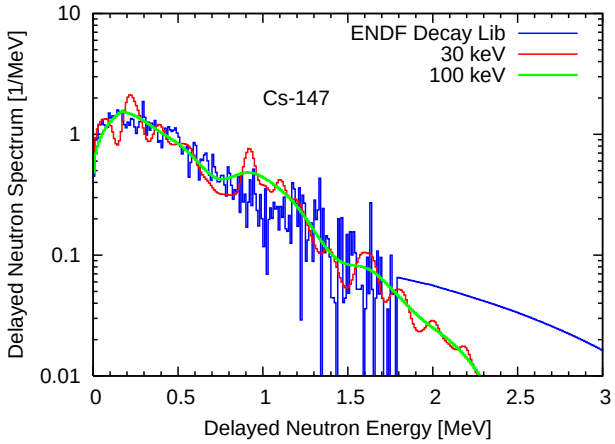












Sometimes ENDF data have an extension to higher energies by a simple evaporation spectrum.

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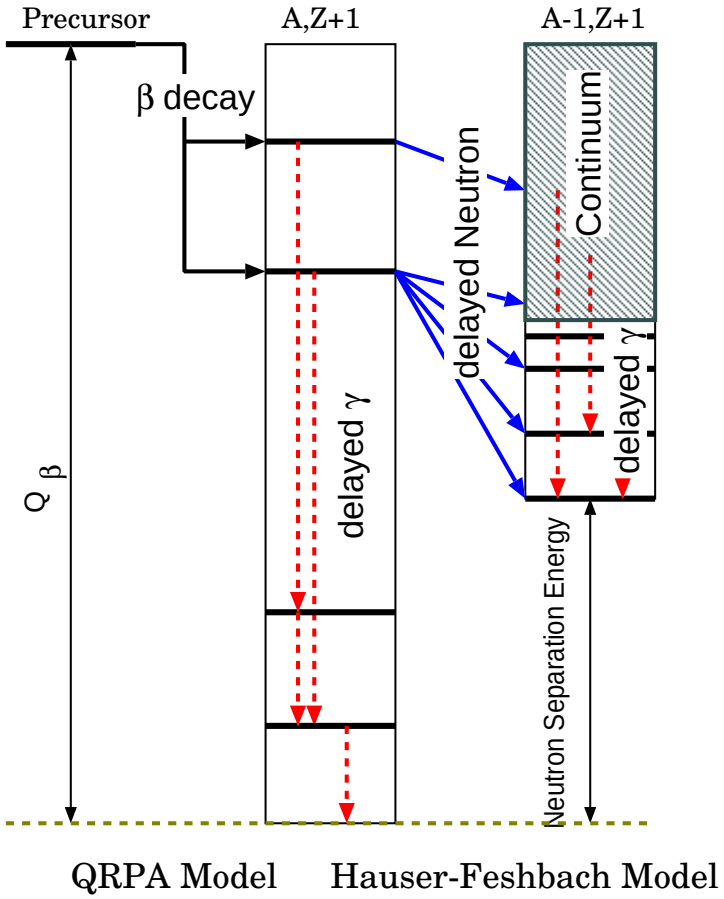
Beta-Delayed Gamma-Ray Emission

Gamma-ray emission multiplicity larger than unity



- γ-ray emission takes place in both daughter and grand-daughter nuclei.
- To calculate the delayed γ spectra, we need to follow all γ-ray cascade.
  - Individual low-lying transitions are important.
  - The evaluated structure data in ENSDF are incorporated;
    - β-decay to discrete levels
    - γ-ray branching ratios
- The whole decay process, including γ n, is calculated with the Hauser-Feshbach model (but with wider energy bins).

