Combining the Statistical Model with Nuclear Structure Data for Nuclear Decay Property Studies

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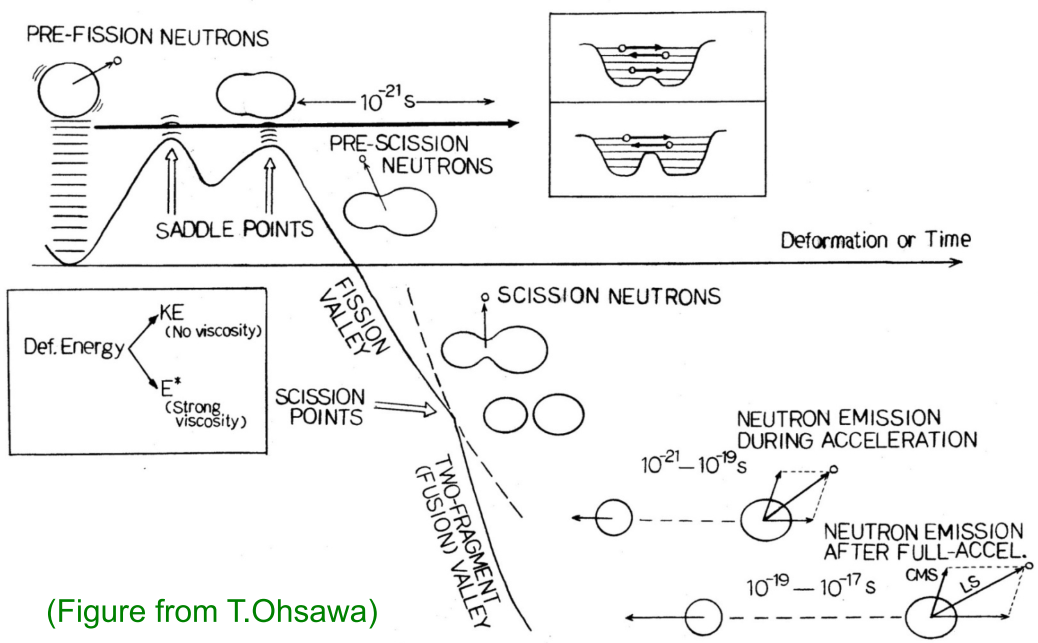
Workshop on Gamma Strength and Level Density in Nuclear Physics and Nuclear Technology

Dresden-Rossendorf, August 31, 2010

Introduction



(Figure from T.Ohsawa)

- **Several stages:**
  - **Pre-scission** (compound nucleus)
  - **Scission** (neck break-up)
  - **During acceleration**
  - **After full-acceleration**

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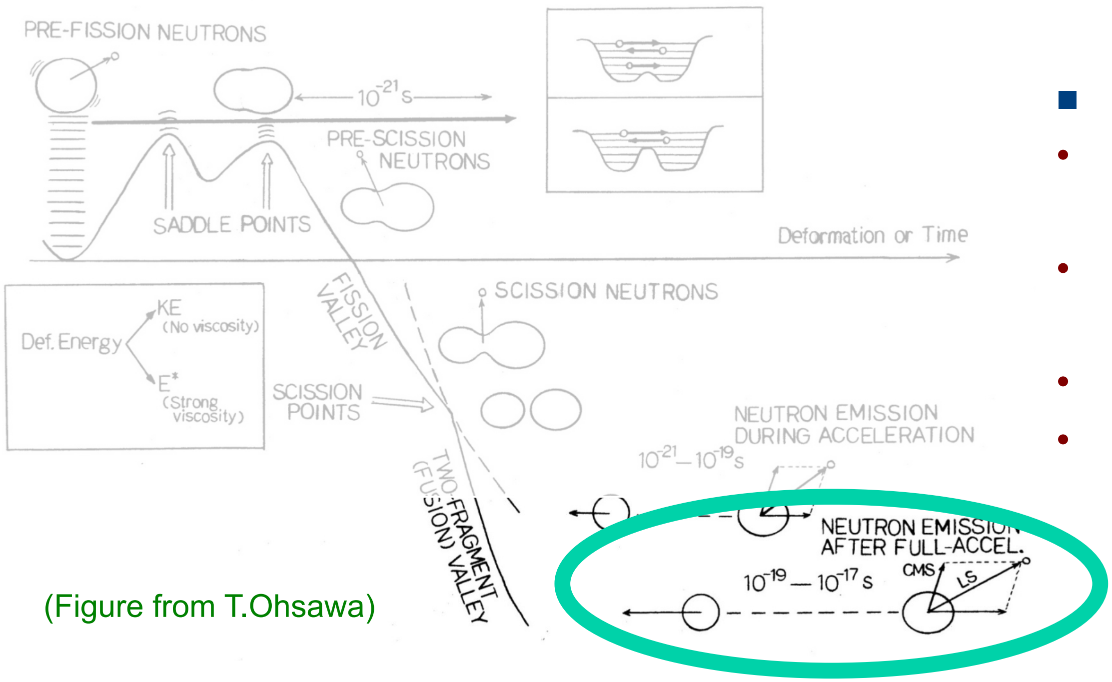

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- **Several stages:**
- **Pre-scission** (compound nucleus)
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Interested in these "later" time processes – "prompt" & "delayed" particle production

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"prompt"

two fission fragments (FF) emit prompt n and γ-rays, de-excite to their ground state.

Probes of:

- nuclear configurations @ scission pt
- characteristics of the fission process - distribution of excitation energy, spin, etc.

"delayed"

~10% of energy released via β-decay

Complicated β-decay chain

Delayed neutrons produced when $E_f > S_n$.

Emitted n, β, γ contribute to heating, reactor controls, etc. (ν, non-reactive)

A detailed knowledge

- individual precursors
- fragment yields

needed to fully characterize the delayed particles.

Experimental data is incomplete.

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History - ENDF Decay Data Library

Evaluation for Delayed Neutron Spectra

- Brady M.C. & England evaluated 271 precursors (late 1980's)
- Delayed neutron energy spectra obtained for individual precursors
- BETA code employed to extend incomplete experimental data
- Modified evaporation model for unmeasured spectra
- 36 important precursors: Ga, As, Br, Rb, Y, In, Sb, Te, I, Xe and Cs

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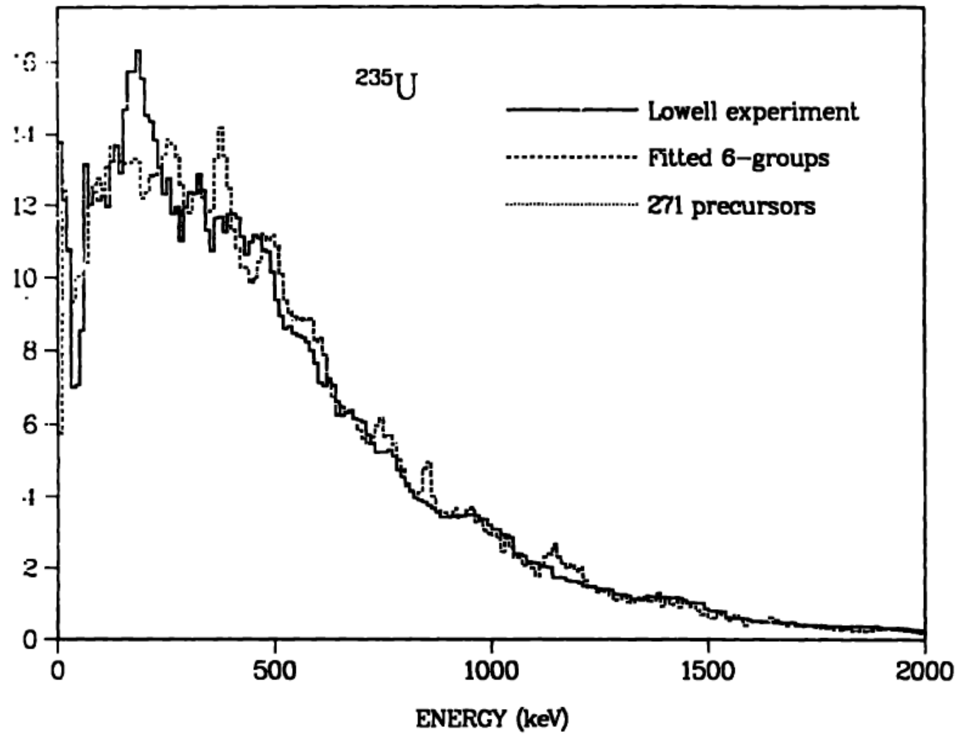
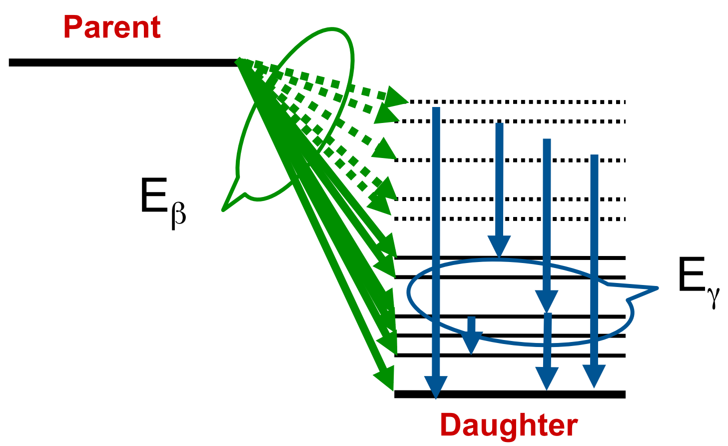


Fig. 1. Comparisons with Lowell equilibrium spectra for $^{235}U(T)$.

History - Delayed γ and β

- Early calculations utilizing standard nuclear data libraries, suffered from the "pandemonium" effect (Hardy et al., Phys. Lett. 71B, 307 (1977)).



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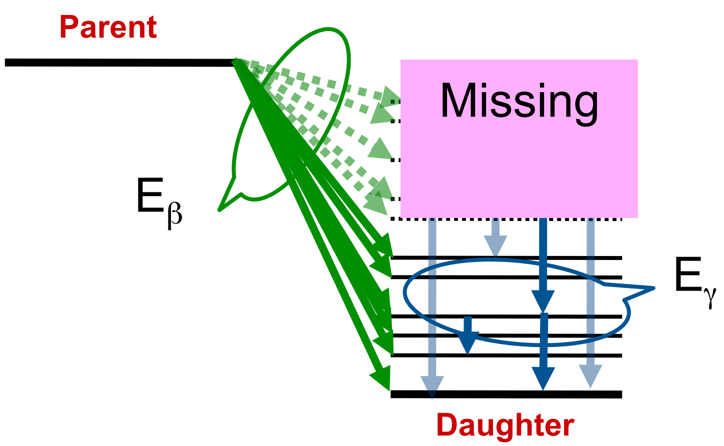


