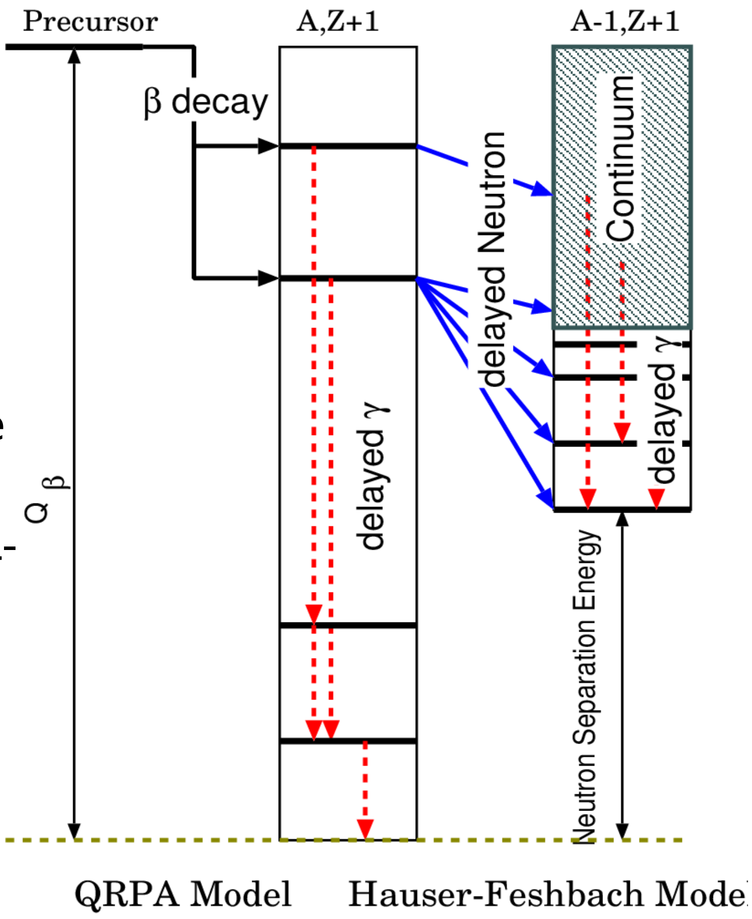
Statistical Theory for the Beta-Delayed Neutron and Gamma-Ray Emission

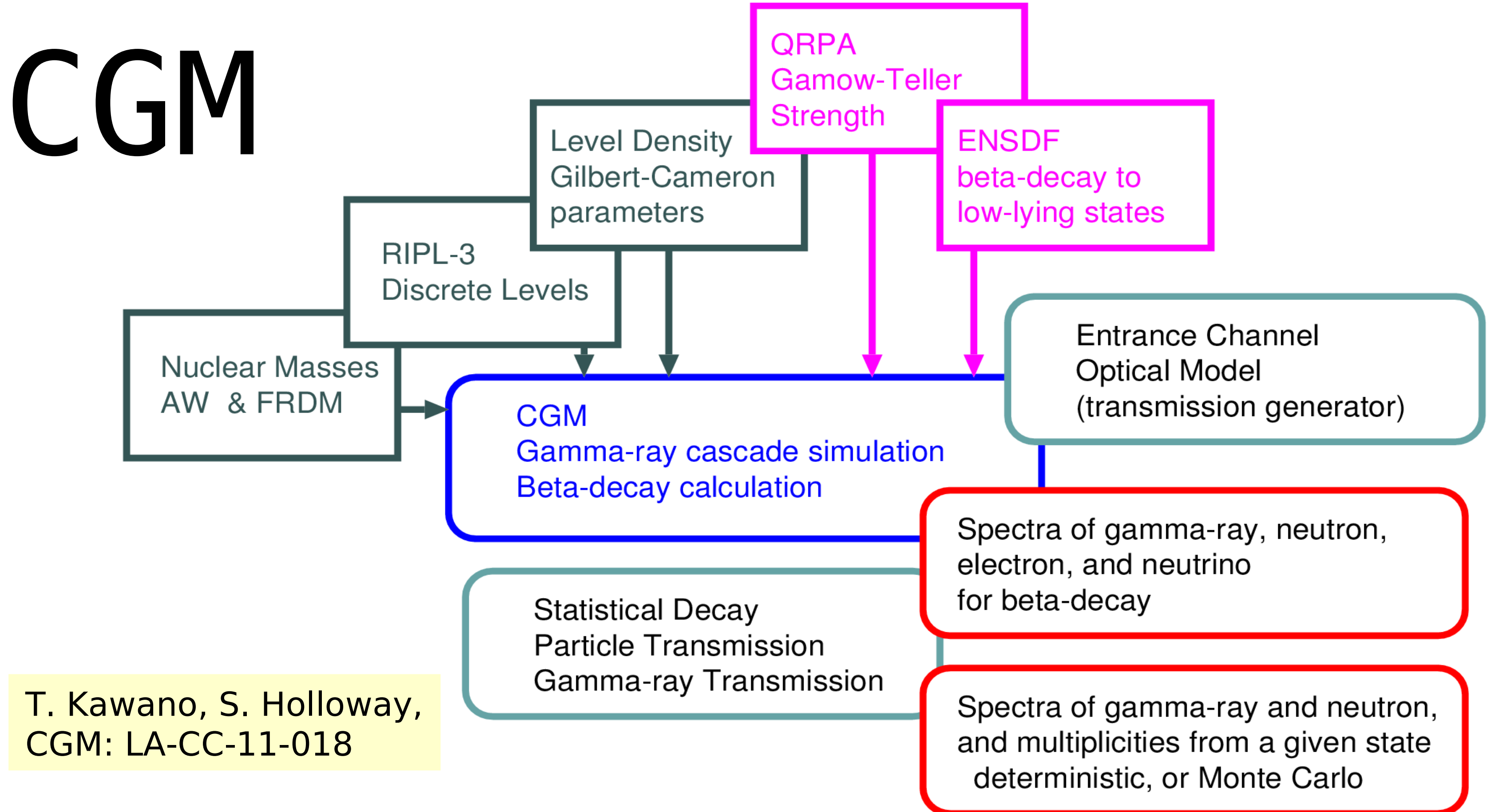
T. Kawano, P Möller
Theoretical Division, Los Alamos National Laboratory

Combining QRPA Calculation and Statistical Decay

- **Nuclear Structure**
  - Beta-decay rate
    - Q_β from FRDM
    - GT strength from QRPA
    - Data from ENSDF
- **Nuclear De-excitation**
  - Neutron and gamma emission rate
    - Hauser-Feshbach theory
    - Discrete level data from RIPL-3 (ENSDF)
  - Integrate over all possible decay processes
  - Neutron-gamma competition included



