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

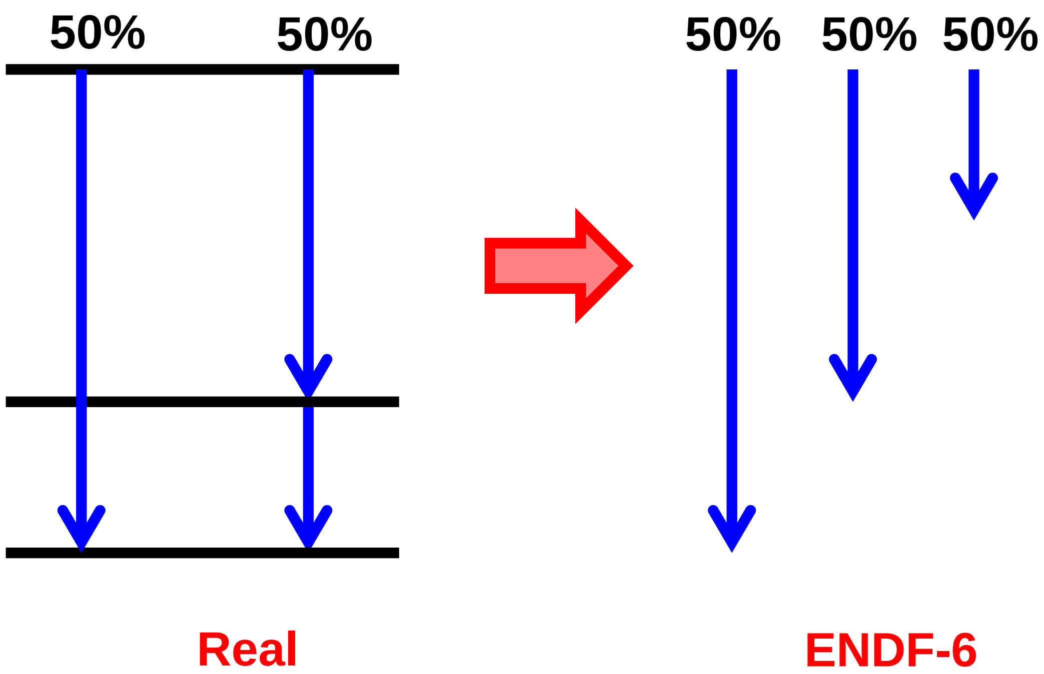
GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

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.



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.

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With this information:

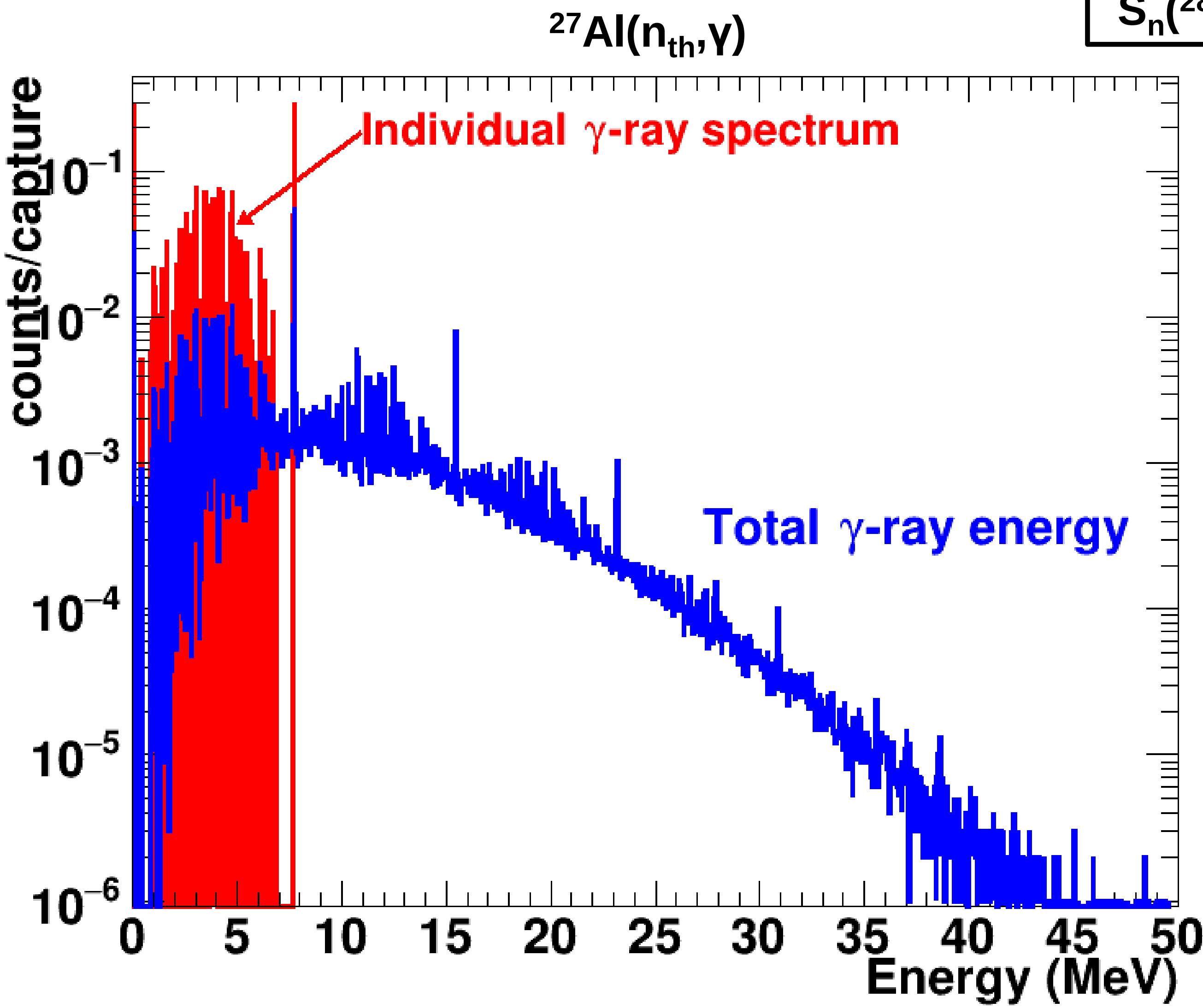
- ✓ total energy of the emitted γ-ray cascade
- ✓ average multiplicity
- ✓ γ-ray energy spectra
- ✘ energy conservation in each reaction
- ✘ γ-ray coincidences

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

$S_n(^{28}Al)=7.7$ 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*.

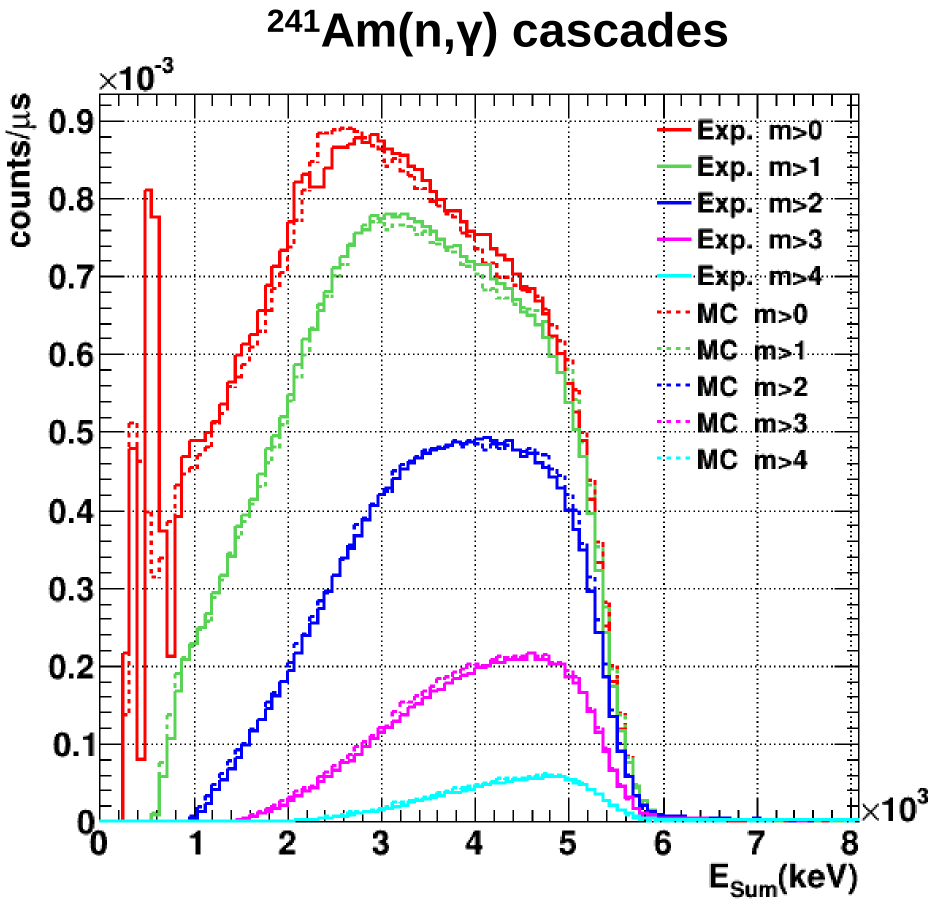
This model operates in a similar way as **DICEBOX** [*F.Bečvář, NIMA 417, 434 (1998)*] or **DECAYGEN** [*J.L. Taín and D. Cano-Ott, NIMA 571, 719 (2007)*], but:

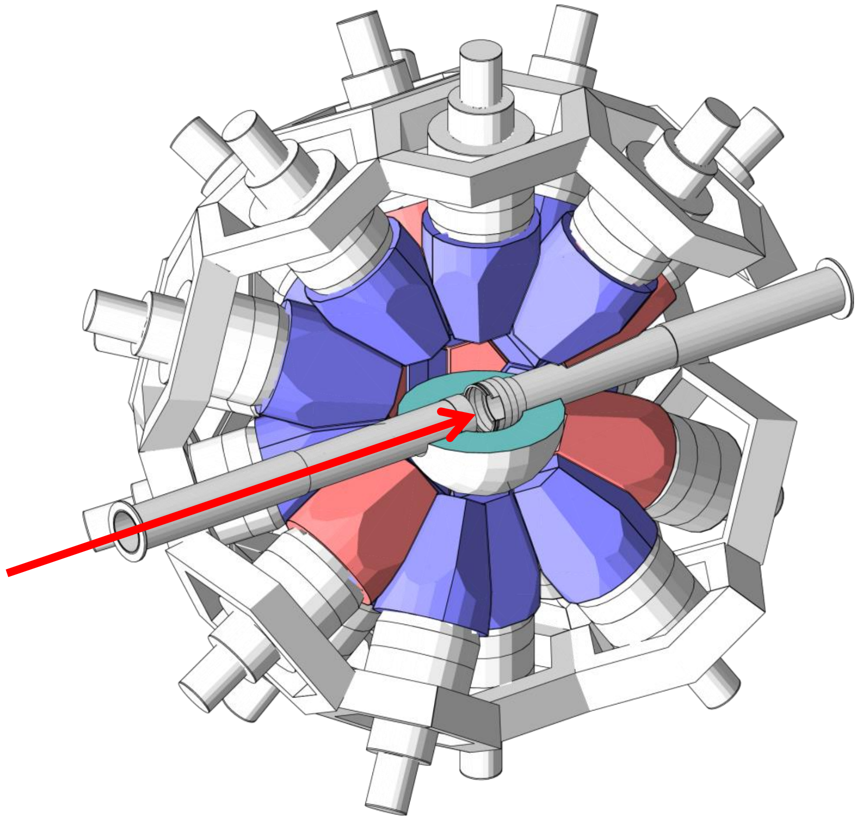
1- This code is able to generate automatically cascades for a large variety of nuclei (at least 100-200) without requiring a specific input for each particular isotope

2- It has been written in C++, and it can be be inserted into Geant4.