(This is an on-going project. The calculated results are preliminary)

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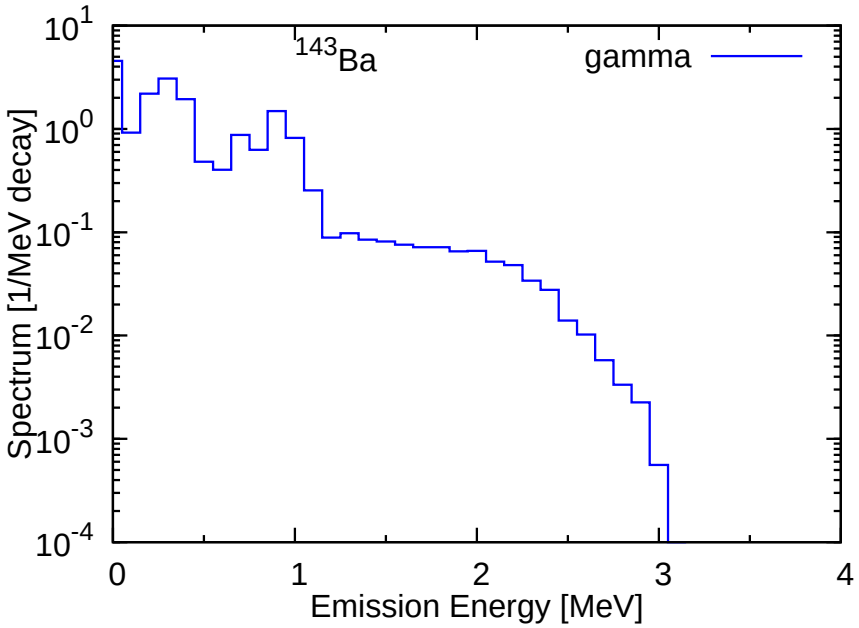
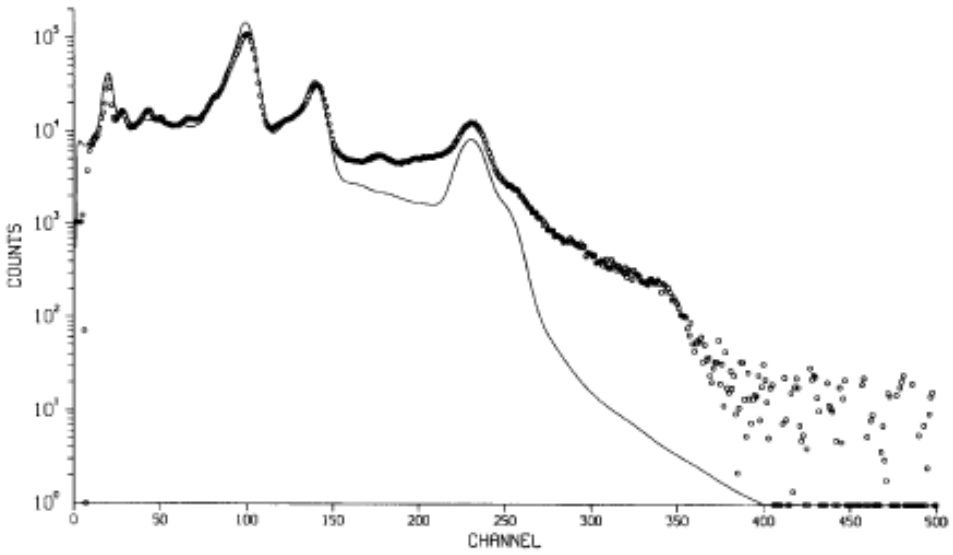
Comparison With TAGS Experiment

TAGS: Total Absorption Gamma-ray Spectrometer

R.C. Greenwood, et al. Nucl. Instr. Methods A **390**, 95 (1997).





- No delayed neutron case.
- The calculated spectrum mainly from discrete levels in ENSDF, but strength determined by the QRPA calculation.