Hauser-Feshbach Neutron and Gamma Decay Code



T. Kawano, S. Holloway,
CGM: LA-CC-11-018

Hauser-Feshbach Emission Probability

- **gamma-ray emission**

$$P(\epsilon_\gamma)dE_0 = \frac{T_\gamma(E_x - E_0)\rho(Z,A,E_0)}{N}dE_0$$

gamma-ray strength function

- **neutron emission**

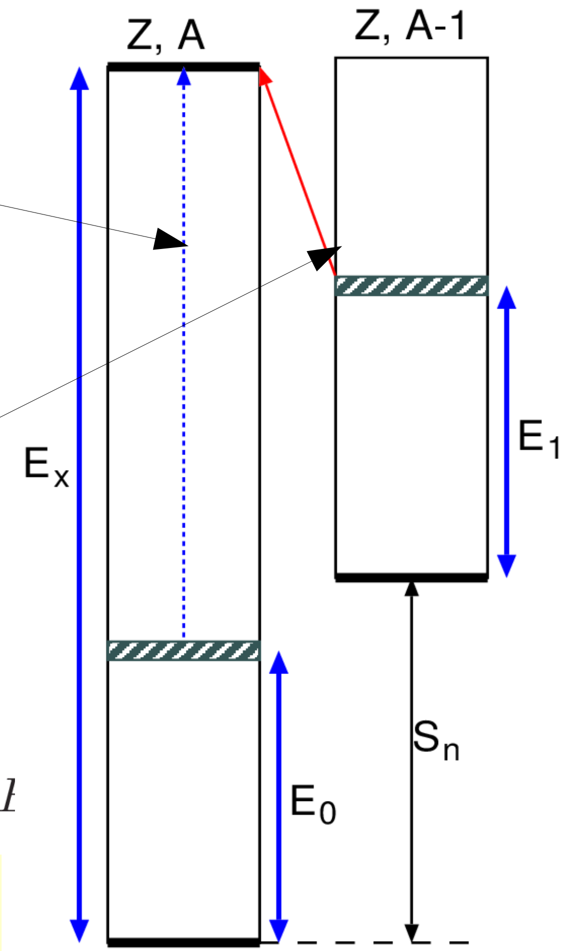
$$P(\epsilon_n)dE_1 = \frac{T_n(E_x - S_n - E_1)\rho(Z,A-1,E_1)}{N}dE_1$$

spherical optical model

- **normalization**

$$\begin{aligned} N &= \int_0^{E_x} T_\gamma(E_x - E_0)\rho(Z,A,E_0)dE_0 \\ &+ \int_0^{E_x - S_n} T_n(E_x - S_n - E_1)\rho(Z,A-1,E_1)dE_1 \end{aligned}$$

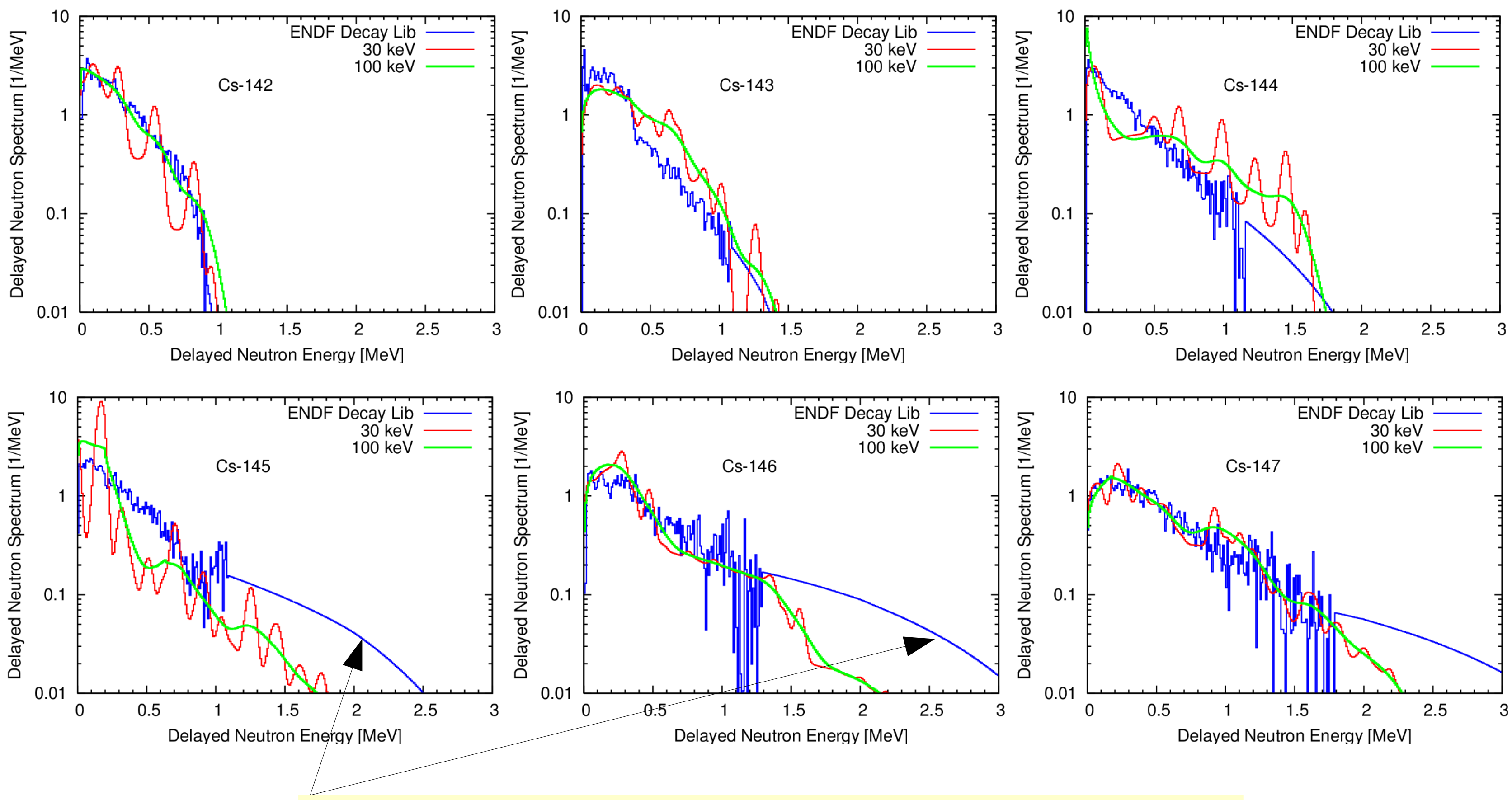
Integration performed only for spin and parity conserved states