Motivation

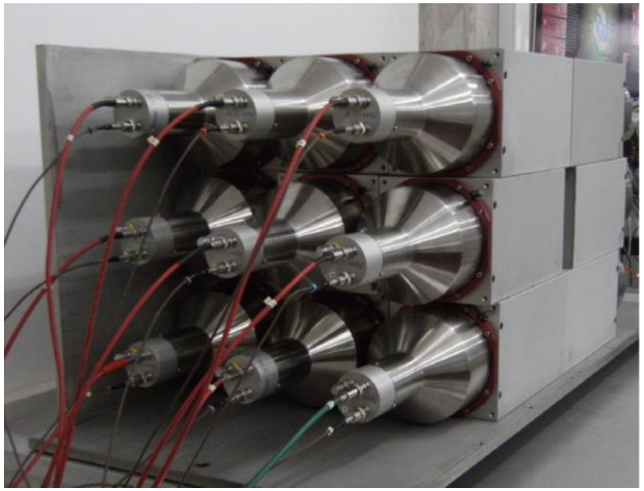
Purpose of the model: cross section measurements + study of (n,γ) cascades + **simulation of detector responses.**

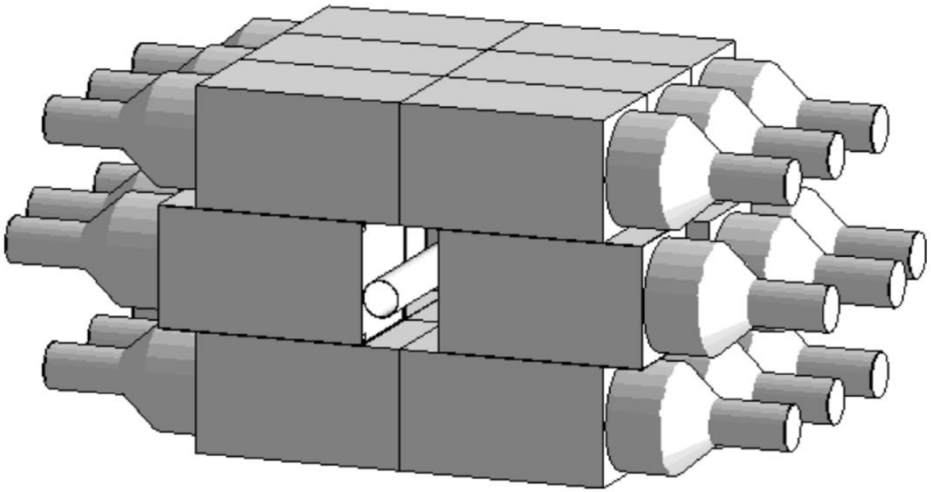


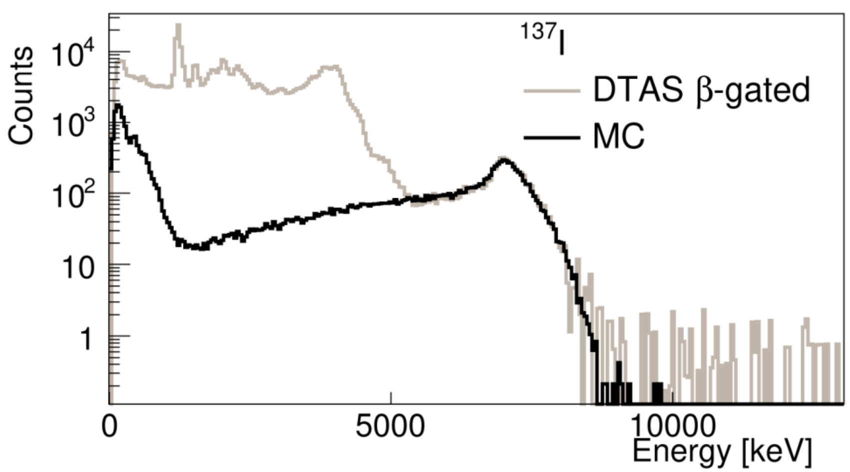


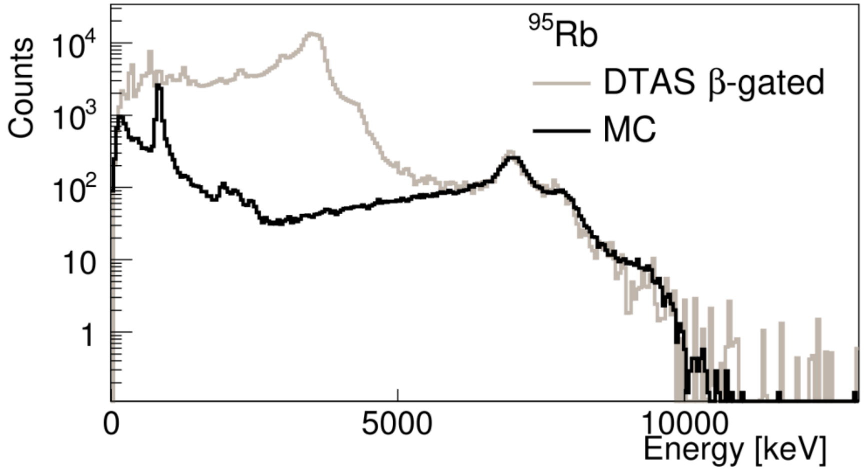
Motivation