Limitations in Ge detectors

Miss β transitions to higher levels

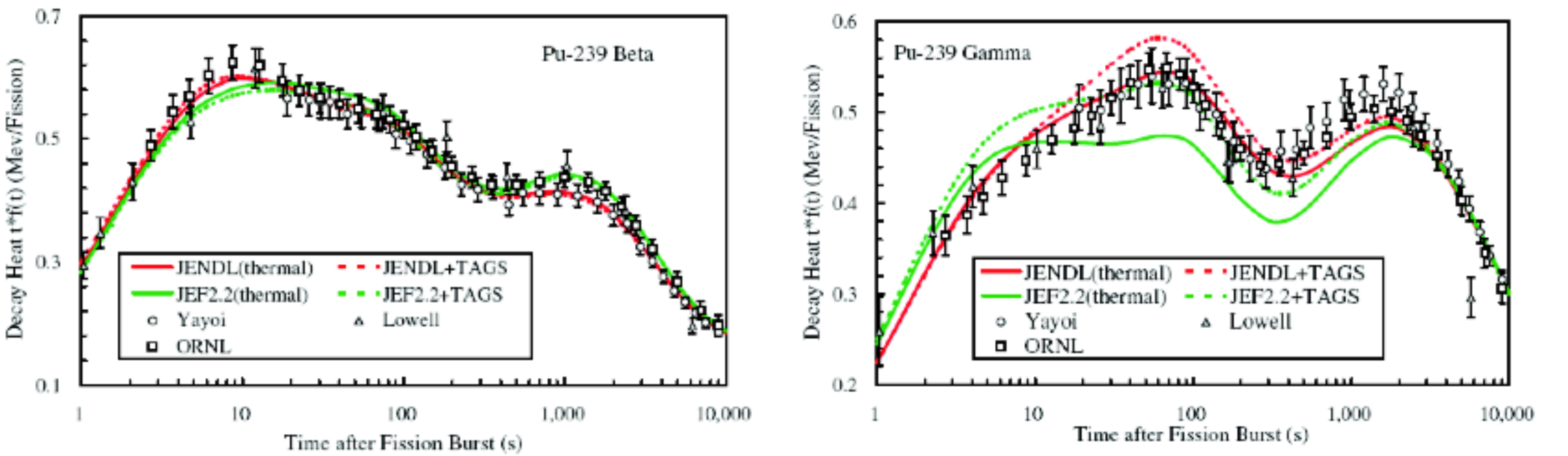
- **E_β overpredicted**
- **E_γ underpredicted**

History - Delayed γ and β

Most data libraries supplement with Gross Theory of Beta-decay

(K. Takahashi, M.Yamada, T. Kondoh, At. Data Nucl. Data Tables **12**, 101 (1973))

Fairly good agreement with experiment.



N. Hagura, T. Yoshida, T. Tachibana J. Nucl. Sci. Tech. **43** (2006) pg. 497

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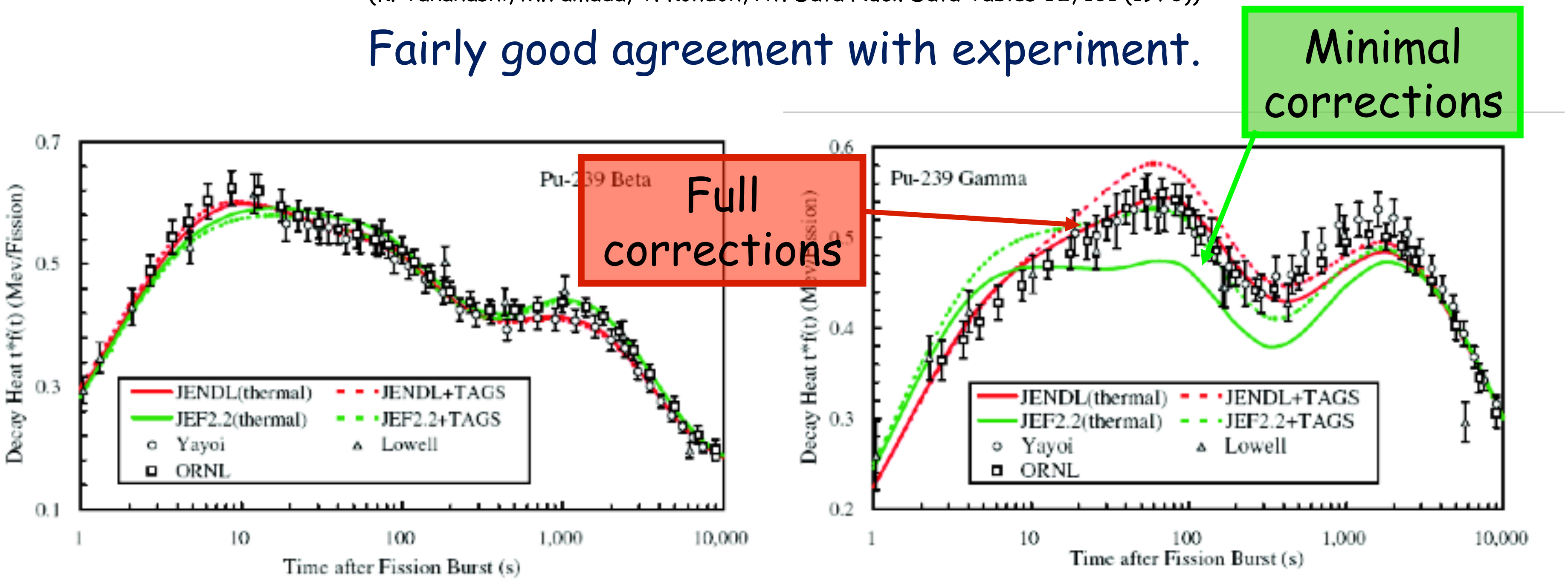

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History - Delayed γ and β

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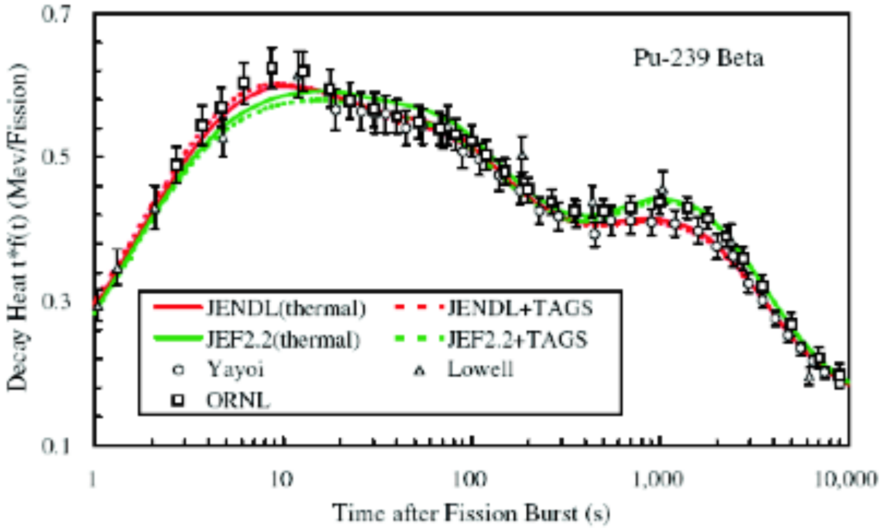
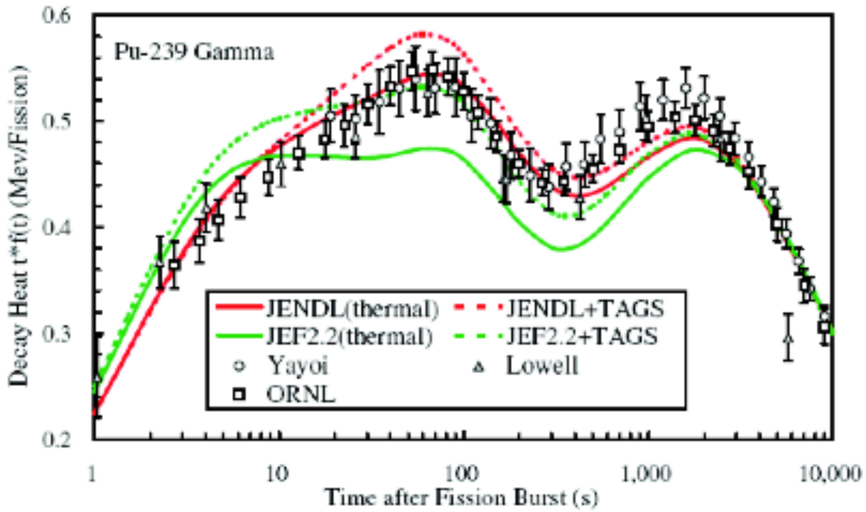
- **However, when individual nuclei are replaced with TAGS results, the agreement with experiment deteriorates.**





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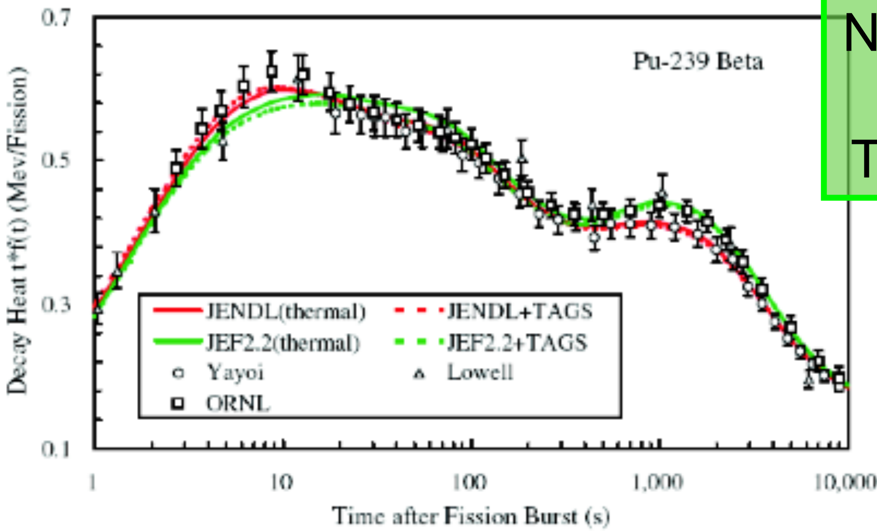

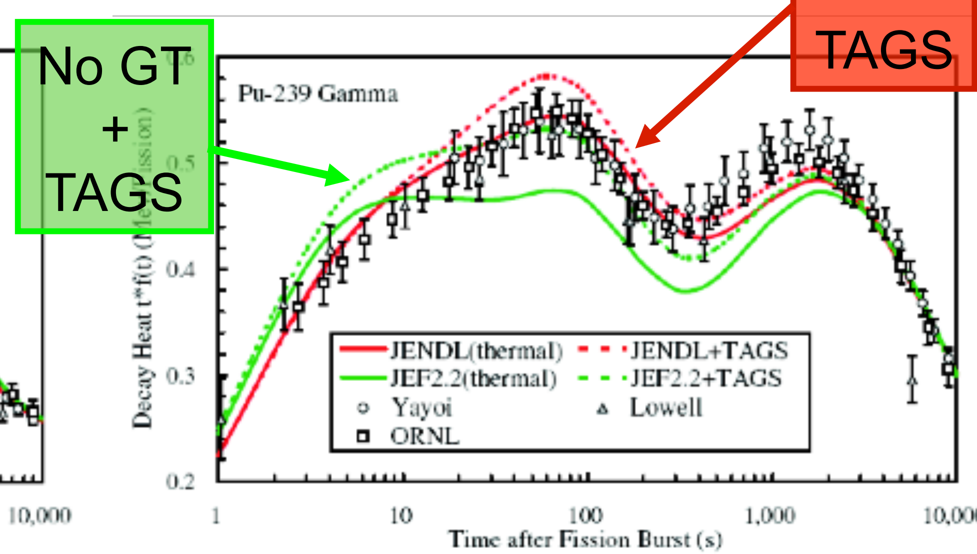

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Objective

Develop a "more microscopic" approach to delayed particle production

Combine

- Statistical Hauser-Feshbach
- Nuclear structure

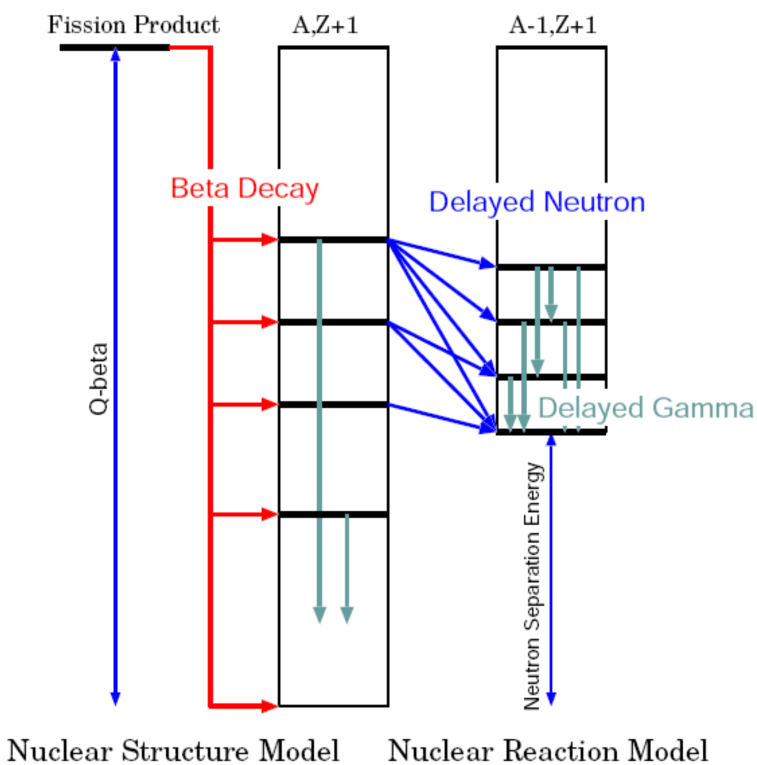
Obtain (for each individual precursor)