Model Parameters in CGM

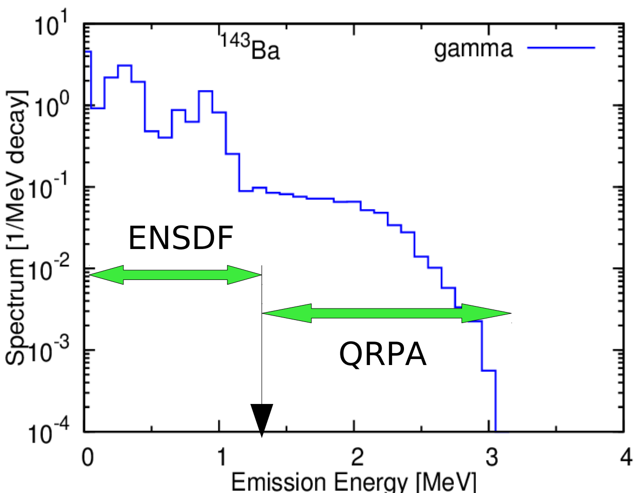
- **Optical potential**
  - Koning-Delaroche global optical potential parameter
  - CGM solves optical model internally to generate transmission coefficients for any compound nucleus
- **Level density**
  - Gilbert-Cameron-type composite formula (constant temperature and Fermi gas), with shell correction by Ignatyuk et al.
  - parameter systematics same as the Hauser-Feshbach code CoH3
- **Gamma-ray strength function**
  - GDR parameter systematic by RIPL-3
  - generalized Lorentzian model for E1
  - E1, M1, E2 included
- **Discrete levels**
  - RIPL-3 / ENSDF

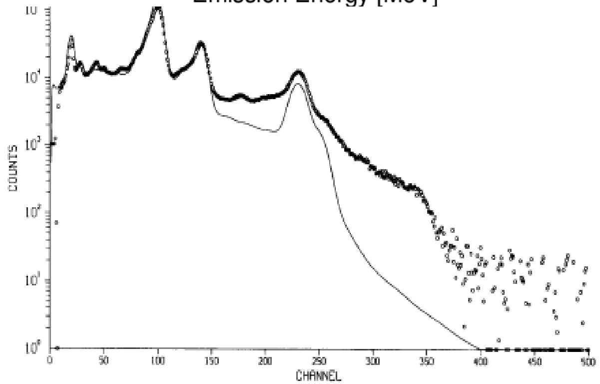
Calculated DN Energy Spectra from Cs Isotopes



simple evaporation is used to extrapolate the spectra in ENDF/B-VII.0 (ENDF/B-VI) decay data library

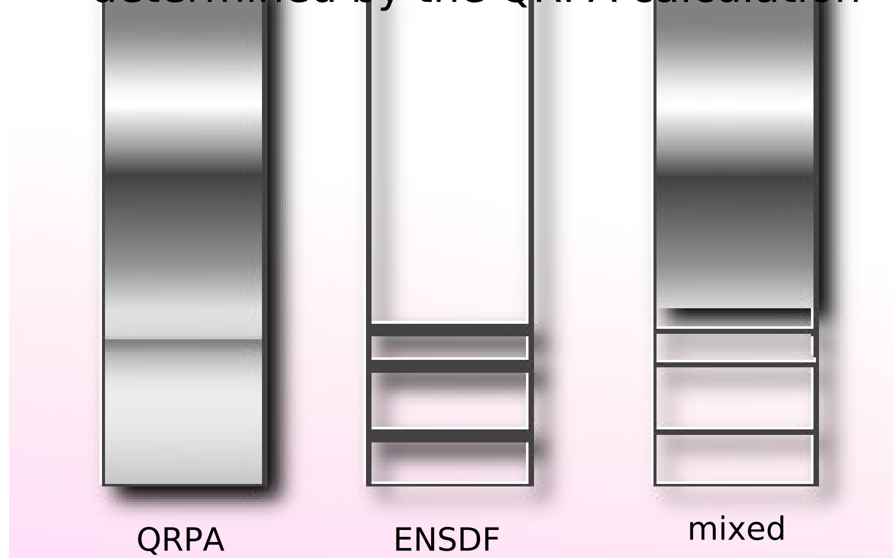
Determination of Discrete/Continuum Strength





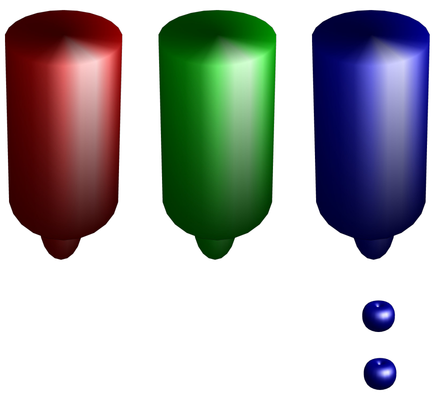
R.C. Greenwood, et al. NIM A390, 95 (1997)

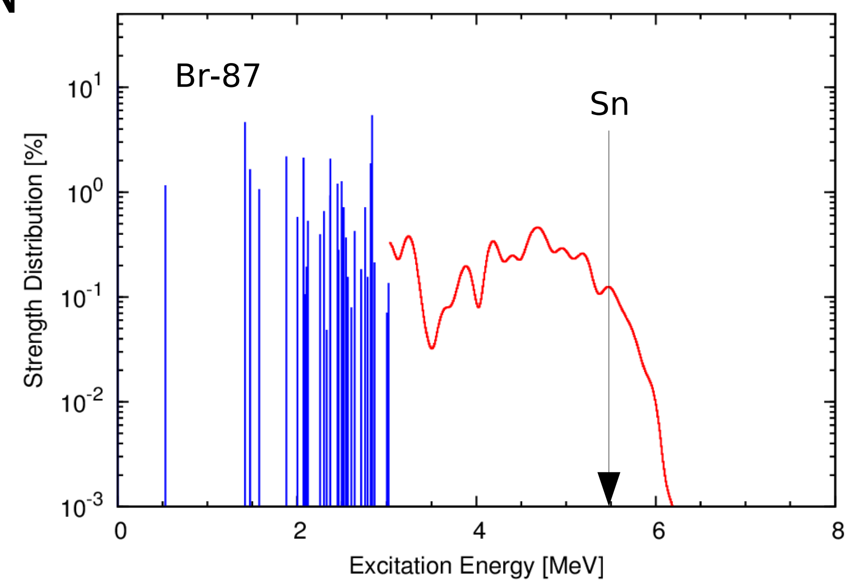
- **Ba-143 Beta Delayed Gamma Spectrum**
  - no delayed neutron case
  - calculated spectrum mainly from ENSDF discrete levels
  - however, those strengths are determined by the QRPA calculation