An example: the NaI(Tl) DTAS detector → *V. Guadilla et al. NIMA 910, 79 (2018)*









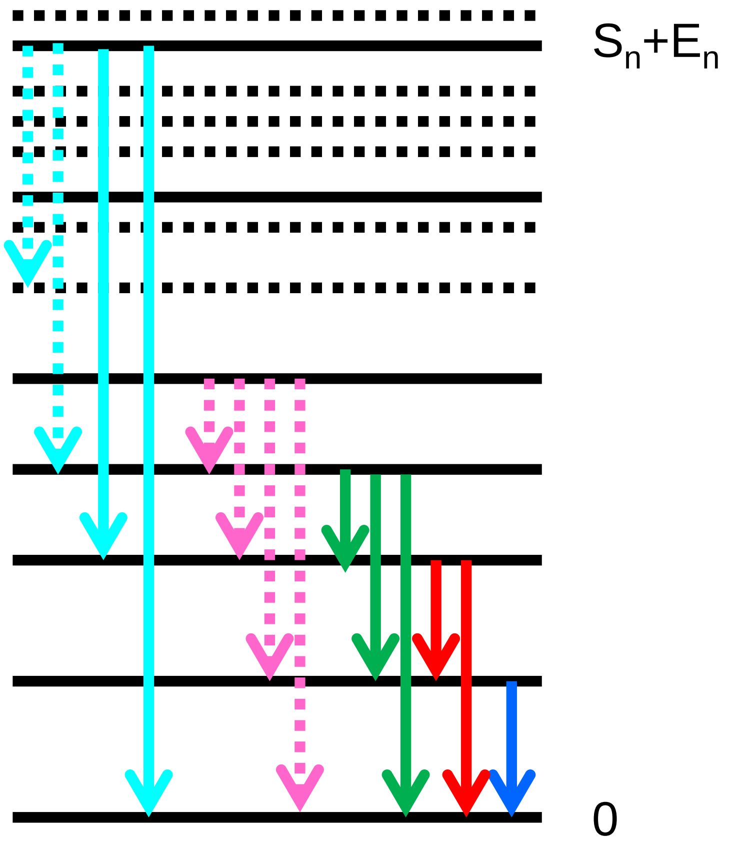
The code

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 …

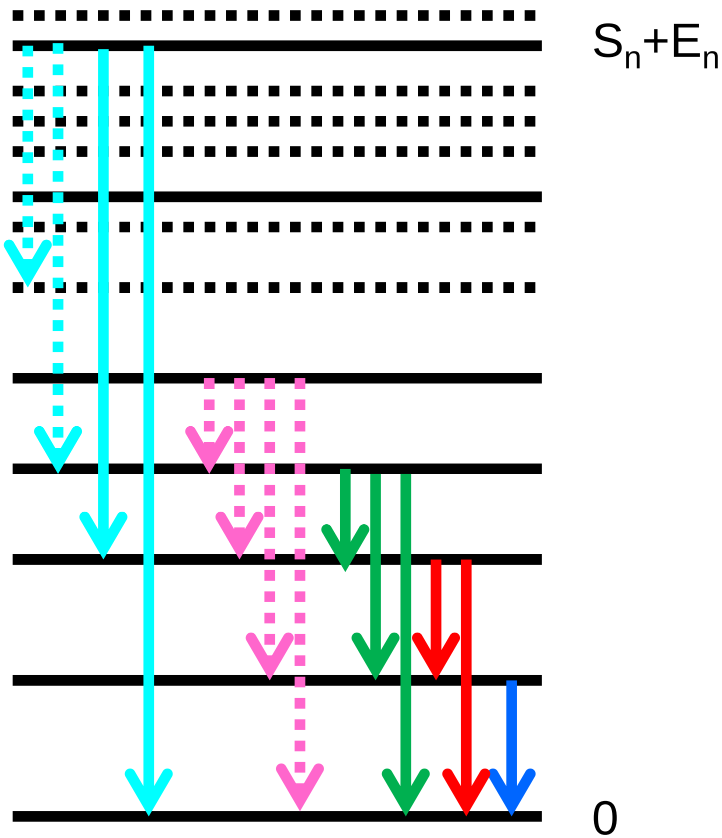


$n + {}^{A}X \rightarrow {}^{A+1}X$

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.



