Use of MT=900+ for primary gamma two-body channels, MT=102 being derived from these for backward compatibility

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Dave Brown, Ian J Thompson, Bret Beck

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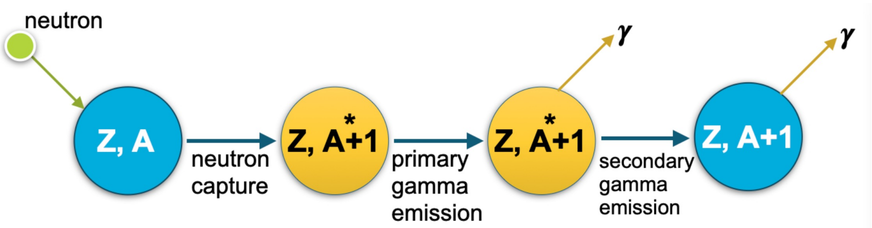
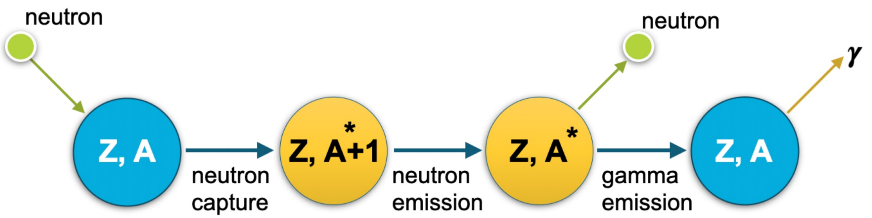
Primary capture gammas vs. secondary gammas

- *Primary* gammas: Each primary gamma can be its own two-body reaction (z,g) with the residual being left in the excitation state for that primary gamma
  - Primary gammas have energy that rises with incident projectile energy
- *Secondary gammas:* The residual is then decayed using transition probabilities to produce the correlated *secondary* (discrete) gammas on an event-by-event bases
  - e.g, n + O16 -> primary gamma + (O17_e3 -> O17 + transition gammas)
  - Secondary gammas have energies that are fixed, independent of projectile energy.

Thermal neutron capture gammas



Inelastic reaction gammas



Formats to specify primary capture gammas

- The ENDF format currently does not allow for correlated primary/secondary gammas.

- MT=102 format is complicated as it must describe both primary and secondary gammas.
  - MF=6 way: List separately primary, secondary, continuum gamma multiplicities, energies and angular distributions

  - MF=12/13/14 way:
    - MF=12: List separately primary, secondary, continuum gamma multiplicities & energies
    - MF=14: List angular distributions

- MF=12 has gamma cascade BR matrix. Can be used for discrete level excitations (=2-body processes) to model a proper gamma cascade, just not for MT=102 since is not a 2-body process

Current ENDF/B-VIII.0 with primary γ channels

n-001_H_002.endf:	1 primary - only explicit two-body primary.
n-003_Li_006.endf:	2 primaries
n-003_Li_007.endf:	2
n-005_B_010.endf:	6
n-005_B_011.endf:	6
n-006_C_012.endf:	2
n-007_N_014.endf:	11 (rather old)
n-014_Si_029.endf:	23
n-014_Si_030.endf:	8
n-017_Cl_035.endf:	69
n-017_Cl_037.endf:	22

GRIN ENDF/B-VIII.1 candidates:
- C13: 4 primaries
- O16: 2
- F19: 29
- Si28: 13

All of these are candidates for conversion to MT=900-999.

Evaluations in red can be converted unambiguously

More will be added from GRIN project.

Much better to use in R-matrix fits rather than Reich-Moore sums

Proposal: MT=900-999 for primary capture gammas

- Use new MT numbers 900-999 to describe all primary gammas:
  - MT=102 becomes a summed-cross-section channel like 4, 103-107.
  - Can be reconstructed from 900-999 if present
- New MT Definitions for ENDF6 manual Appendix B:
  - MT=900: Production of a primary-γ particle leaving the residual nucleus in the ground state
  - MT=901-998 Production of a primary-γ particle, with residual in 1st to 98th excited state
  - MT=999: Production of a primary-γ particle in the continuum not included in the above discrete representation. Formatted like previous MT=102
  - MT=102: Radiative capture: production of one or more gammas (photons) plus a residual. Redundant: sum of MT=900-999, if they are present.
- For backward compatibility:
  - In a PREPRO-like step before processing with older codes, make another file version by Reconstructing MT=102 with distributions (averaged of necessary) and delete MT 900s. (See code MT900s2MT102.py later).

Consequences for Gamma Data

If using new MT numbers, then

- The secondary decay gammas must be specified either:
  1. **by transition probability arrays with MF=12 data (preferred),** or
  2. separately for each of discrete MT channels (900-998), or
  3. in a discrete or continuum distribution for MT channels 999 (like 102).

- All the primary gammas MT=900-998 are 2-body channels.
  - Can use MT=999 :
    - for channels not covered by MT 900 to 998 [MT 91 for MT 50 to 90 for (n,n')]
    - if primary channels not known for a gamma
    - If data only gives continuum distribution of gamma production

- MT=102 can now be derived from the new channels if present

- If 900-999 not present, just put inclusive data & distributions in MT=102 as now.

Consequences for Gamma Data

If using new MT numbers, then

- The secondary decay gammas must be specified either:
  1. **by transition probability arrays with MF=12 data (preferred),** or
  2. separately for each of discrete MT channels (900-998), or
  3. in a discrete or continuum distribution for MT channels 999 (like 102).

- All the primary gammas MT=90
  - Can use MT=999 :
    - for channels not covered by MT 900
    - if primary channels not known for a
    - If data only gives continuum distribu

Trickiness alert! Post-primary emission secondaries are NOT included in multiplicities or distributions here! When reconstructing MT=102, you have additional homework!

- MT=102 can now be derived from the new channels if present

- If 900-999 not present, just put inclusive data & distributions in MT=102 as now.

Code assistance

We give a FUDGE translation code gnds-capture.py

that converts MT=102 to MT=900-998, 999 primary and secondary data
Works well so far for ENDF/B-VIII.0 and VIII.1 versions of
neutrons on Li6, Li7, B10, C12.

And a FUDGE code MT900s2MT102.py to reconstruct MT=102 from 900-999 & delete these, for backward compatibility.

Like a PREPRO module making a intermediate version

Published ENDF evaluations should not have distributions with both MT=102 and 900-999, to avoid any double counting.

That is, define like MT=103 – 107 for charged particles

Remaining actions

- Modify ENDF-102 to explain summation rules for
  - Cross sections (normal)
  - Production cross sections (less normal)
  - Multiplicities (tricky)
  - Outgoing energy-angle distributions (tricky)

- These sum rules already coded in the Python scripts

Conclusion

- Proposal for explicit description of primary capture gammas from two-body reaction channels
  - No change needed for GNDS 2.0 (only for ENDF6 format)
  - Need relativistic kinematics or at least distinct treatment of photons.
- Resonance parameters should be specified for each channel: for each MT 900 to 998 as needed.
  - No longer for Reich-Moore 'absorption' to give summed capture gammas
- Codes (processing and transport) need to be updated to handle these MTs.
  - Demonstration files available for n + H2, Li6, Li7, B10, C12, C13, O16
- If gamma-then-particle emission, particle resonance width has to be assumed zero (discrete) if MT=900-998. MT=999 is ok.
  - For example the He5 resonance in d + t → gamma + (He5 → He4 + n)