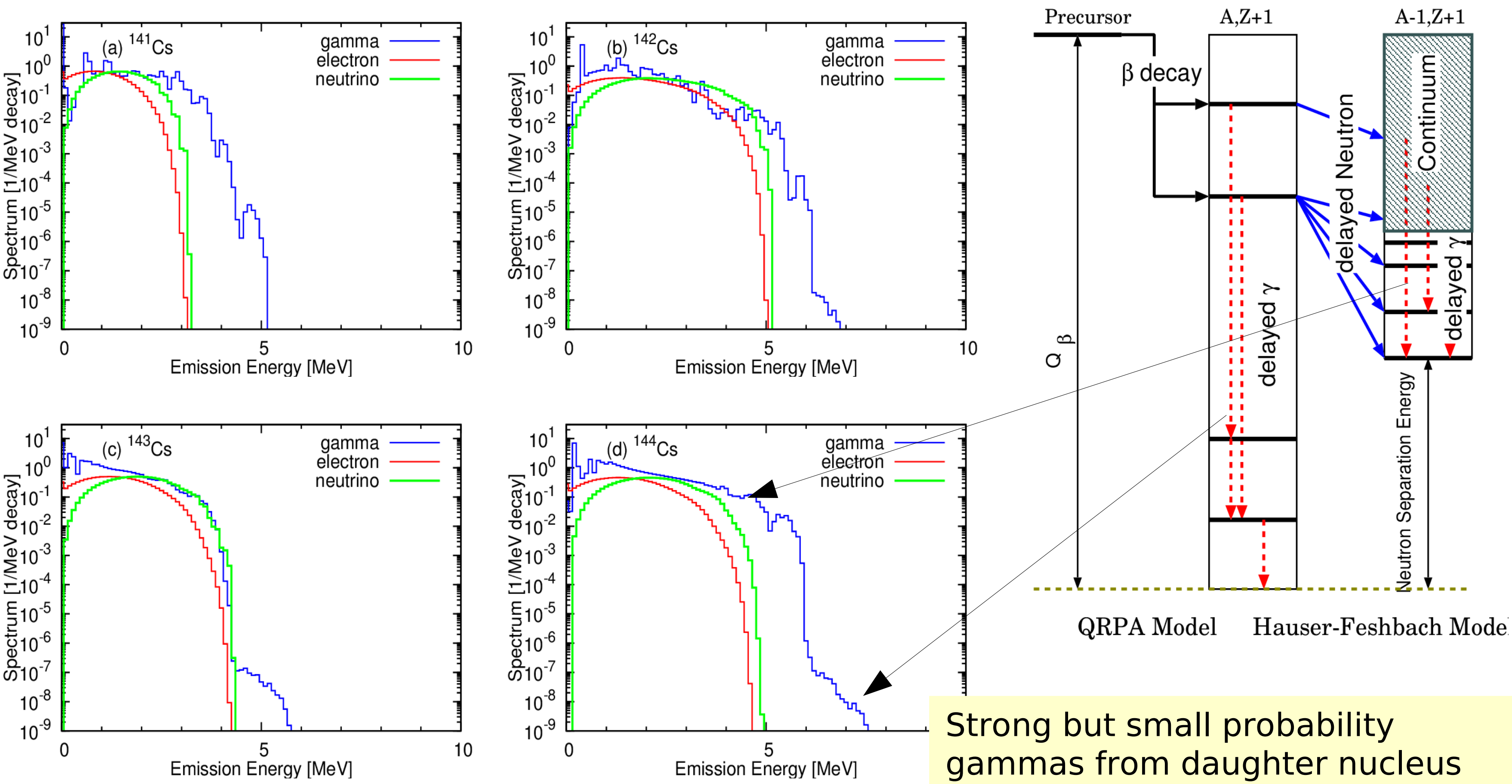
Mixing QRPA and ENSDF Strength Distributions

- **Broaden QRPA strength by 100-keV Gaussian**
- **When ENSDF is thought to be complete**
  - Use beta decay branching ratio data in ENSDF only
- **When ENSDF is not complete**
  - Mix ENSDF and QRPA calculation
  - Re-normalize ENSDF decay branching ratios using QRPA result
- **When no data are given in EN**
  - Use QRPA result only





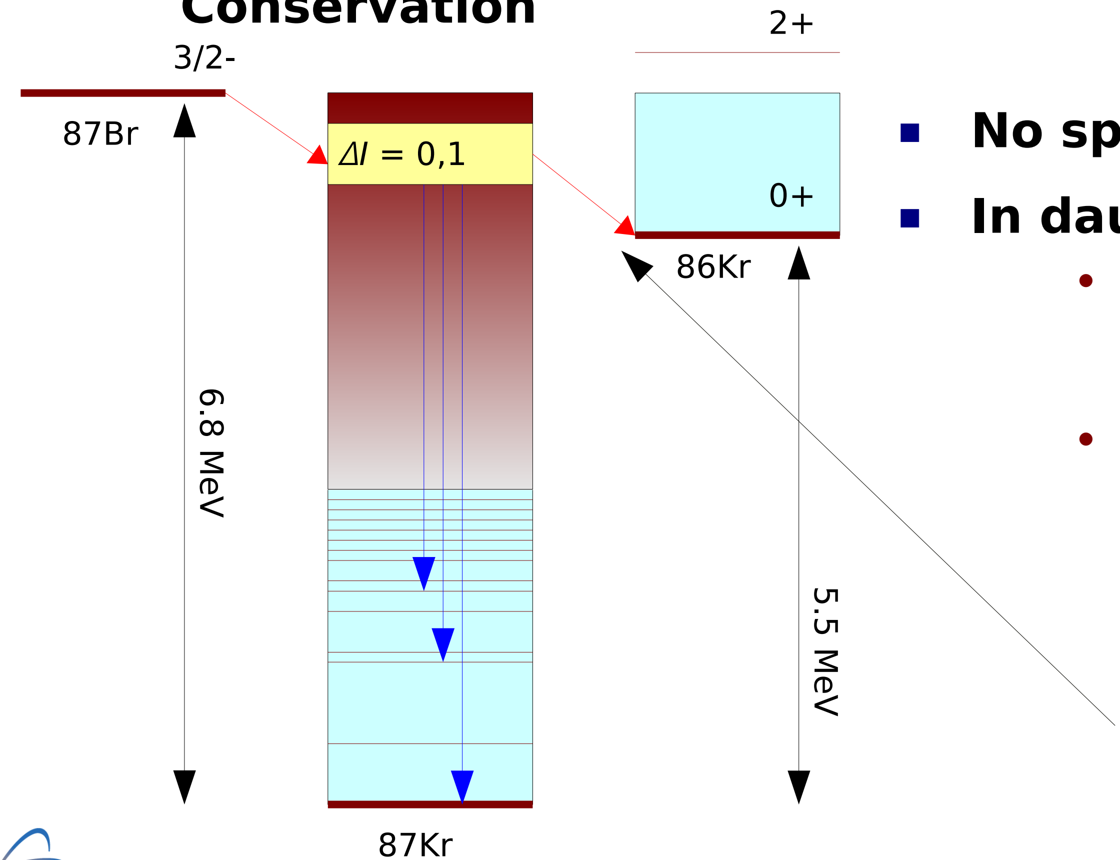
Beta-Delayed Gamma-Rays from Cs Isotopes