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

Branching ratios:

- Known branching ratios from RIPL-3
- Rest of the branching ratios generated according to:

$$BR_{a\to b} \propto \varphi \cdot (E_a - E_b)^{2L+1} \cdot PSF^{XL}(E_a - E_b)$$

- PSF from RIPL

Internal convesion:

- Known ICC from RIPL-3
- Rest of the ICC from BrICC

The code

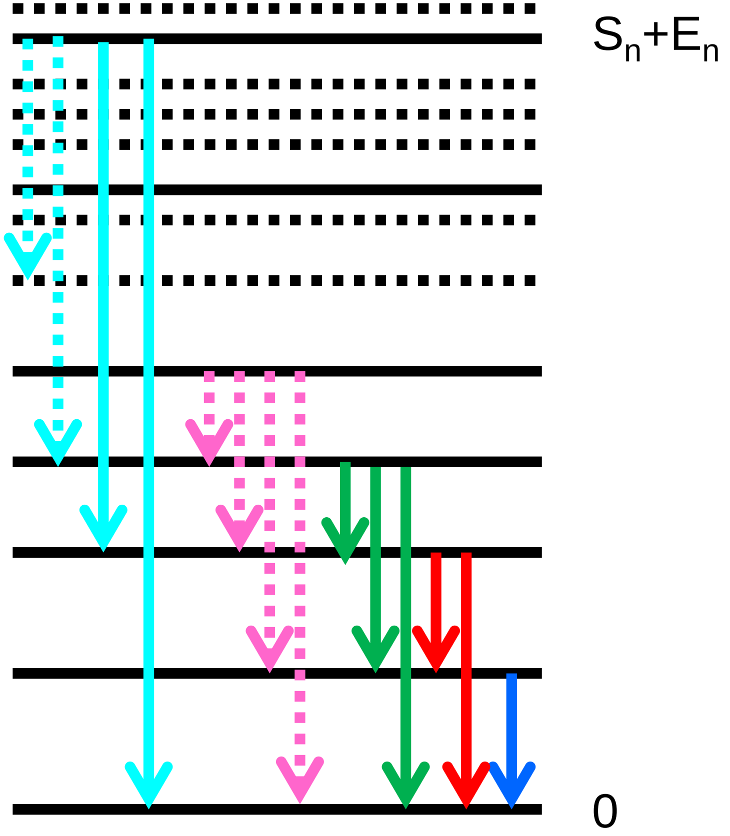
Own database

↓

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

↓

Models (RIPL-3)