- Delayed-neutron yields
- Delayed Particle Energy spectra

Benchmark

- Summation Calculations
- TAGS experiments

Theory Developed



Nuclear Structure

- β-decay rate
  - Q_β from Möller mass model (FRDM)
  - QRPA Decay ME $< f \mid \beta_{GT} \mid i >$ (Möller)
- Low-lying discrete state data from ENSDF

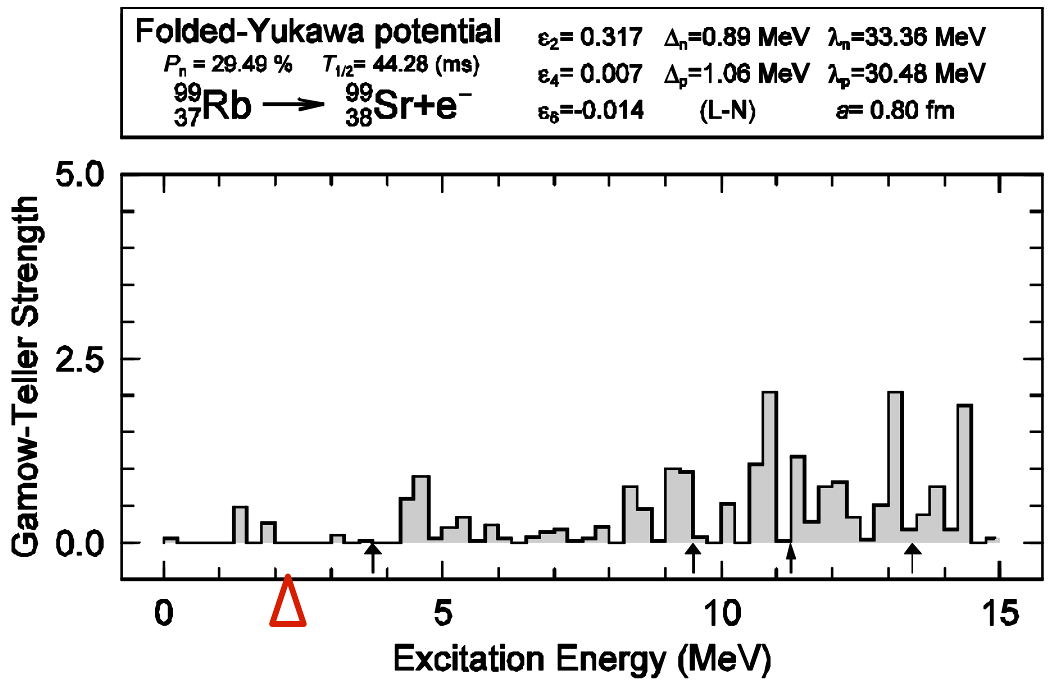
Nuclear De-excitation

- 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 neutron
T. Kawano, P. Möller, W.B. Wilson, PRC 78 0546-1 (2008)

Microscopic Model for β-decay

- **Solve Schrödinger Equation**
  - 3D single-particle potential
  - Residual interactions
    - Pairing
    - Gamow-Teller
- **Calculate**
  - Mass
  - Ground state shape
  - Q-values and wave functions
- **QRPA Decay rates**
  - calculate $\langle f|\beta_{GT}|i\rangle$
  - Obtain $(E^{(k)}, b^{(k)})$
- **If ENSDF β-decay data available, QRPA is replaced**



Transition Probabilities

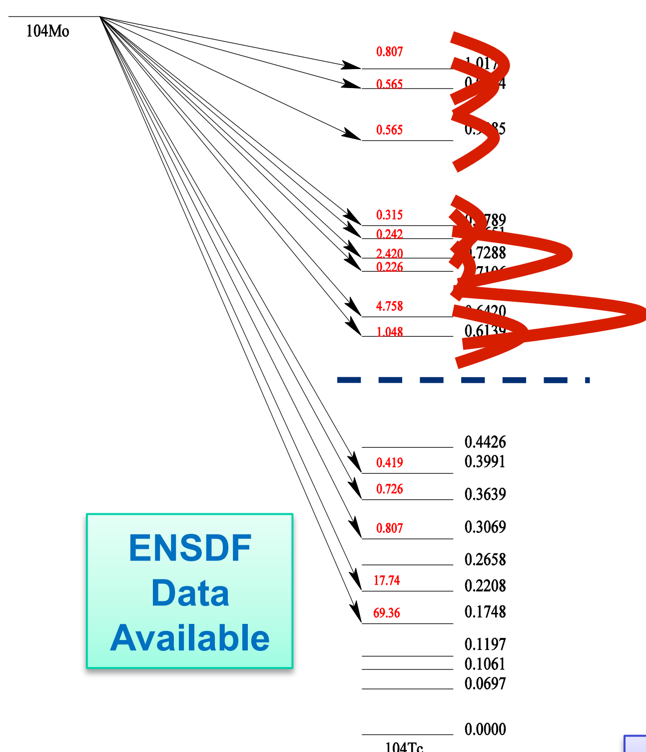
Data Smoothing and Re-normalization

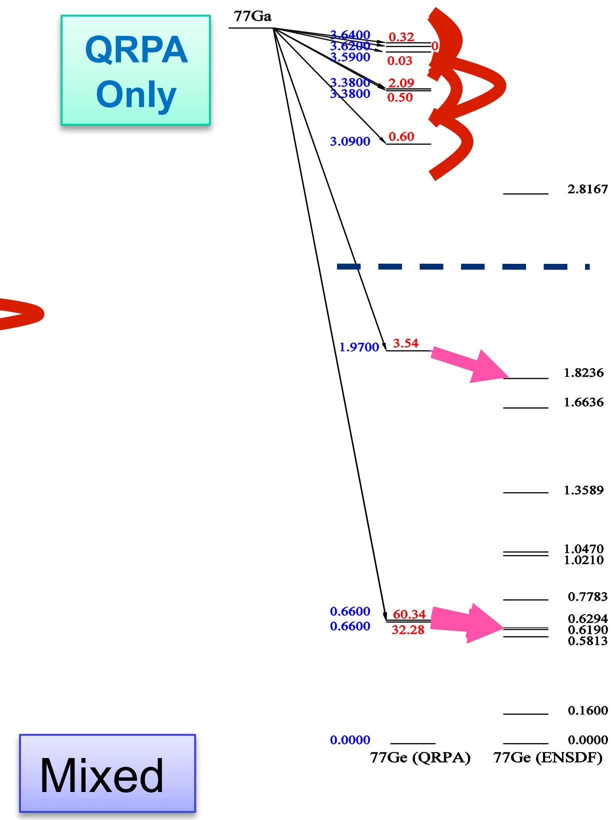
The QRPA calculation includes pairs (E_k,b_k)

E_k = excitation energy of the daughter nucleus

b_k = branching ratio to the state

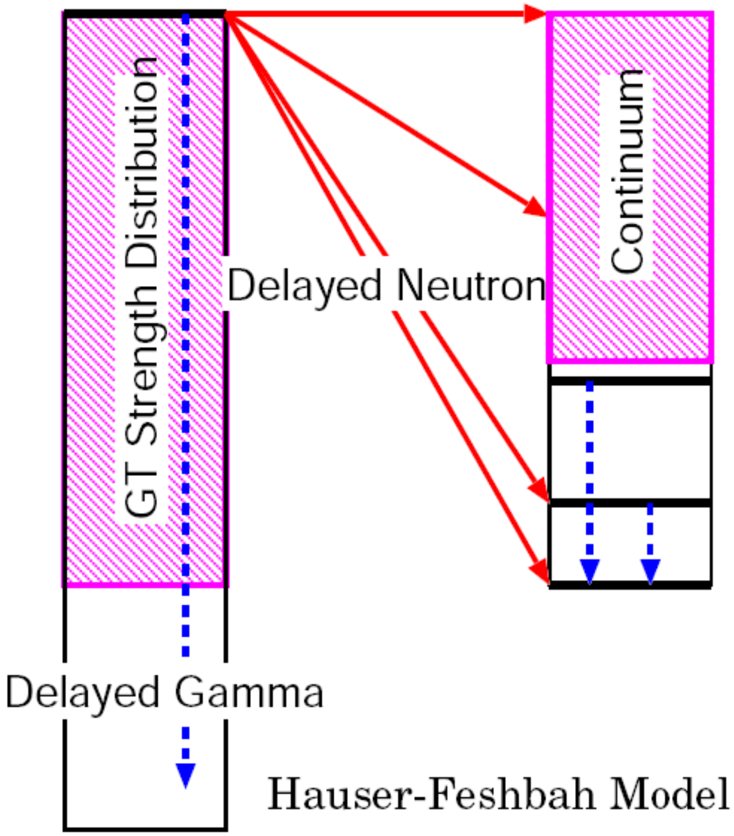
Strength distribution is smoothed by a Gaussian with the width Γ of 30 keV or 100keV





Beta-Delayed Neutron Emission

Neutron emission from the daughter nucleus

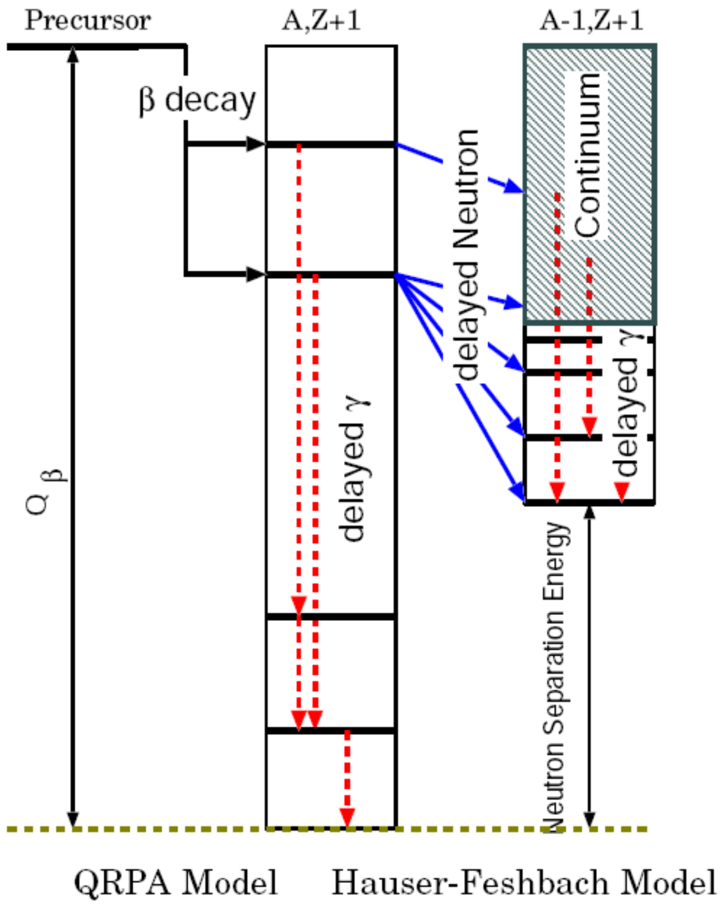


- **Assume excited state <u>after</u> β-decay is a compound state, having fixed *J***

$$|I-1| < J < I+1$$

- **Neutron and γ-ray emissions calculated with the statistical Hauser-Feshbach theory (CGM code).**
- **The γ-ray emission competition is included.**

