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

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Combining QRPA Calculation and Statistical Decay

- **Nuclear Structure**
  - Beta-decay rate
    - $Q_\beta$ 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

CGM

Operated by Los Alamos National Security, LLC for the U.S. Department of Energy’s NNSA
Hauser-Feshbach Emission Probability

- **gamma-ray emission**
  \[ P(\epsilon_\gamma)dE_0 = \frac{T_\gamma(E_x - E_0)\rho(Z, A, E_0)}{N} dE_0 \]

- **neutron emission**
  \[ P(\epsilon_n)dE_1 = \frac{T_n(E_x - S_n - E_1)\rho(Z, A - 1, E_1)}{N} dE_1 \]

- **normalization**
  \[ N = \int_0^{E_x} T_\gamma(E_x - E_0)\rho(Z, A, E_0)dE_0 \]
  \[ + \int_0^{E_x - S_n} T_n(E_x - S_n - E_1)\rho(Z, A - 1, E_1)dl \]

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

- 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 ENSDF**
  - Use QRPA result only

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**Sn**

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**Br-87**

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**Excitation Energy [MeV]**

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**Strength Distribution [%]**

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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 granddaughter nucleus, including spin/parity conservation

- **87Br**
  - $\Delta I = 0, 1$

- **87Kr**
  - 6.8 MeV

- **86Kr**
  - 5.5 MeV

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

Br87

No gamma-ray from Br-86

Br88
Pn Changes When Gamma Channel Is Competing

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

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

HF: 16.4%
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

Spectrum [1/MeV decay]

Emission Energy [MeV]

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Calculated Decay Heating (example)

- **U-235**

**Gamma 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