Strong but small probability gammas from daughter nucleus (neutron emission probability is large)

Spin Selection in CGM

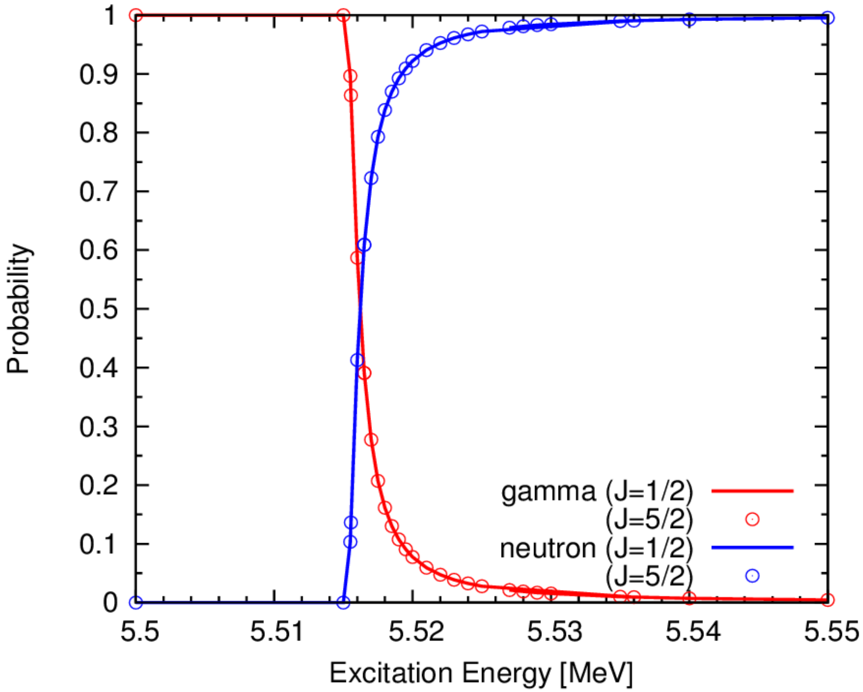
- **Neutron Emission Suppressed By Spin/Parity Conservation**



- **No spin prediction by QRPA**
- **In daughter nucleus**
  - 3 spin states in the continuum considered as the compound states
  - Hauser-Feshbach decay calculation to the grand-daughter nucleus, including spin/parity conservation