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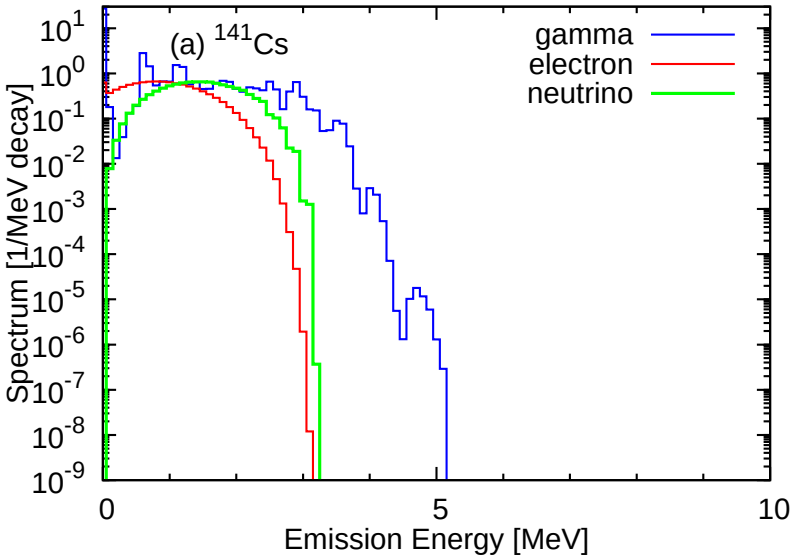
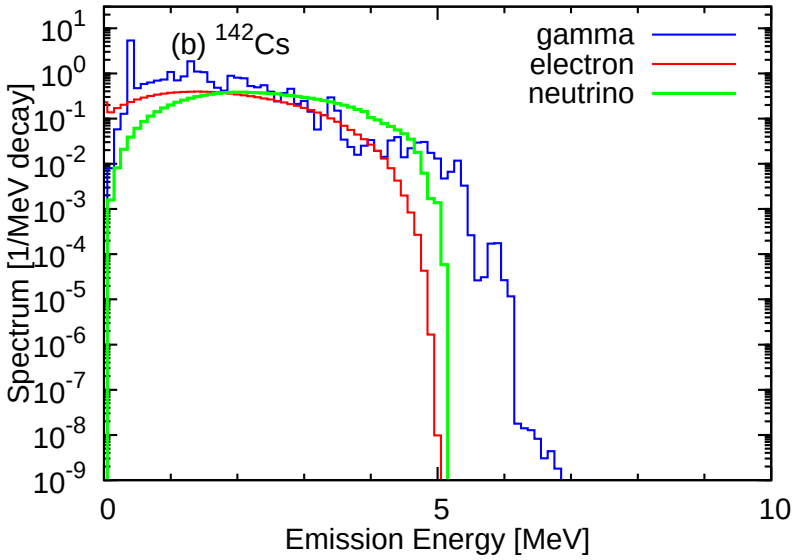
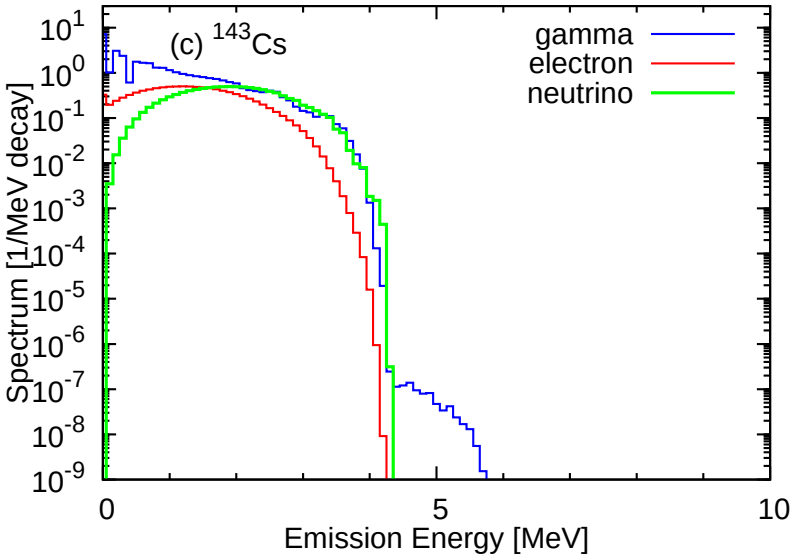
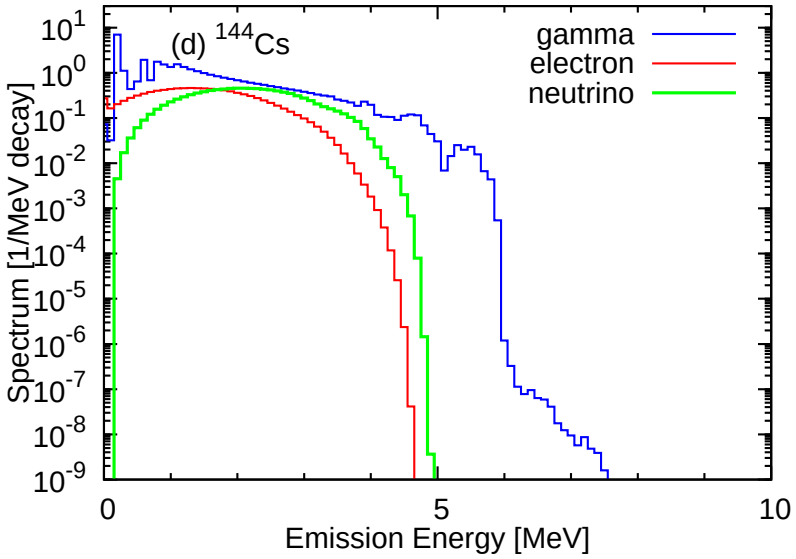
Cs Isotopes