Beta-Delayed Gamma-Ray Emission



Gamma-ray emission multiplicity larger than unity

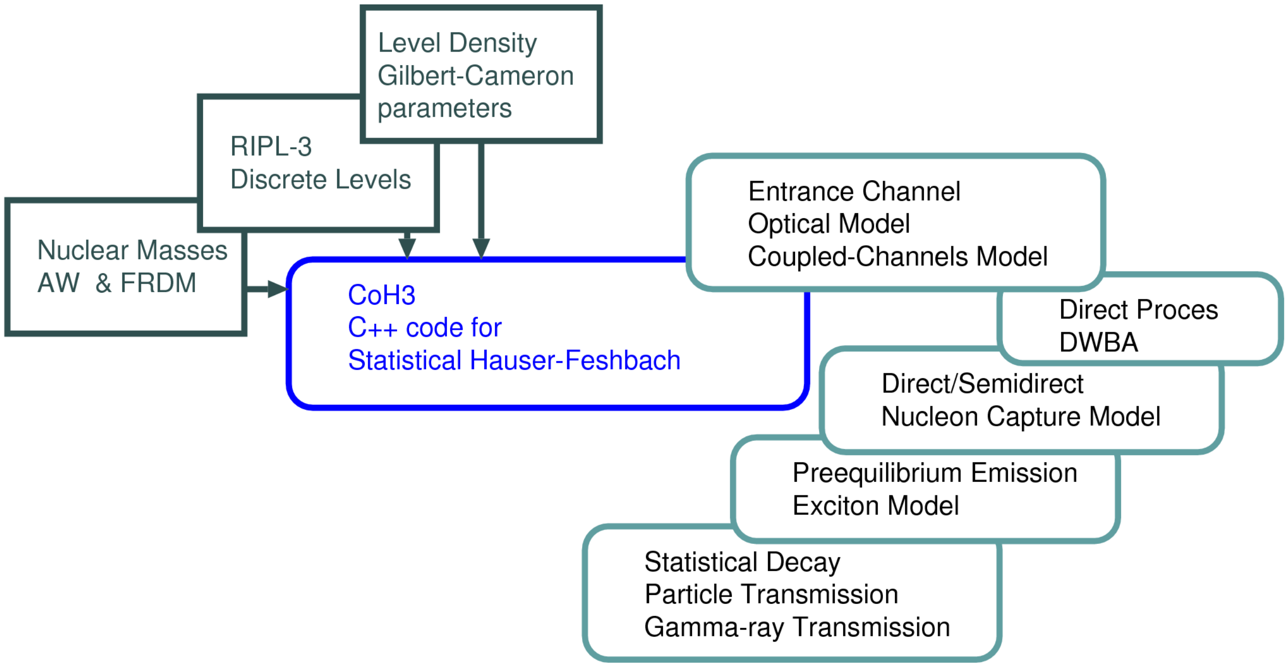
γ-ray emission takes place in both daughter and grand-daughter nuclei

To calculate delayed γ spectra, follow all γ-ray cascade

- Individual low-lying transition is important
- The evaluated structure data in ENSDF are incorporated
  - β-decay to discrete levels
  - γ-ray branching ratios

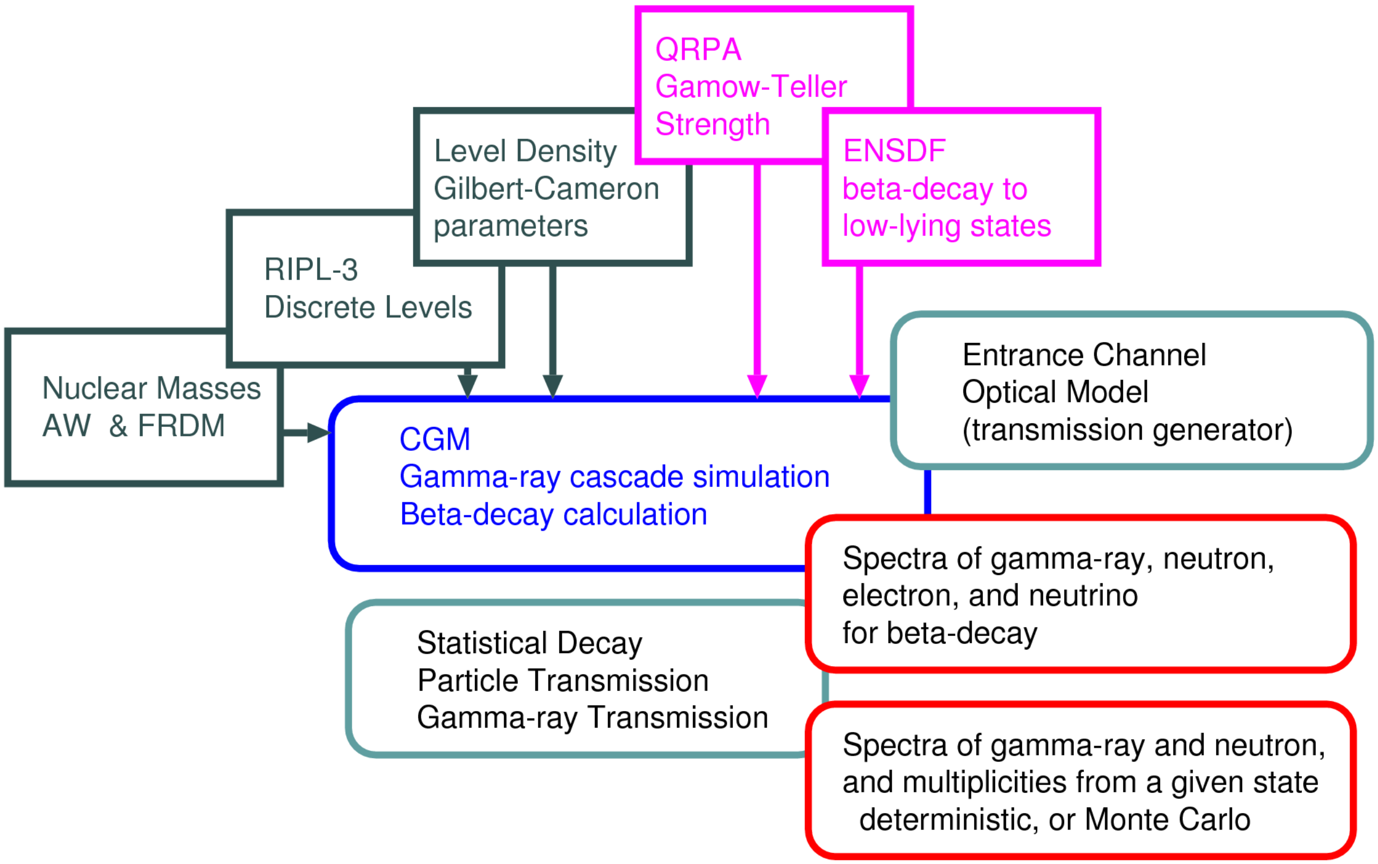
The whole decay process, including γn, is calculated with Hauser-Feshbach model.

Statistical Hauser-Feshbach Code, CoH

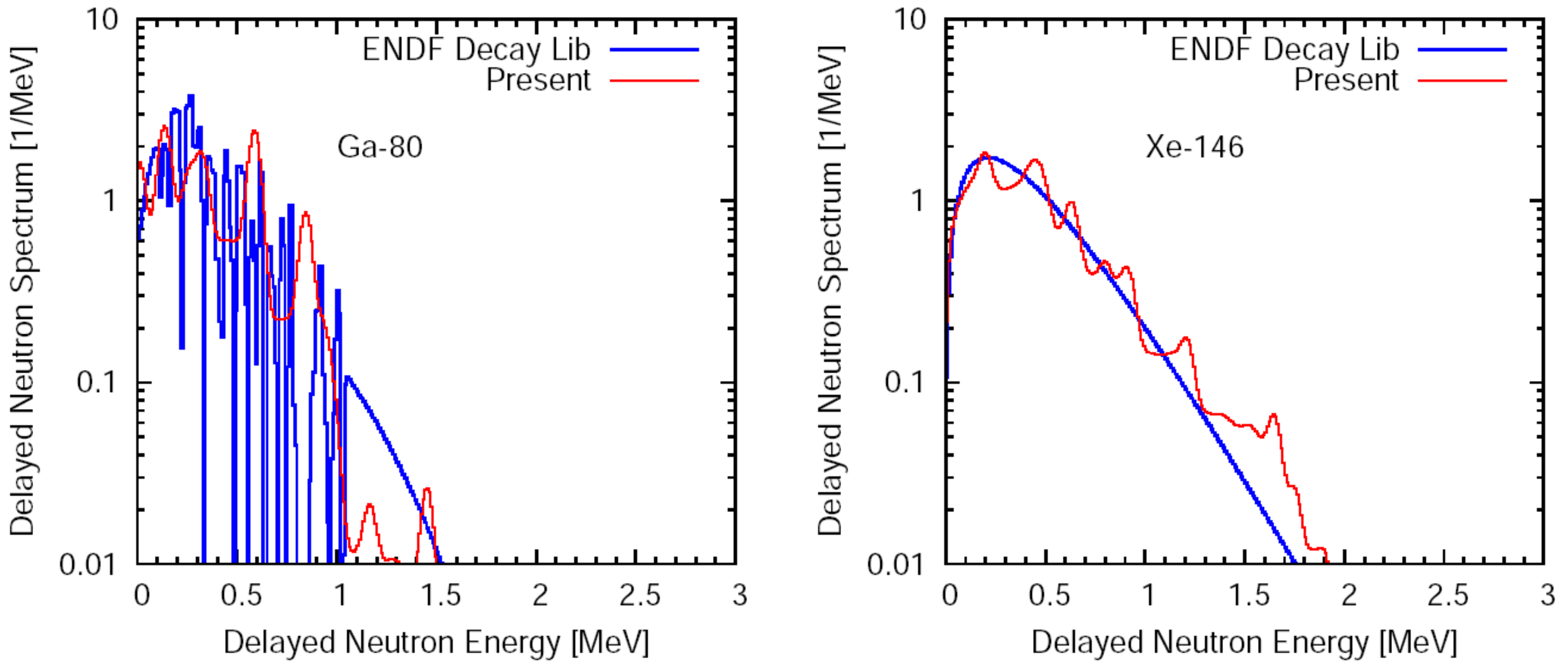


CoH calculates particle or γ-ray induced reactions on medium and heavy nuclei – reaction cross sections, particle and γ-ray energy spectra, isomer production in the MeV energy range.