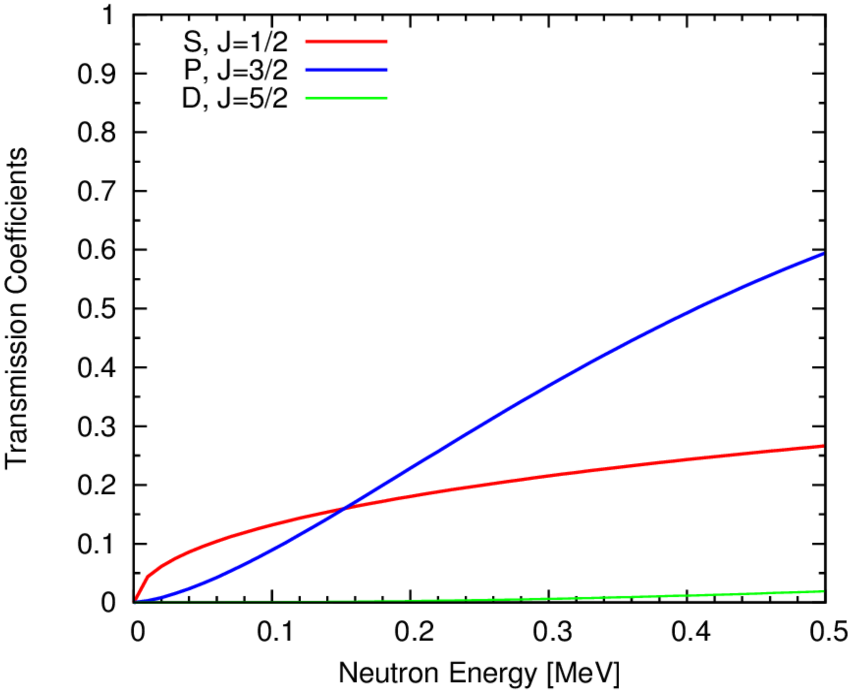
s-wave forbidden

Neutron and Gamma-Ray Competition

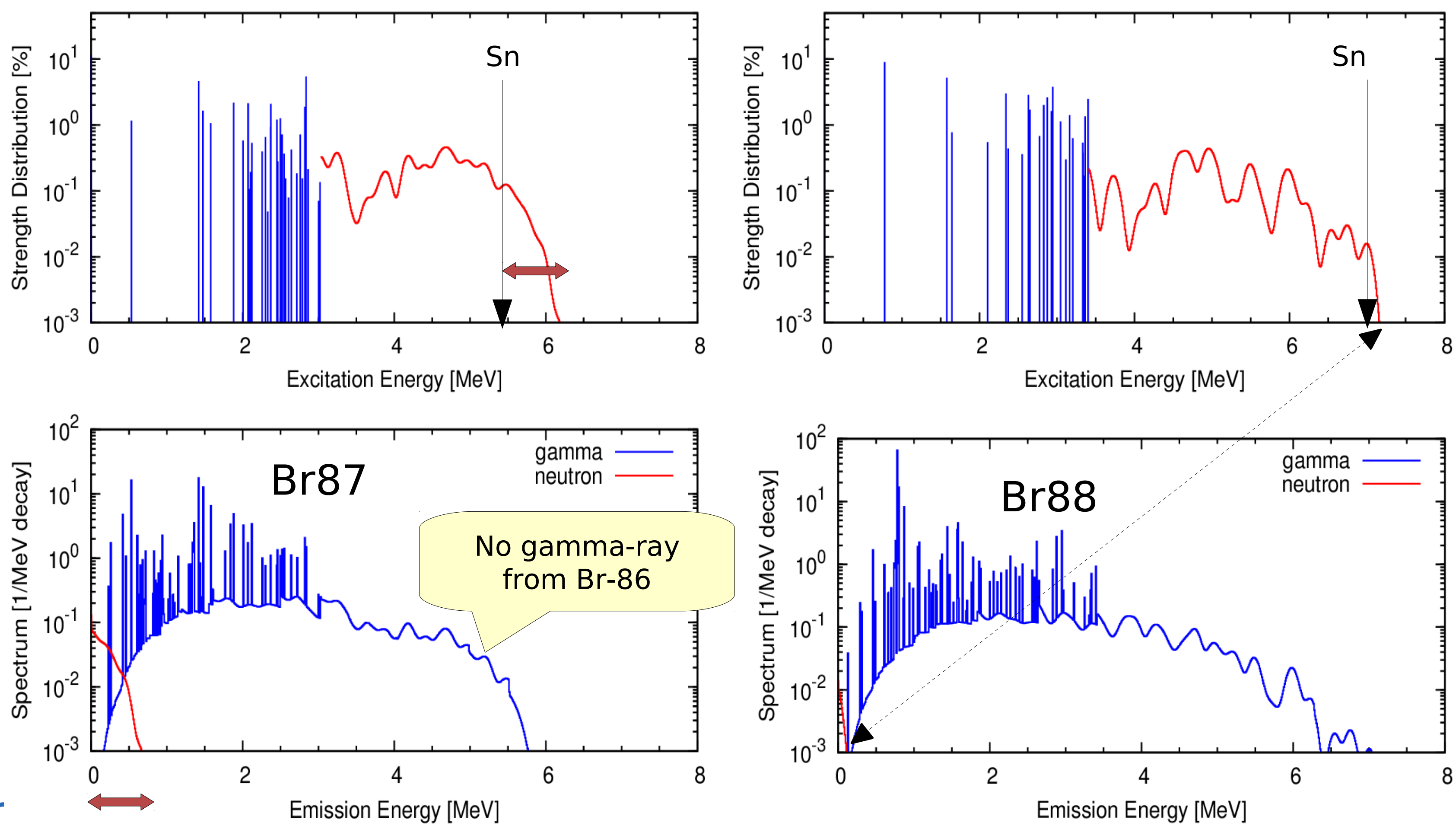


Emission Probability from
Excited Kr-87 Near Sn

Neutron transmission coefficients
for n+Kr86



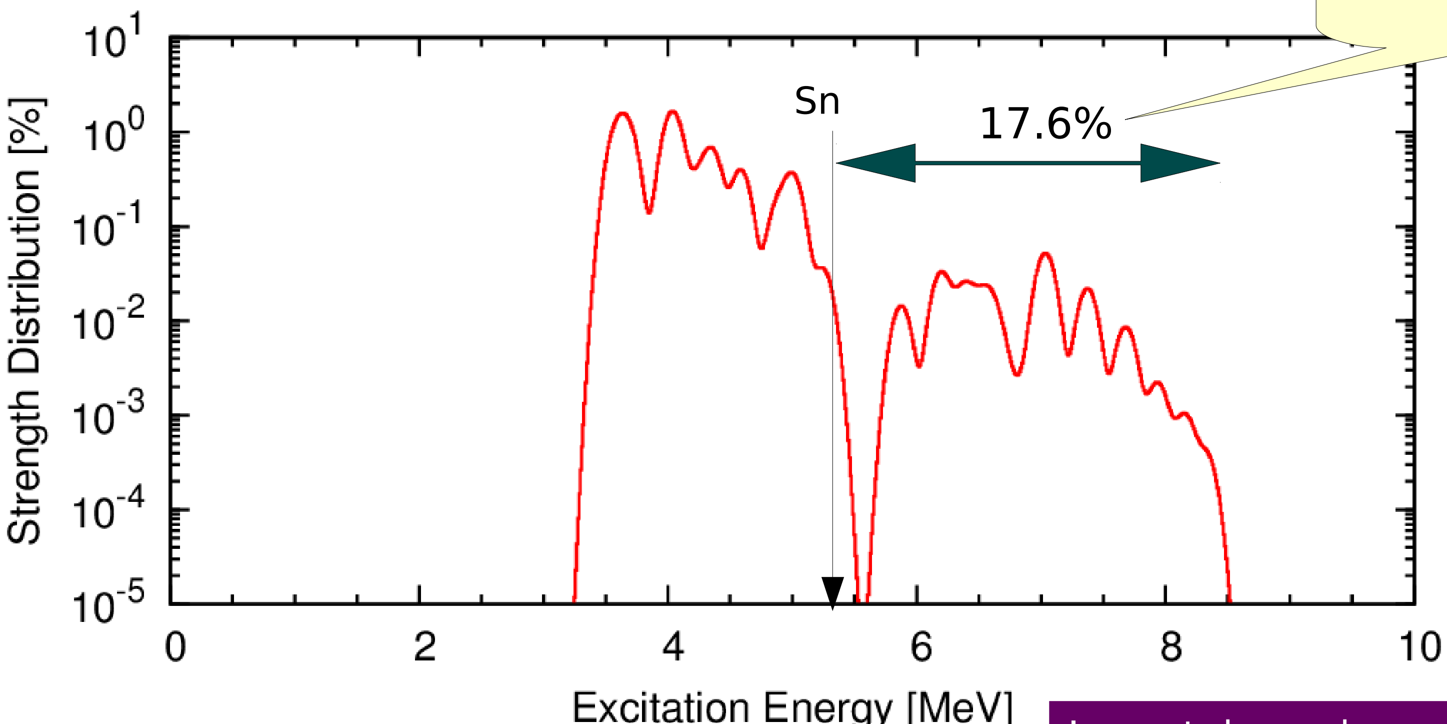
Br-87,88 Beta-Delayed Neutron and Gamma



Pn Changes When Gamma Channel Is Competing

- **Broadened Beta-Strength of As-85**

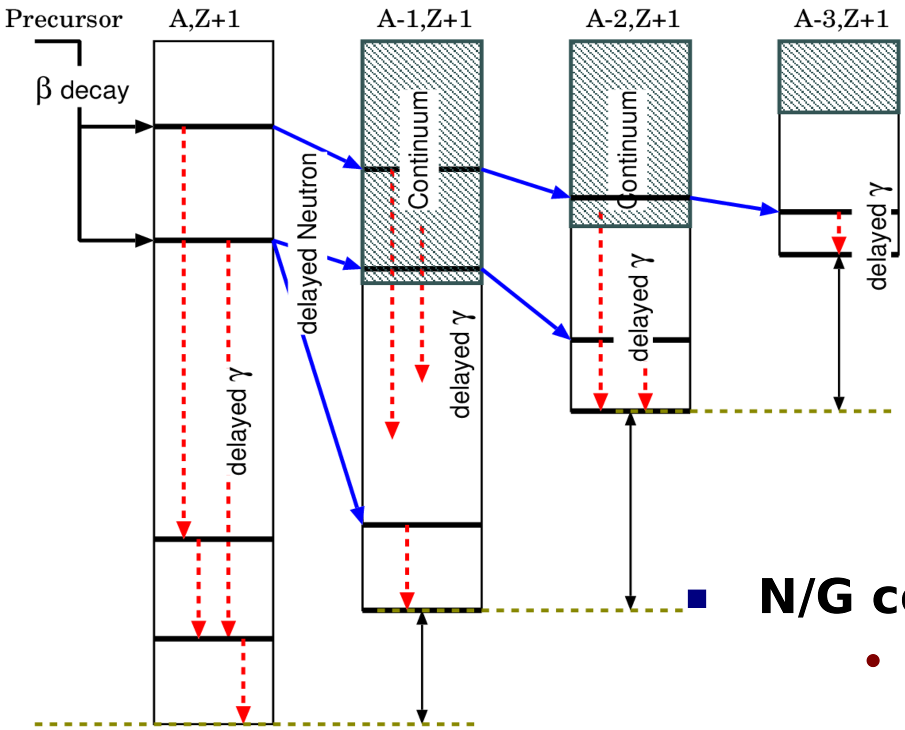
HF: 16.4%



Impact depends on
Q-value,
energy available for delayed neutron,
level structure in daughter nucleus