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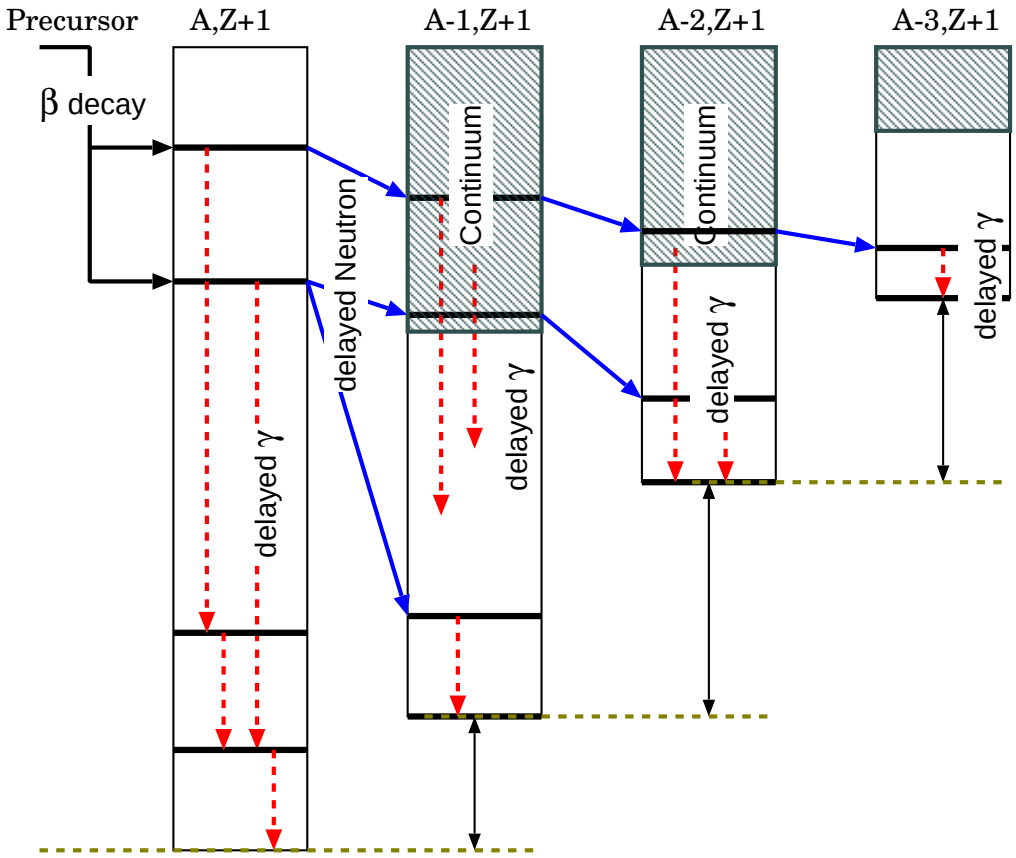
Multiple Neutron Emission

Several neutrons can be emitted when S_n is small (neutron-rich).



- We have extended CGM to include all γ-rays, even if more than one neutron is emitted.
- Calculation performed at every 10 keV energy bin.
  - very time consuming calculations
  - in some cases, takes a week

We calculated the delayed neutron and γ-ray spectra for 1412 precursors, and converted the results into CINDER library.