Neutron and Gamma Decay Code, CGM

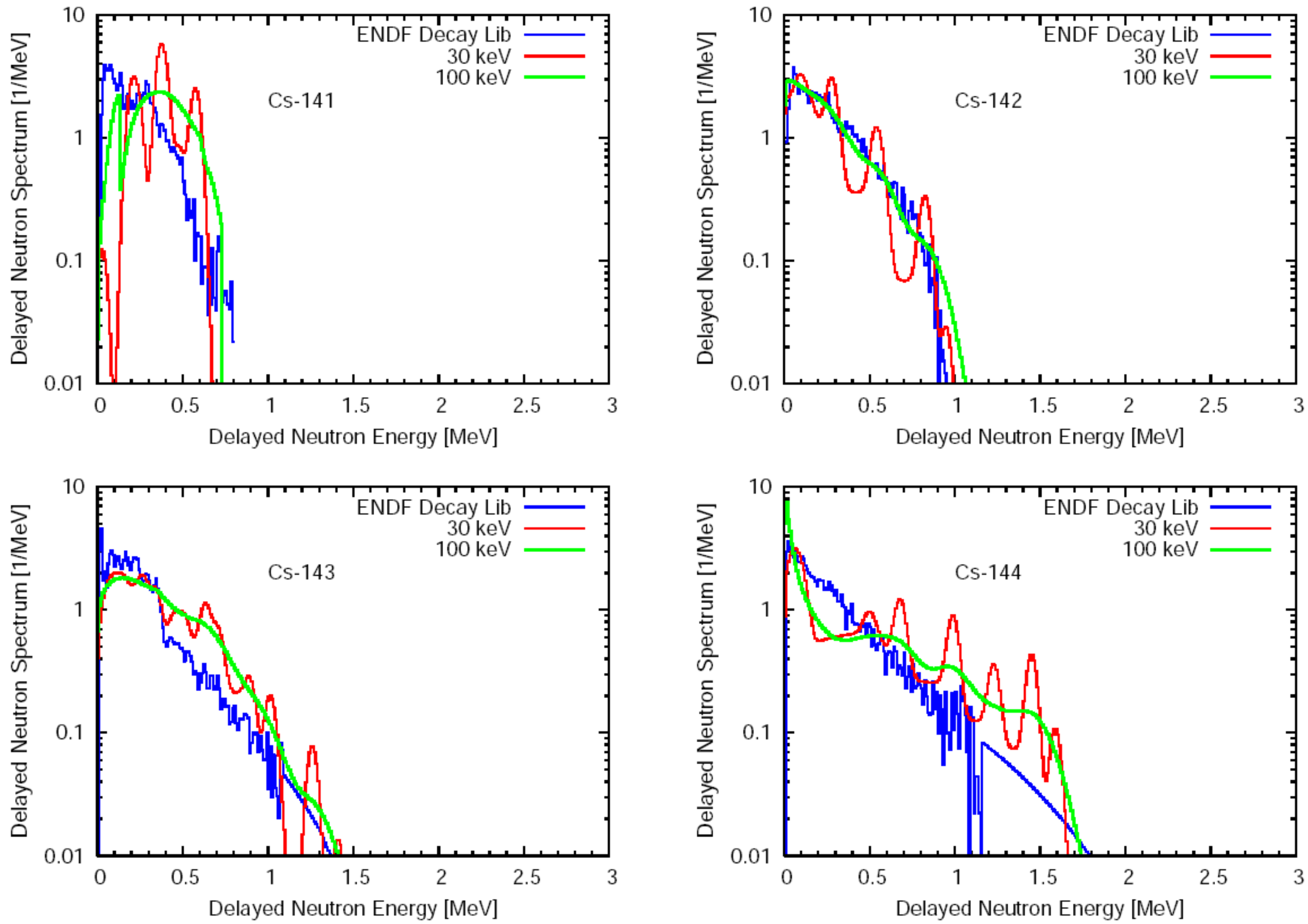


Calculated Neutron Spectra

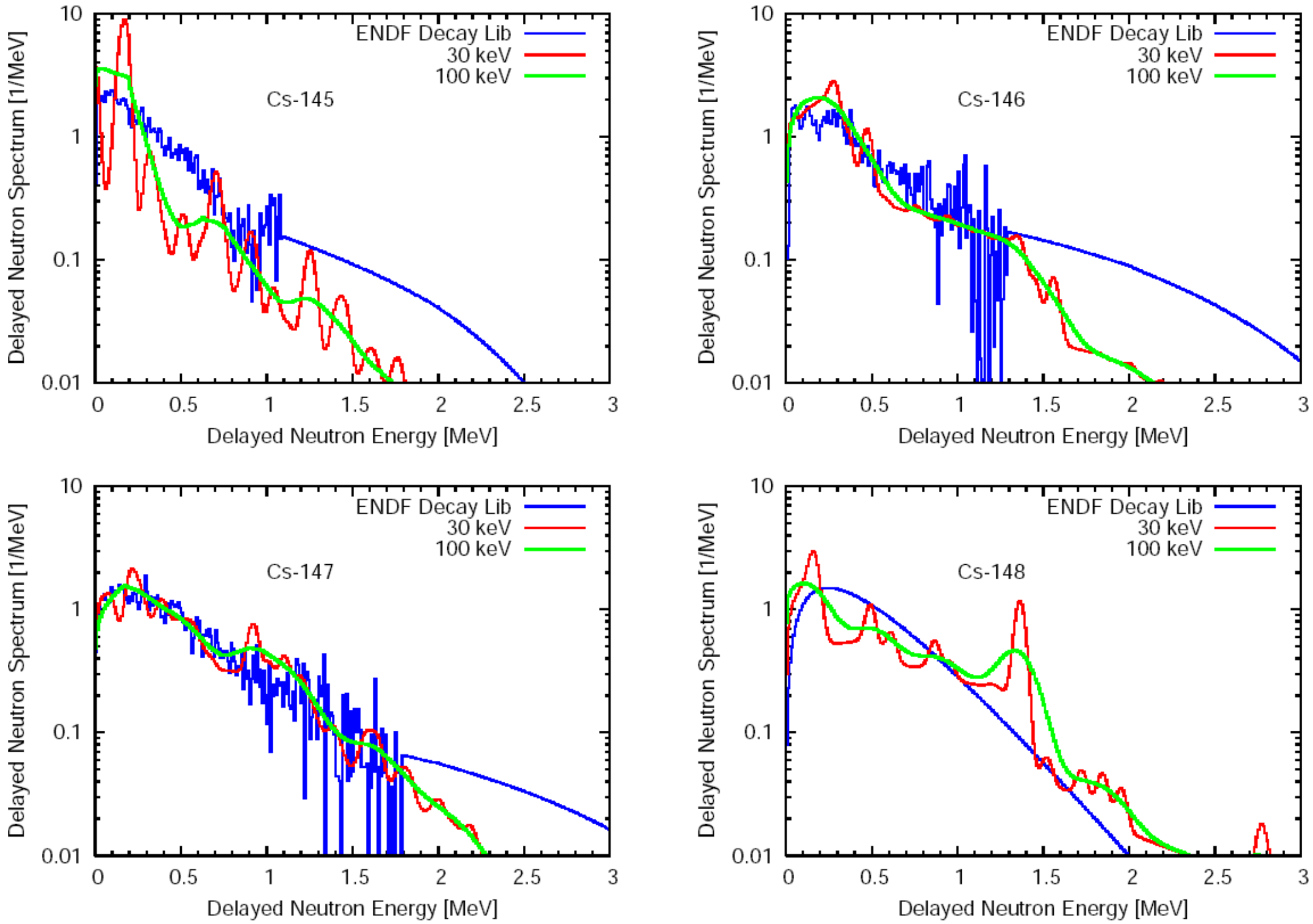


- ENDF decay library gives a simple evaporation spectrum
- 30 keV of energy resolution adopted
- In our calculations, structures in the spectra persist

