A new Photon Evaporation model for Geant4

E. Mendoza, D. Cano-Ott
CIEMAT – Madrid, Spain

D. Jordan, J.L. Taín, A. Algora
IFIC – Valencia, Spain
Motivation

Geant4 allows to use the information available in ENDF-6 format data libraries for the transport of low energy neutrons (up to 20 MeV), using the G4ParticleHP package.

In general (not always) the photon production is given in the ENDF-6 files as a list of γ-ray yields $y_k(En)$, with $k = 1, 2, ..., nk$. A continuous distribution can be provided as well.
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With this information:

- total energy of the emitted γ-ray cascade
- average multiplicity
- γ-ray energy spectra
- energy conservation in each reaction
- γ-ray coincidences

Exceptions: (n,n’) reactions → fast neutron detectors
ENDF-6 data cannot be used to simulate the response function of a detector due to (n,γ) reactions.
**Motivation**

$^{27}\text{Al}(n_{th},\gamma)$

$S_n(^{28}\text{Al})=7.7 \text{ MeV}$
Motivation

Alternative in Geant4 for (n,γ) reactions → G4PhotonEvaporation model, which is used:

1- If no data, i.e. no γ-rays after capture in the ENDF-6 data file
2- If G4NEUTRONHP_USE_ONLY_PHOTONEVAPORATION environmental flag defined.

The G4PhotonEvaporation model generates the cascade from the capture level using statistical models.

Our new Photon Evaporation model does the same, but with more detail.

This model operates in a similar way as DICEBOX [F. Bečvář, NIMA 417, 434 (1998)] or DECAYGEN [J.L. Taín and D. Cano-Ott, NIMA 571, 719 (2007)], but:

1- This code is able to generate automatically cascades for a large variety of nuclei (at least 100-200) without requiring a specific input for each particular isotope
2- It has been written in C++, and it can be inserted into Geant4.
Motivation

Purpose of the model: cross section measurements + study of \((n,\gamma)\) cascades + simulation of detector responses.

\[^{241}\text{Am}(n,\gamma)\) cascades\]
Motivation

An example: the NaI(Tl) DTAS detector → \textit{V. Guadilla et al. NIMA 910, 79 (2018)}
The code

What is needed:
- Levels
- Branching ratios
- Internal conversion coefficients

What the code does is to create the full level scheme + branching ratios + internal conversion coefficients, from:

- **Experimental information:** RIPL-3 + ENSDF → G4-PhotonEvaporation library.

- **Missing information:** Statistical models: level density formulas, photon strength functions (parameters from RIPL-3), BrICC …
The code

Level scheme:
- RIPL-3 contain levels from ENSDF with unambiguous spin and parity.
- Information concerning up to which energy the level scheme is complete.
- The rest of the levels are generated from level density formulas (Back-Shifted Fermi Gas, Gilbert-Cameron) with parameters from RIPL-3.

Branching ratios:
- Known branching ratios from RIPL-3
- Rest of the branching ratios generated according to:
  \[ BR_{a \rightarrow b} \propto \varphi \cdot (E_a - E_b)^{2L+1} \cdot PSF^X_L(E_a - E_b) \]
- PSF from RIPL

Internal conversion:
- Known ICC from RIPL-3
- Rest of the ICC from BrICC

\[ n + ^A X \rightarrow ^{A+1} X \]
The code

Own database

RIPL-3
https://www-nds.iaea.org/RIPL-3/

Models (RIPL-3)

$n + ^AX \rightarrow ^{A+1}X$

$S_n+E_n$
The code

Some characteristics of the model:

- Since levels and BR are generated *randomly* → different *realizations* of the same nucleus.

- Number of levels and BR can be very high. For actinides \( \sim 10^6 \) levels, i.e. \( \sim 10^{12} \) BR → binning is allowed.
Examples

thermal neutrons

CsI 10x10 cm

Incident neutron data / ENDF/B-VII.1
// MT=102 : (z,y) / Cross section

Cross-section (b)

Counts/(neutron·MeV)

Incident energy (MeV)

Energy (MeV)

ČsI - detector response

ParticleHP
PhotonEvaporation
NewCascadeGenerator

$S_n(^{134}\text{Cs})=6.9$ MeV
$S_n(^{128}\text{I})=6.8$ MeV

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Examples

thermal neutrons

Csl 10x10 cm

Incident neutron data / ENDF/B-VII.1
MT=102: (z,γ) / Cross section

Counts/(neutron·MeV)

133Cs

127I

Energy (MeV)

Cross-section (b)

Incident energy (MeV)
Examples

Note: no photon data in LaBr$_3$ and CeBr$_3$ in G4NDL4.5 $\rightarrow$ G4ParticleHP same as G4PhotonEvaporation.
To check γ-ray intensities from (thermal) neutron capture:

CapGam: https://www.nndc.bnl.gov/capgam/

IAEA-Database for Prompt Gamma-ray Neutron Activation Analysis: https://www-nds.iaea.org/pgaa/
$^{23}\text{Na}(n_{\text{th}},\gamma) - \langle E_{\gamma,\text{tot}}\rangle_{\text{CG}} = 7.08\text{ MeV} - S_n = 6.96\text{ MeV}$

- New PhotonEvaporation
- CapGam

$^{23}\text{Na} -$ Total $\gamma$-ray energy

- G4ParticleHP
- NewPhotonEvaporation
- G4PhotonEvaporation

CG Intensity $\sim 100\%$
$^{27}\text{Al}(n,^\gamma) - \langle E_{\gamma,\text{total}} \rangle_{CG} = 7.50 \text{ MeV} - S_n = 7.73 \text{ MeV}$

- **New PhotonEvaporation**
- **CapGam**

CG Intensity $\sim 100\%$

$^{27}\text{Al}(n,\gamma) - \langle E_{\gamma,\text{total}} \rangle_{CG} = 7.50 \text{ MeV} - S_n = 7.73 \text{ MeV}$

- **G4ParticleHP**
- **CapGam**

$^{27}\text{Al}$

$^{27}\text{Al}(n,\gamma) - \text{Total } \gamma\text{-ray energy}$

- **G4ParticleHP**
- **NewPhotonEvaporation**
- **G4PhotonEvaporation**

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$^{35}\text{Cl}(n,\gamma) - \langle E_{\gamma,\text{tot}} \rangle_{\text{CG}} = 8.62 \text{ MeV} - S_n = 8.58 \text{ MeV}$

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Summary and conclusions

• We have developed a code which is able to generate EM de-excitation cascades by creating full level schemes + BR of a large variety of nuclei.

• The code takes data mainly from RIPL-3: known levels and BR + statistical models.

• Purpose: cross section measurements + study of (n,γ) cascades + simulation of detector responses \( \rightarrow \) neutron capture cascades.

• The code has been written in C++ and can be inserted into Geant4.

• Still work to be done.

• The idea is not to replace the present G4PhotonEvaporation model (time consumption, memory …). It can be used for some specific applications.