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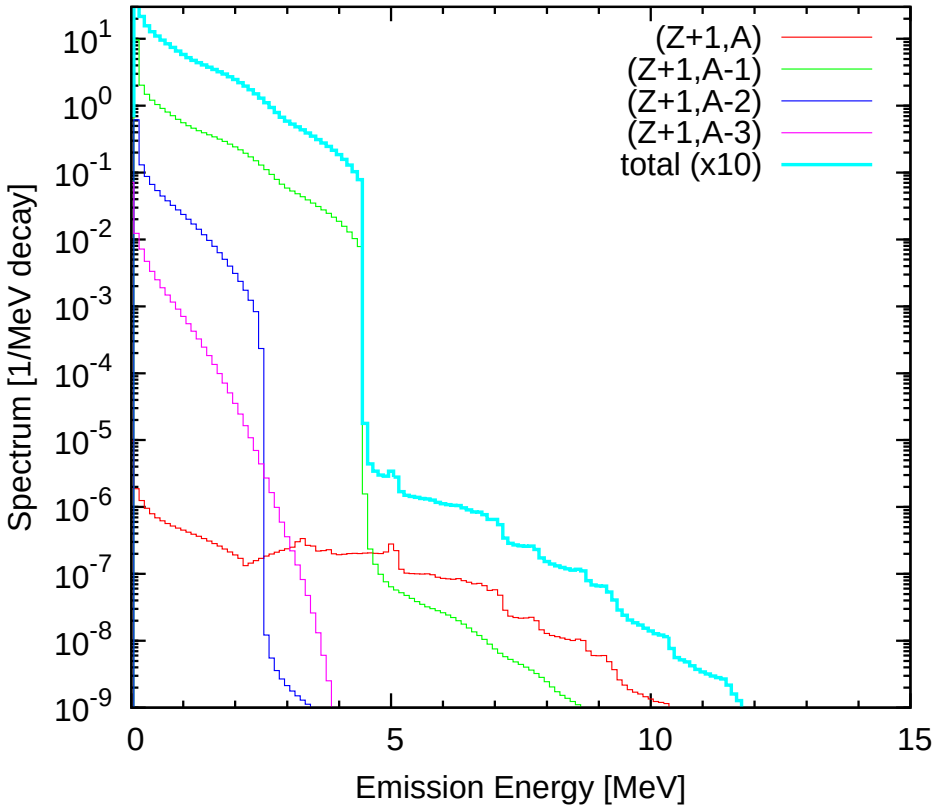
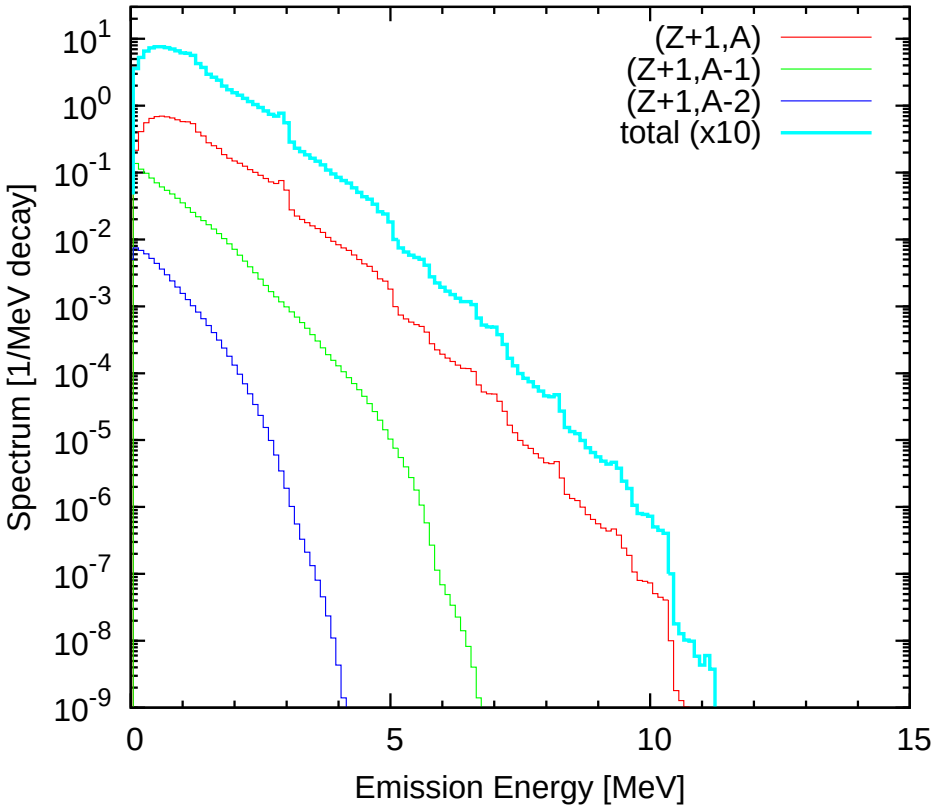
Calculated Spectra (Example) As-93