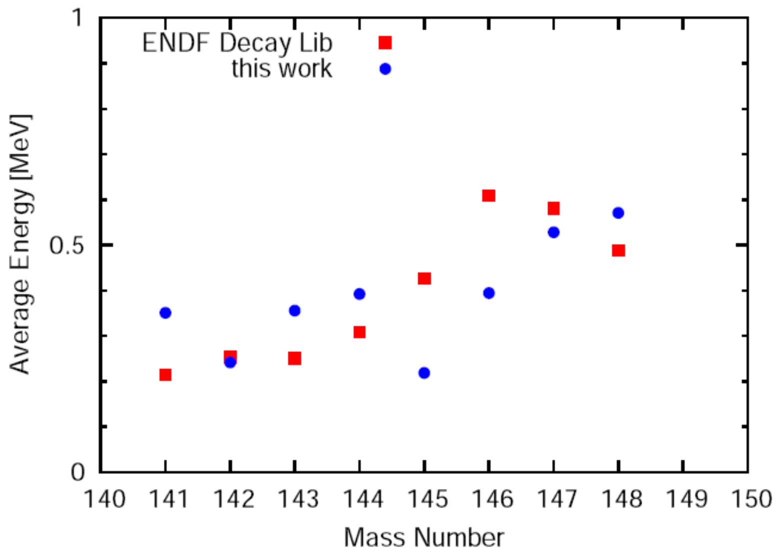
Cs Isotopes, I

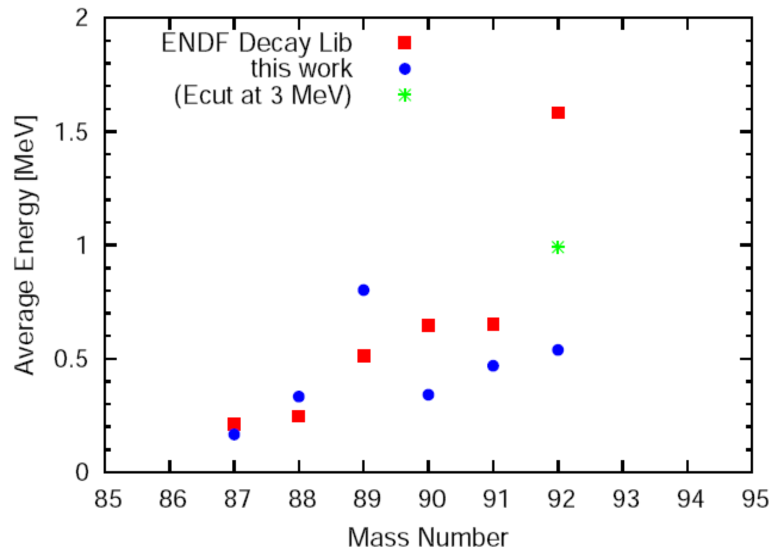


Cs Isotopes, II



Average Energy of the Spectra



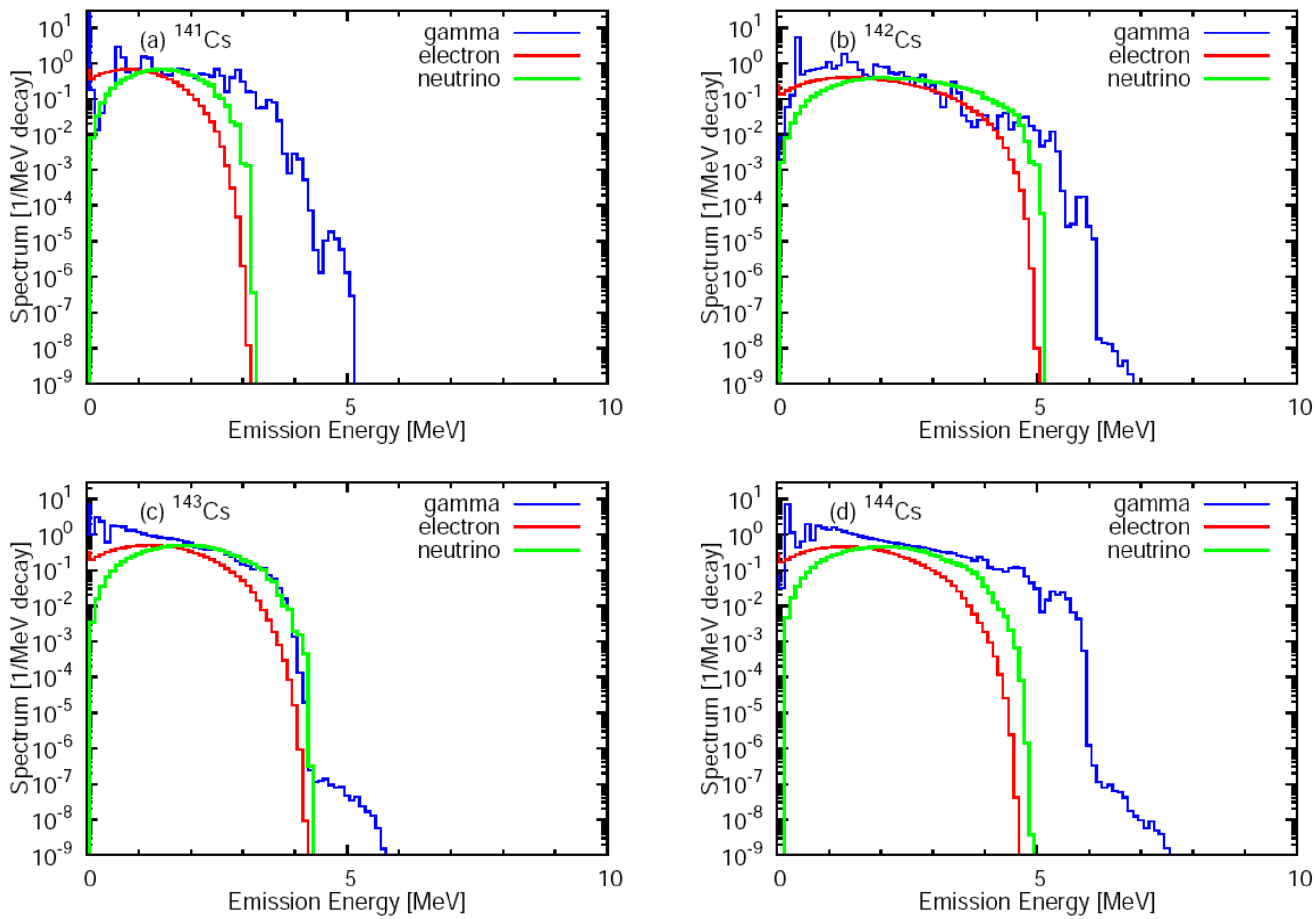


The average energy varies smoothly with nuclear mass

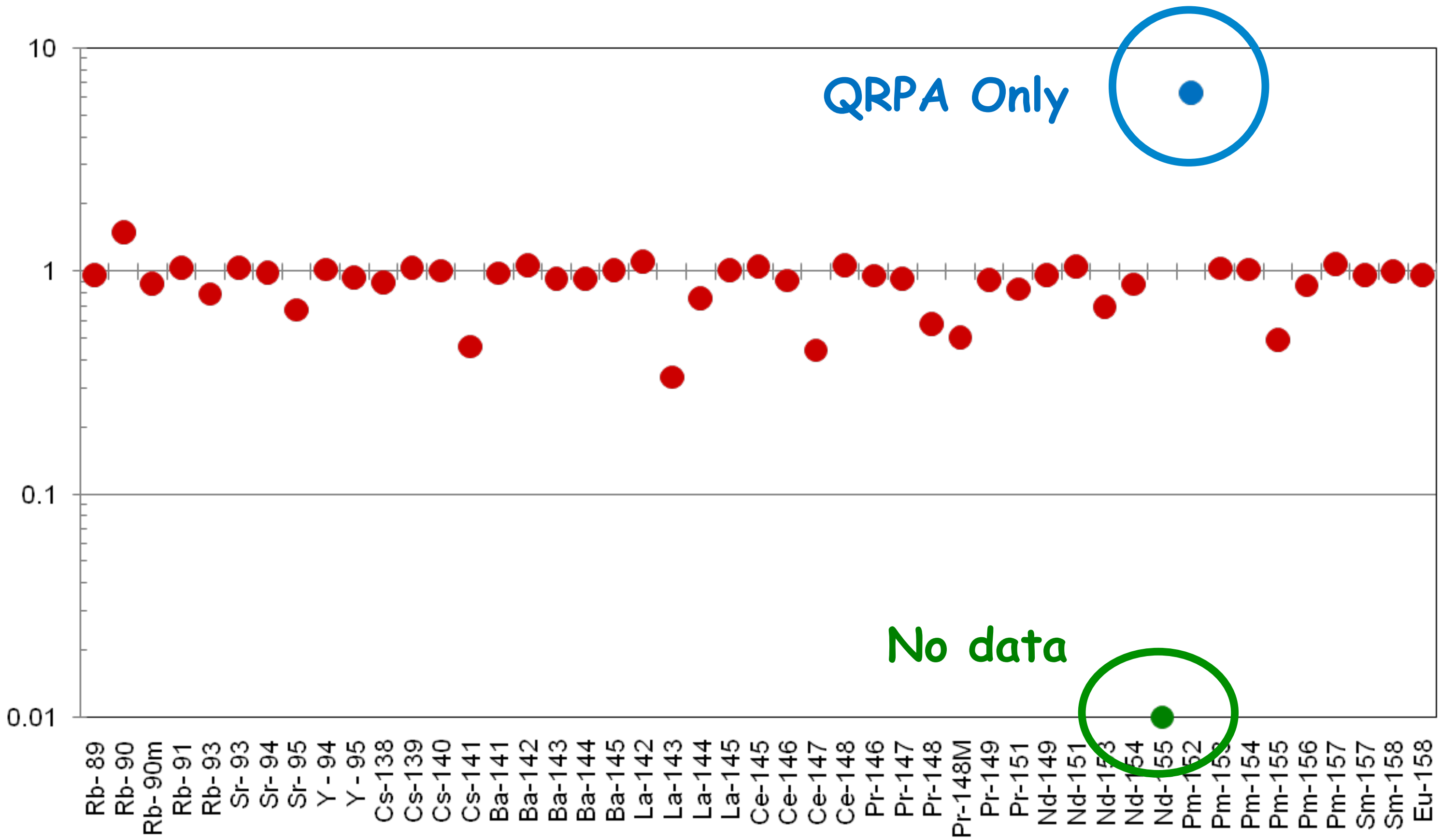
Maximum neutron energy $E_{max} = Q_{\beta} - S_n$

Sudden jump seen in ENDF decay library, due to the extrapolation by using the evaporation spectrum

Cs Isotopes

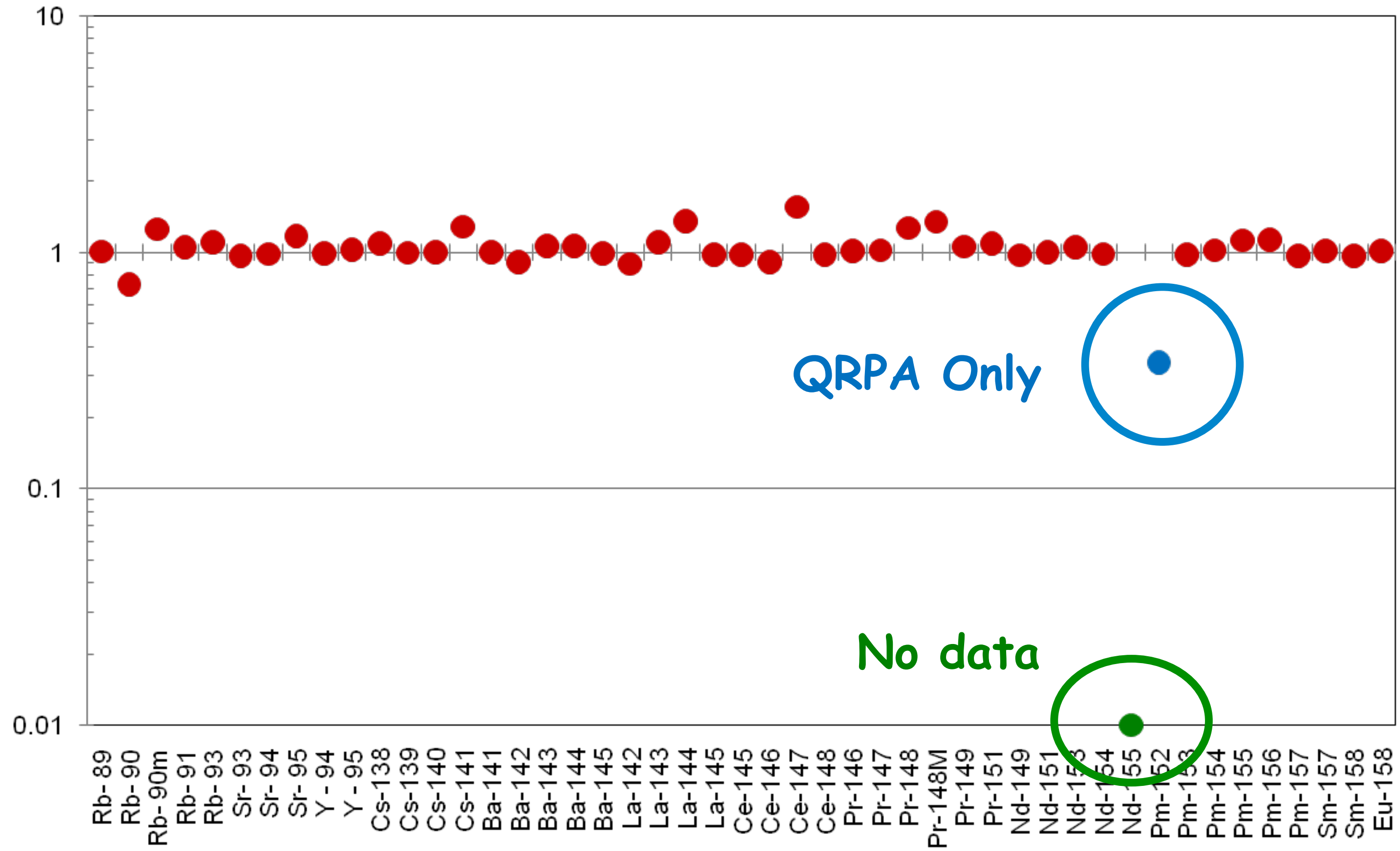

(a) ^{141}Cs
(b) ^{142}Cs
(c) ^{143}Cs
(d) ^{144}Cs
gamma
electron
neutrino
Spectrum [1/MeV decay]
Emission Energy [MeV]
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
0
5
10

Comparison with TAGS - Average E_γ



TAGS data: Greenwood et al.