Multiple Neutron Emission

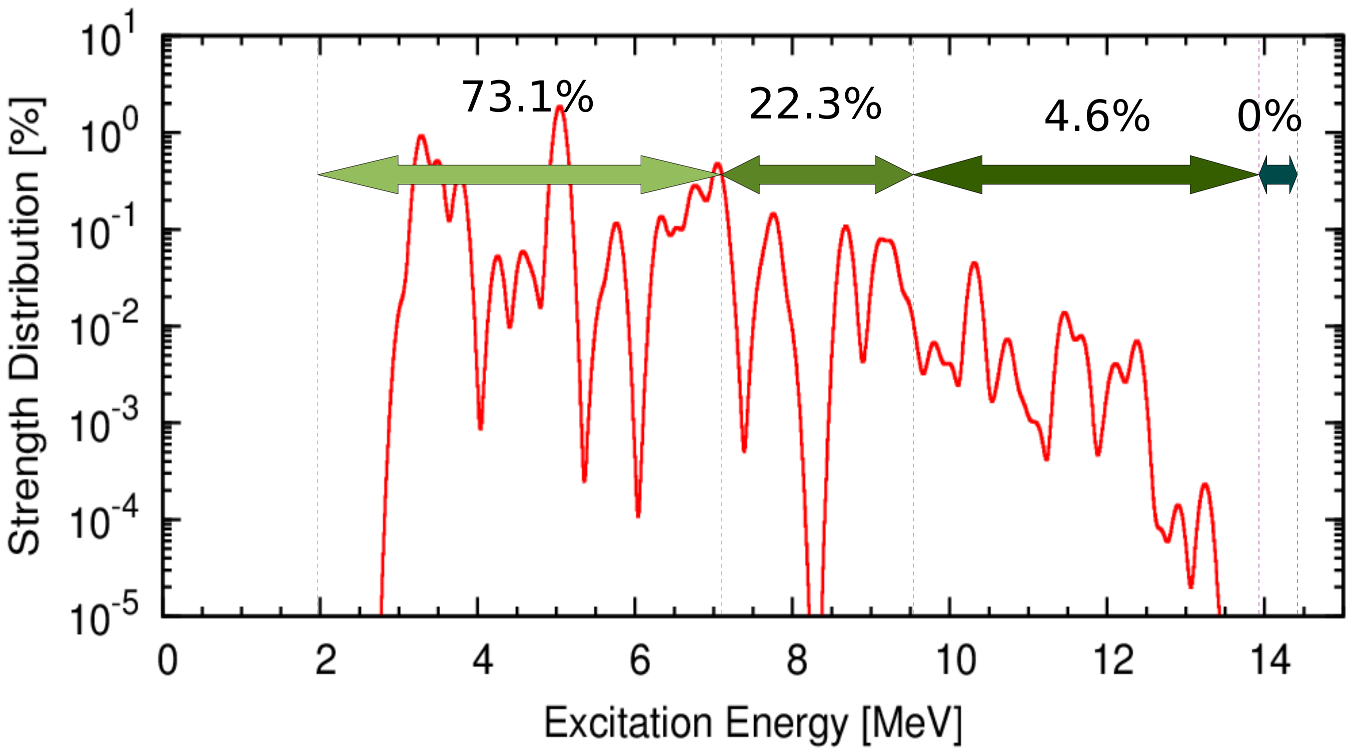
- Several neutrons can be emitted when Sn's are small



- **N/G competition at all the stages**
  - Pn's are given as the calculated neutron multiplicities from each daughter nucleus
  - very time consuming calculation

Calculated Pn, Including Neutron/Gamma Competition

- **As-93, Maximum Four Neutrons**

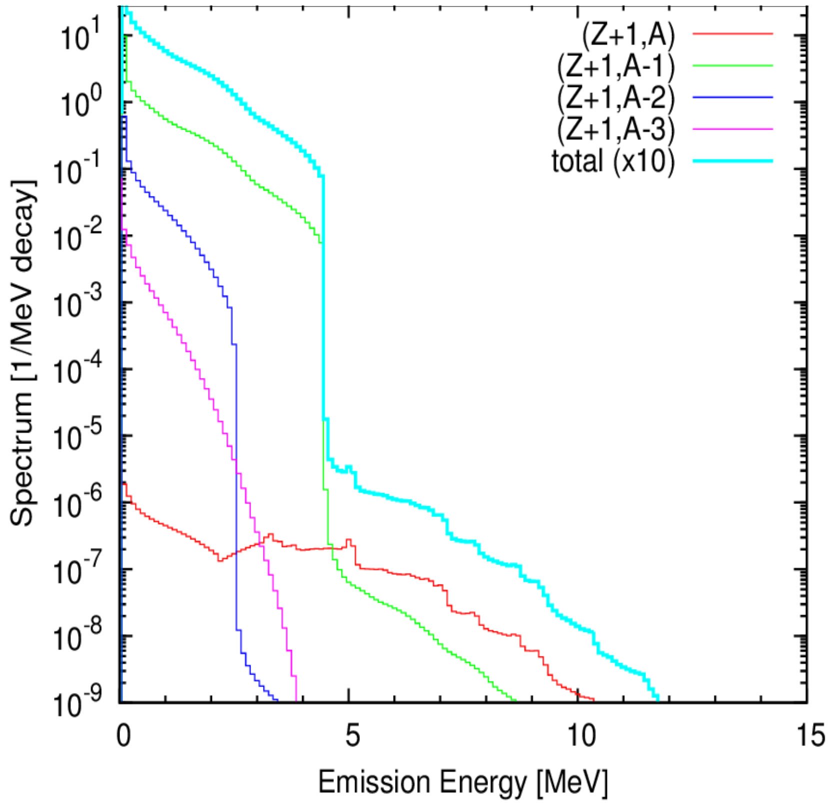


HF calc.