Beta-decay, $^{93}As \rightarrow {}^{93}Se$



Gamma



Neutron

Calculated neutron branching ratios: 1n (93%), 2n (8.5%), 3n (0.5%)

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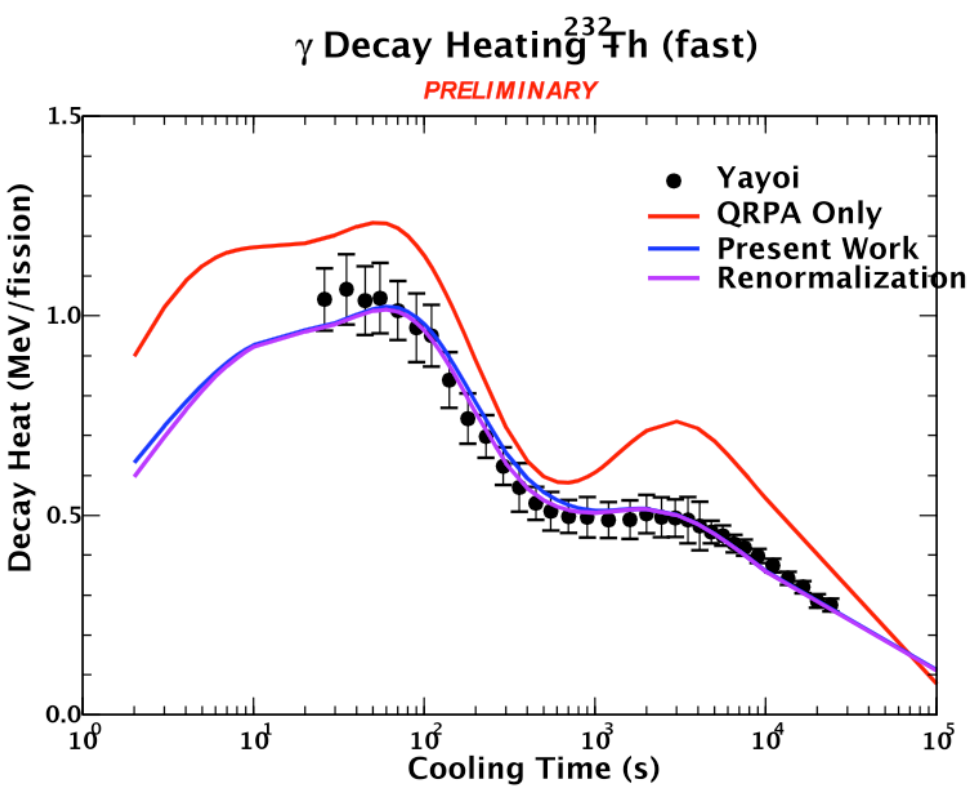
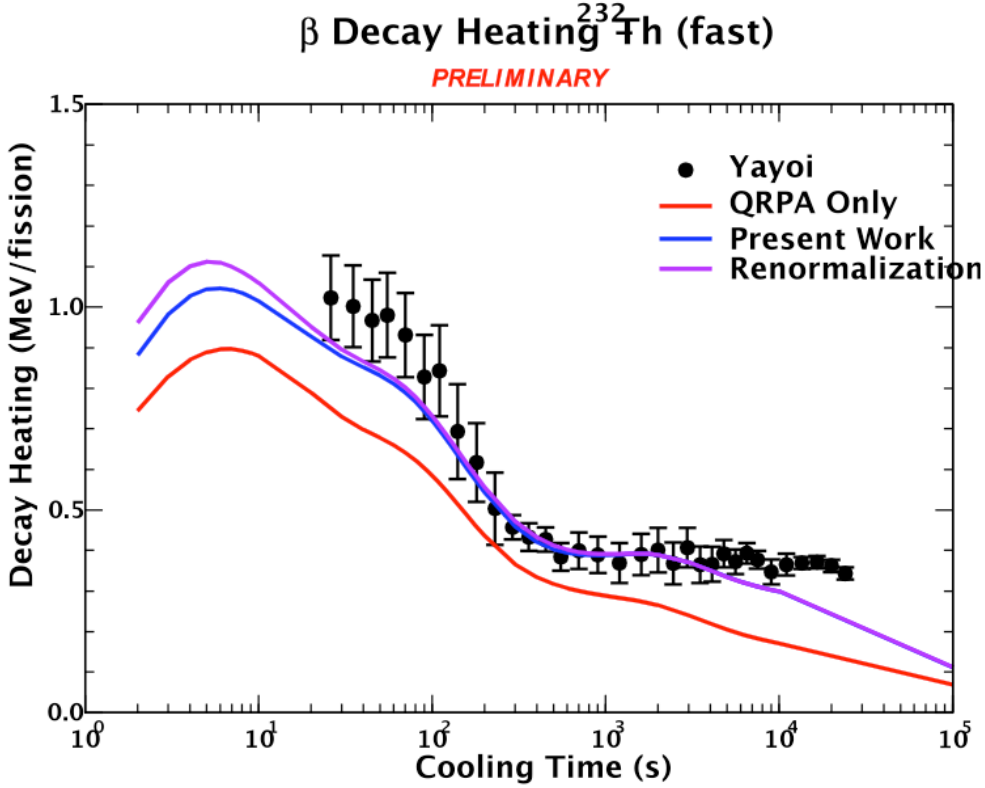
Calculated Decay Heating (Preliminary)