Comparison with TAGS – Average E_{β}



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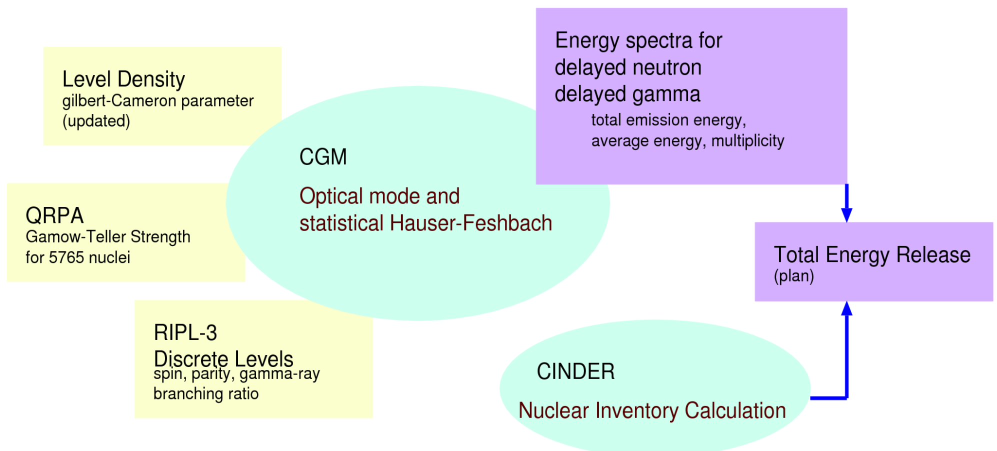
UNCLASSIFIED

Decay Heat Calculations

Assembling microscopic data to compare with aggregated data

We perform the CGM calculation (average/total γ and β energies) for all fission products

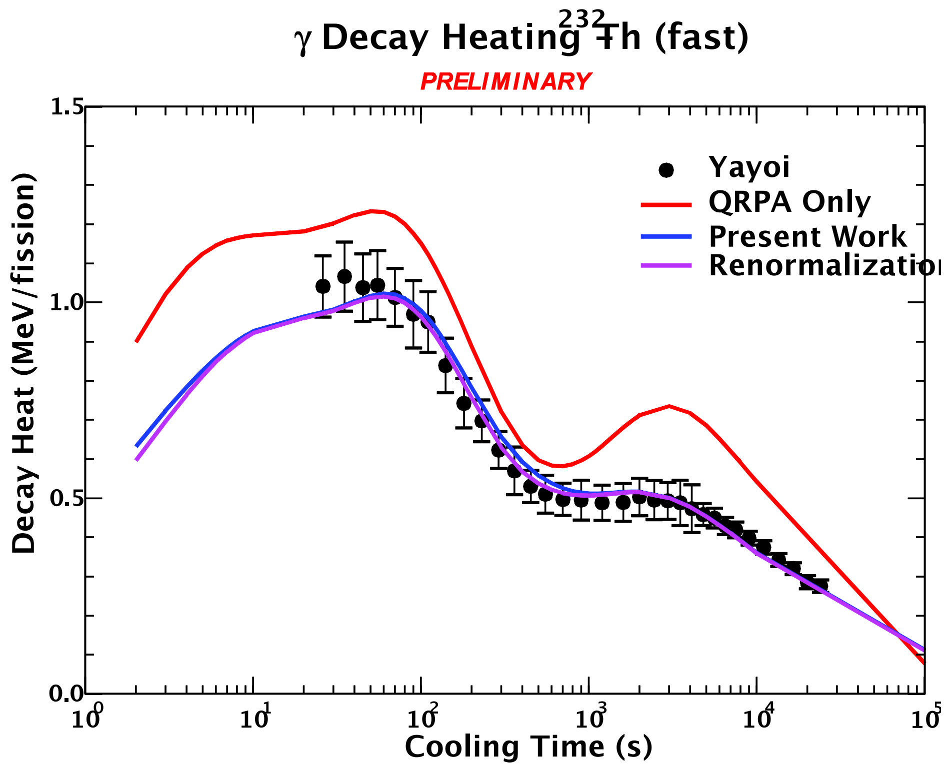
Nuclear inventory calculation, by CINDER, gives temporal abundance of each fission product.

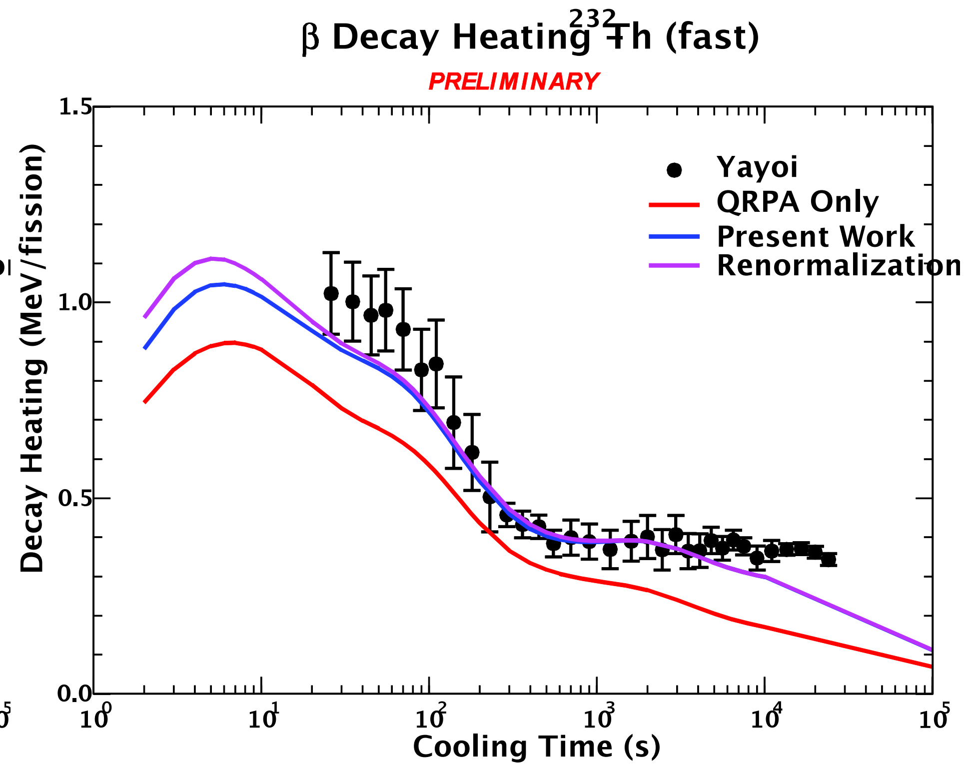


We can obtain

- β and γ heating after fission burst
- Dn spectra in a 6-group structure (reactor application)
- delayed γ-energy spectra for fission

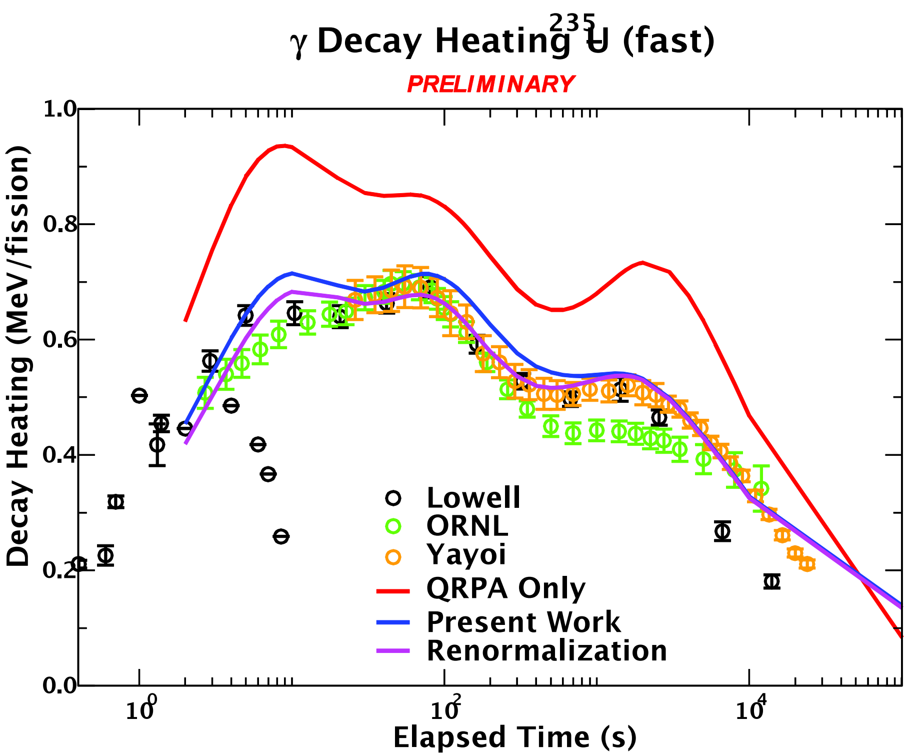
Calculated decay heating 232Th

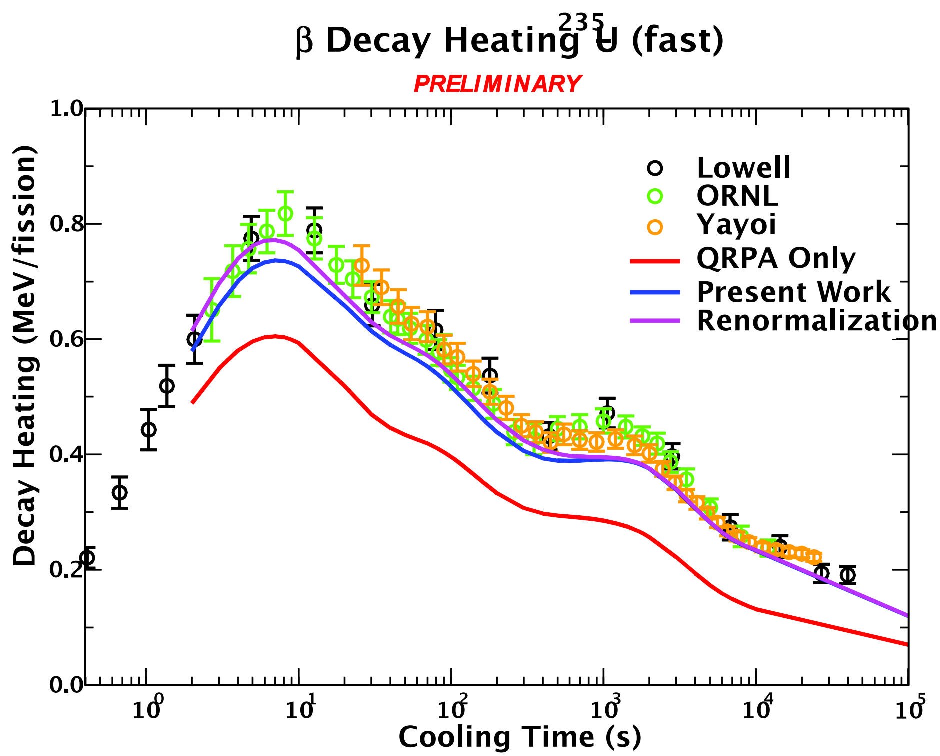




M. Akiyama & S. An, Proc. Nuclear Data for Sci. Tech., Antwerp (1982) p. 237

Calculated decay heating 235U





M. Akiyama & S. An, ibid

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

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

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Monte Carlo Simulation of Fission Fragment Evaporation – PFNS and more!