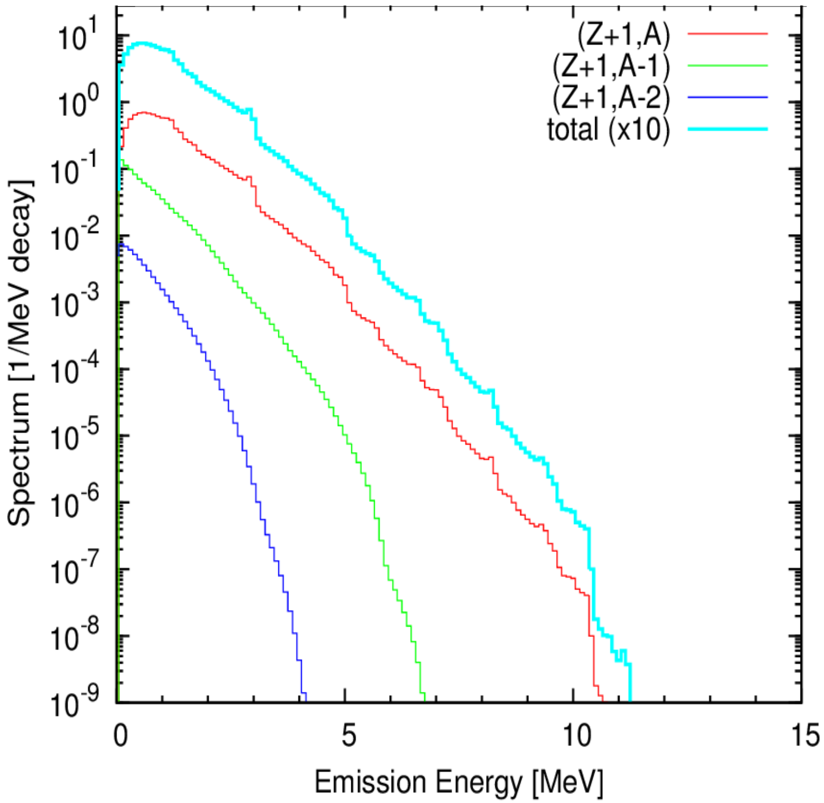
- 1n 93%
- 2n 8.5%
- 3n 0.5%
- 4n 0%

Calculated Spectra for Multi-Neutron Emission, As-93

gamma-ray



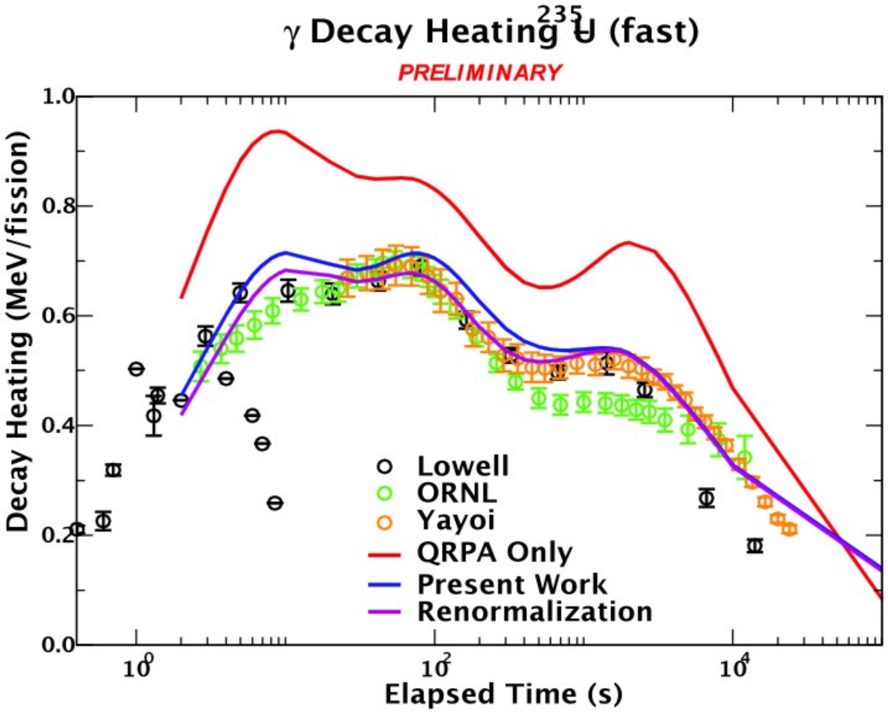
neutron



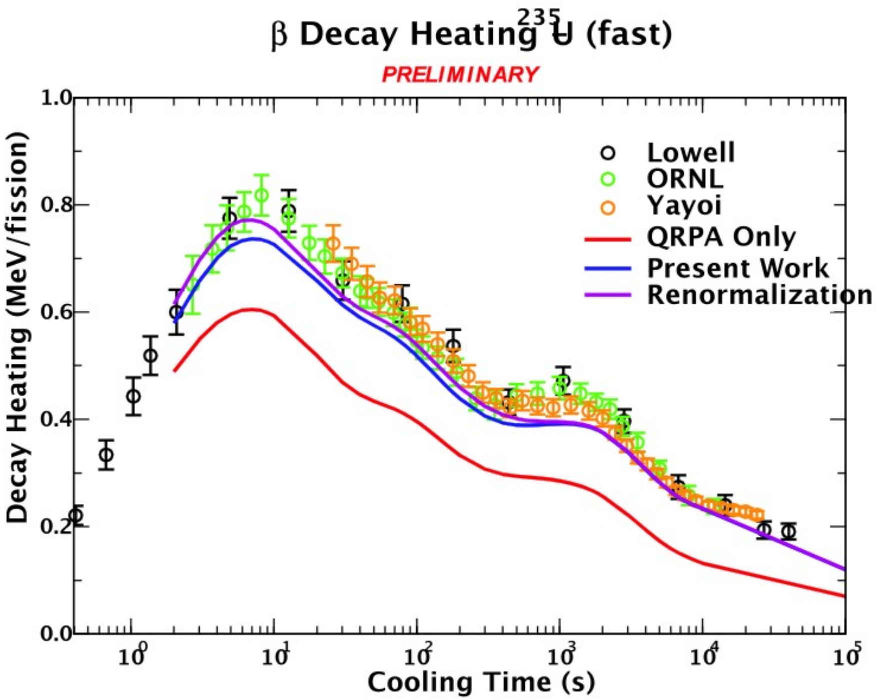
Calculated Decay Heating (example)

- **U-235**

S. Holloway, T.Kawano, P.Moller, at ND2011



Gamma Heating



Beta Heating

Discrepancies come from difficulties in predicting level energies with the QRPA method
We are looking at +/- 100keV differences above 8 MeV!

Concluding Remarks

- **More microscopic technique to calculate beta-delayed neutron and gamma-ray energy spectra**
    - the FRDM and QRPA models,
    - the statistical Hauser-Feshbach model for neutron and gamma-ray emission probabilities
    - ENSDF if available
- **Neutron spectra**
    - calculated spectra reasonably agree with those evaluated based on experimental data
- **Gamma-ray spectra**
    - exact neutron and gamma-ray competition included
    - consider all daughter nuclei after multiple neutron emission
    - pure QRPA calculation tends to over-predict gamma heating
- **Calculated spectrum data available through ENDF decay data library**