Th-232





M. Akiyama and S. An, Proc. Nuclear Data for Sci. Tech., Antwerp (1982) p.237.

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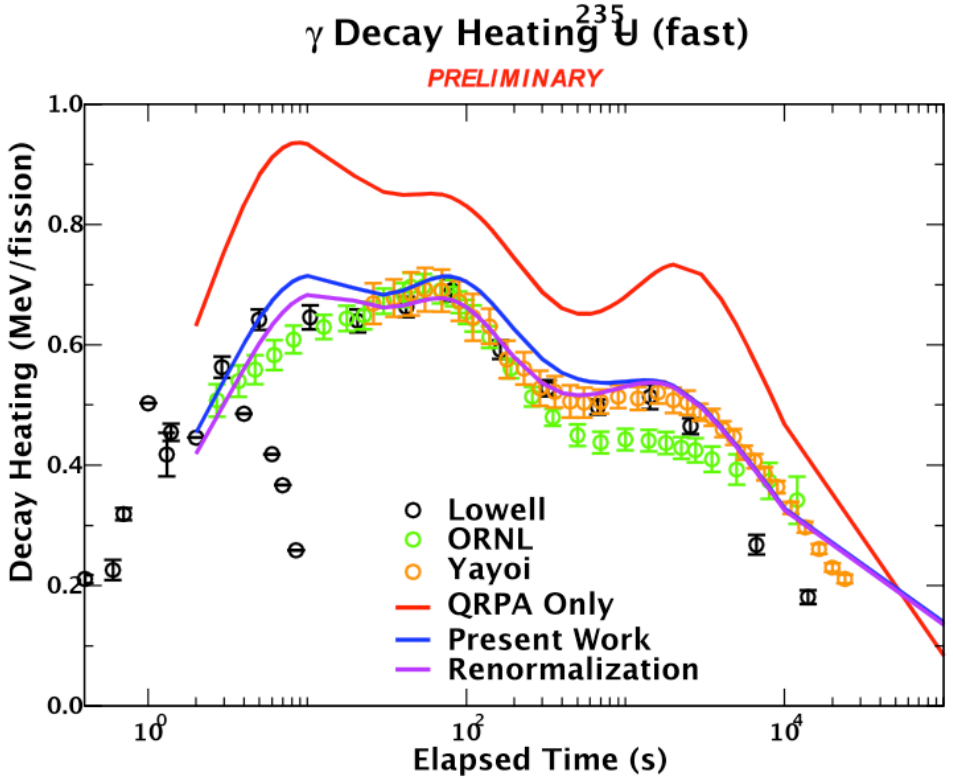
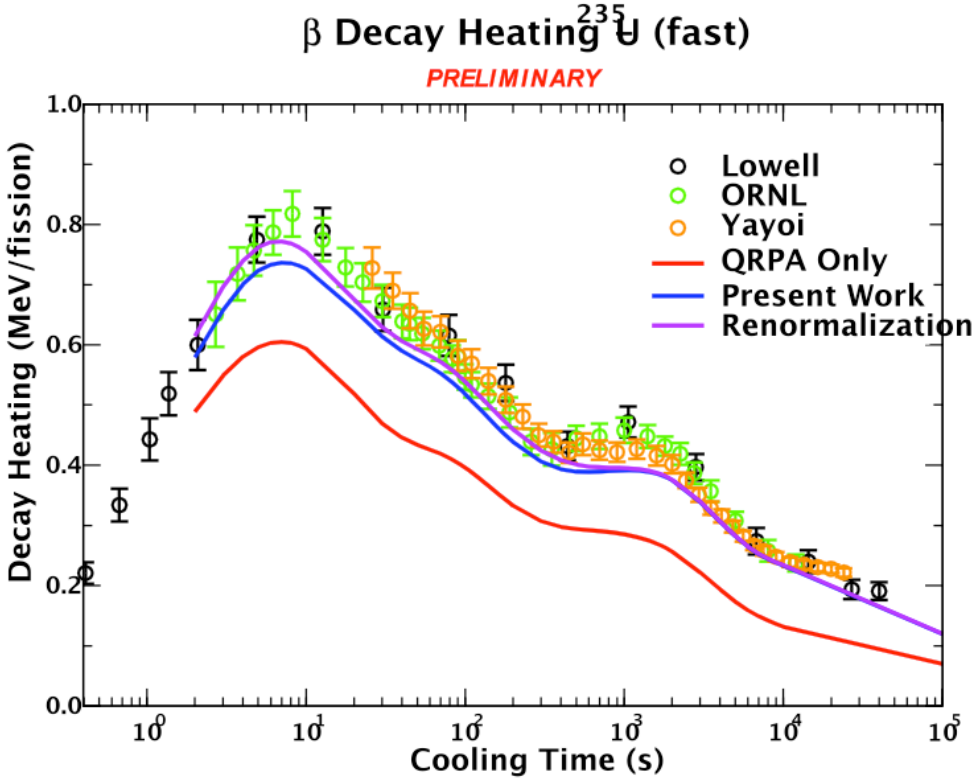
Calculated Decay Heating (Preliminary)

U-235





M. Akiyama and S. An, *ibid*

J.K. Dickens et al., Nucl. Sci. Eng. **74** 106 (1980); Nucl. Sci. Eng. **78** 126 (1981).

H. Nguyen et al., Nuclear Data for Sci. Tech., Trieste (1997) p.835.

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Concluding Remarks

Microscopic Theory for β-Delayed Neutron and γ Spectra

- We developed a new, more microscopic technique to calculate the delayed-neutron and γ energy spectra from
  - the FRDM and QRPA models,
  - the neutron and γ-ray emission probabilities from the statistical Hauser-Feshbach model, and
  - ENSDF (Evaluated Nuclear Structure Data File).
- The calculated delayed-neutron spectra reasonably agree with those evaluations that are based on experimental data.
- The calculations were extended to neutron-rich precursors, from which more than one neutrons can be emitted.
- The aggregated γ and electron energy releases from fission products were compared with the decay heat measurements.