Madland-Nix or Los Alamos model:

- Average over entire fission fragment distributions **and** neutron cascades
- Several important assumptions regarding what happens near scission
- Main advantage: very few tunable parameters!
- Main disadvantage: computes averages only:
  - Average neutron multiplicity $\langle n \rangle$
  - Average neutron spectra $\langle \chi \rangle (E_{in}, E_{out})$

From the prediction of a few average quantities (χ,n) to detailed exclusive quantities: P(n), $\chi_{(n=1,2,\ldots)}$, n-n correlations, …

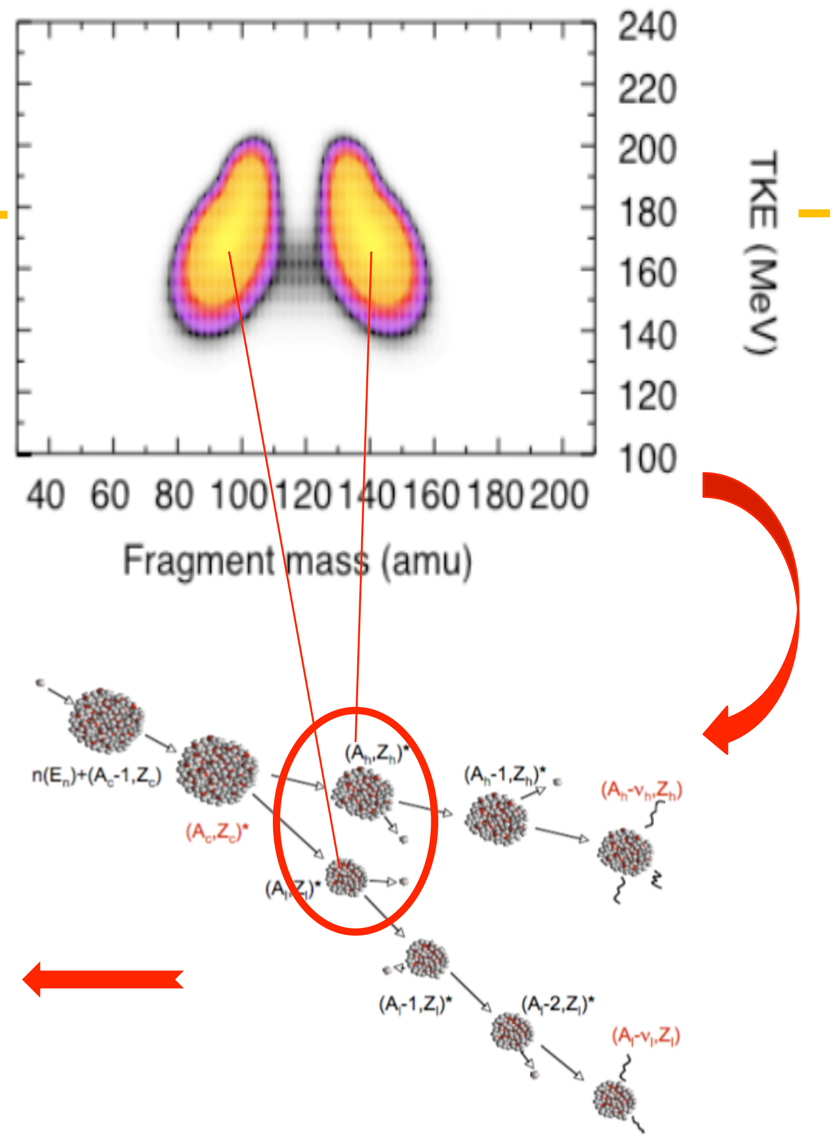
→ Monte Carlo simulation of the de-excitation of the primary fission fragments

Much more physics

→ to be used in advanced transport simulations

Monte Carlo Hauser-Feshbach Simulations

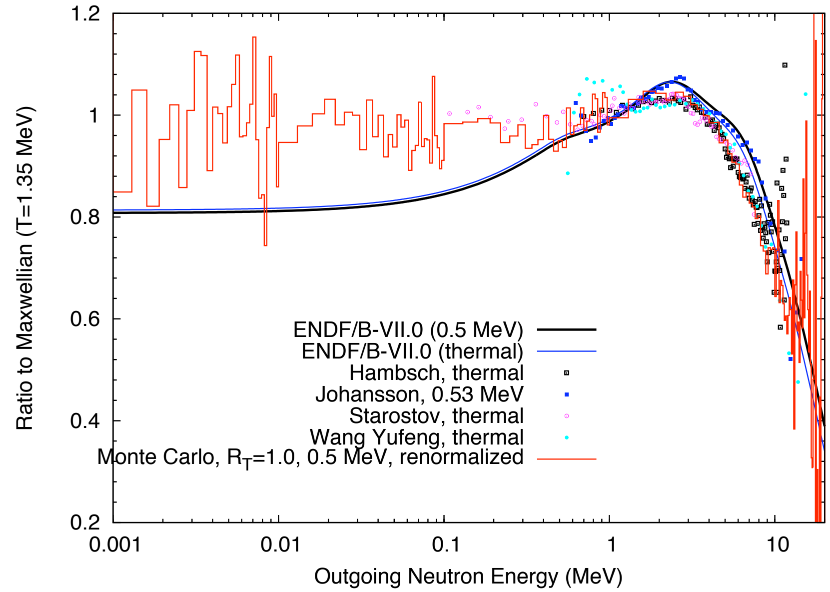
1. Sample from Y(A,Z,TKE) distribution
2. Infer E^*_{tot} and $\langle J_{tot} \rangle$, and partition between the two fragments
3. Infer temperatures T_l and T_h → $R_T = T_l / T_h$
4. Apply Hauser-Feshbach equations



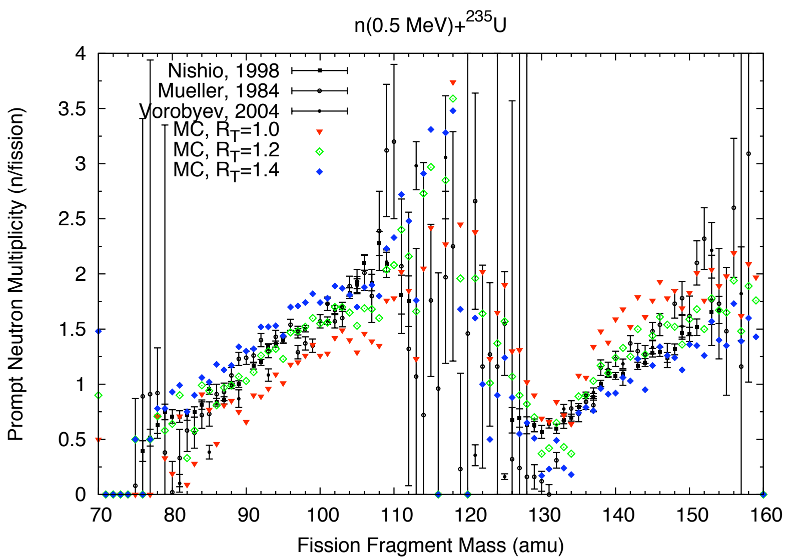
$\langle \chi \rangle(E)$, $\langle n \rangle$, $P(n)$, $\chi(E)|_n$, n-n correlations, etc.

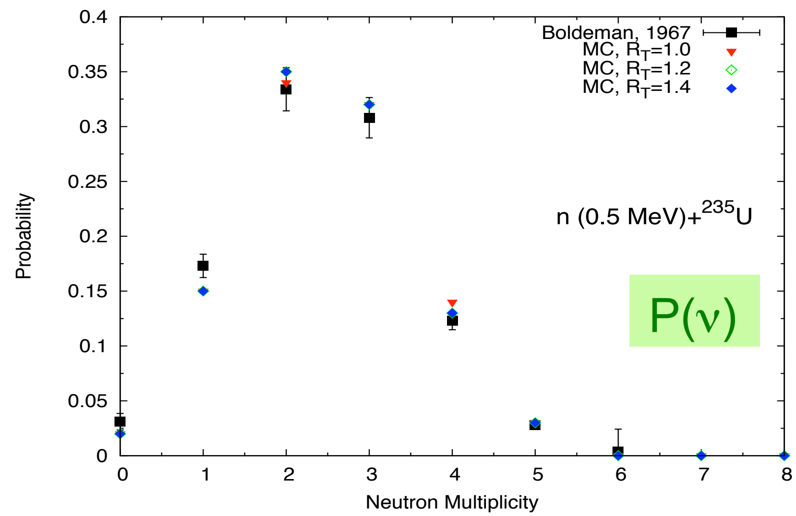
Application to n+^{235}U

Using experimental primary fission fragment yields $Y_{exp}(A,KE)$
[F.-J.Hambsch, private communication]



<ν>(A)





P(ν)

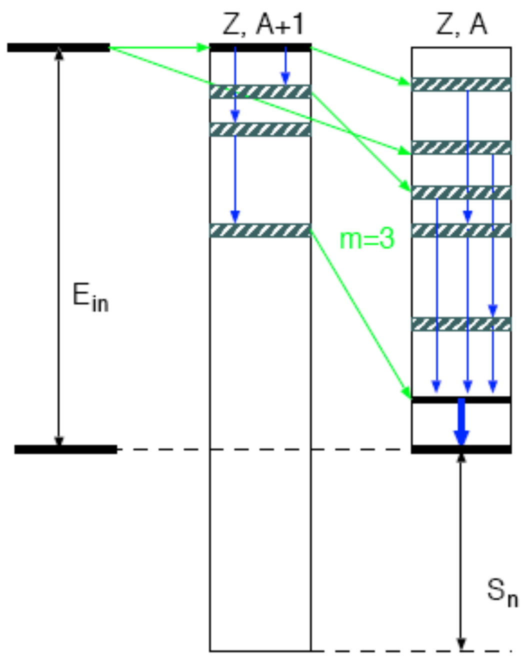
Prompt Fission Gamma Rays…

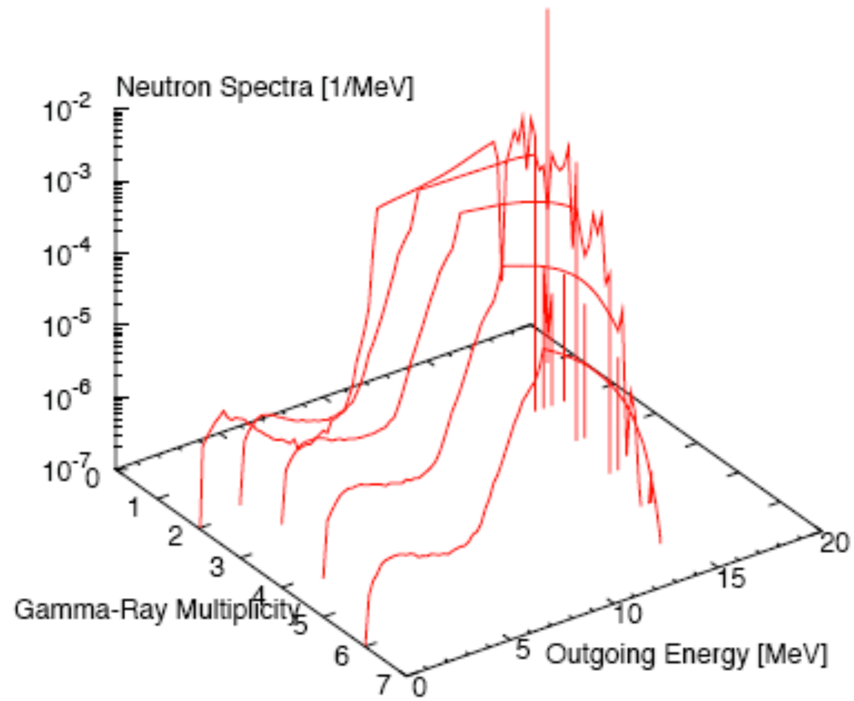
Monte Carlo Hauser-Feshbach Simulations

Towards a fully Monte Carlo Hauser-Feschbach solution

New code being developed in our group → *to be applied to this problem*

Example: n(20 MeV)+^{56}Fe gated on 0^+-2^+ E2 transition





Concluding Remarks

- **Microscopic Theory of β-delayed neutron and γ spectra**
- **We developed a new, more microscopic technique to calculate the delayed-neutron and γ energy spectra**
- **This technique obtains the β-decay rates from**
  - The FRDM and QRPA models, and
  - The neutron and γ-ray emission probabilities from the statistical Hauser-Feshbach model
- **The calculated average energies for the spectra tend to be similar to those for the data in ENDF decay library.**
- **The aggregated γ and electron energy releases from fission products were compared with the decay heat measurements**
- **This method can be extended to include prompt fission spectra (in progress).**
  - MC -> No longer limited to average quantities – exclusive processes teach us more!

Thank you!