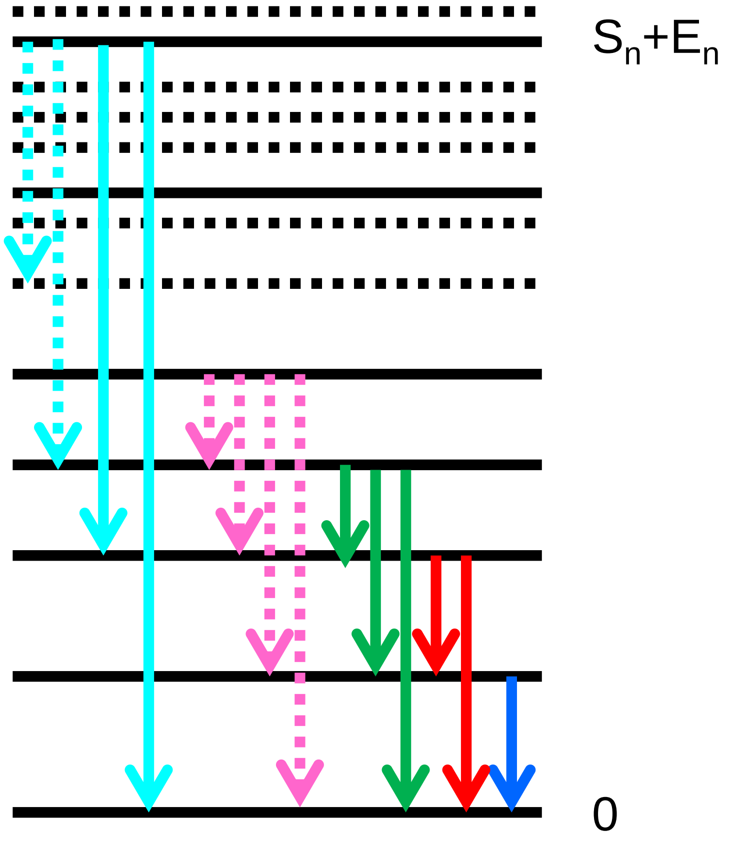
n + ^{A}X → $^{A+1}$X

The code

Some characteristics of the model:

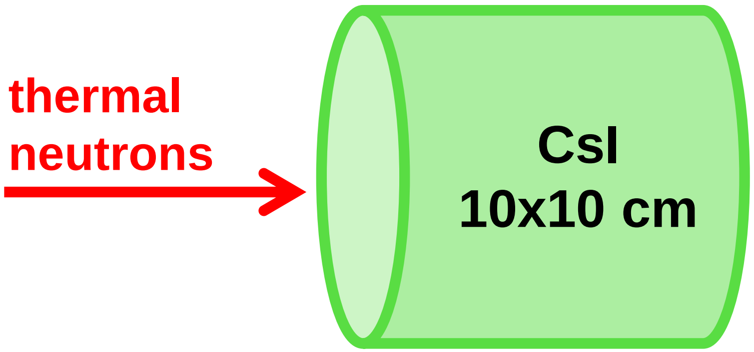
- Since levels and BR are generated *randomly* → different *realizations* of the same nucleus.

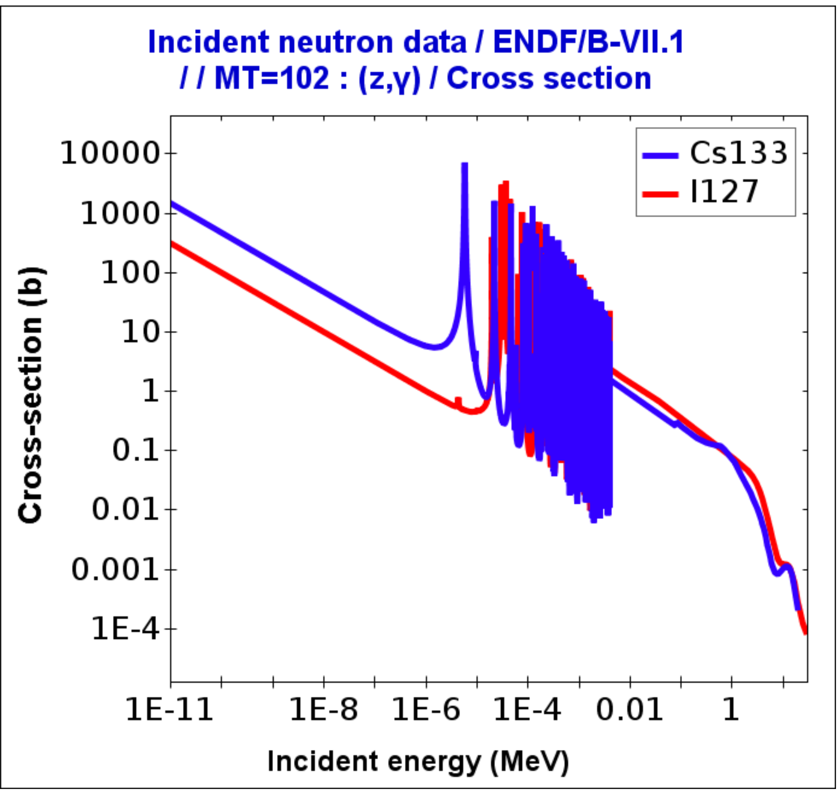
- Number of levels and BR can be very high. For actinides ~10^6 levels, i.e. ~10^{12} BR → binning is allowed.

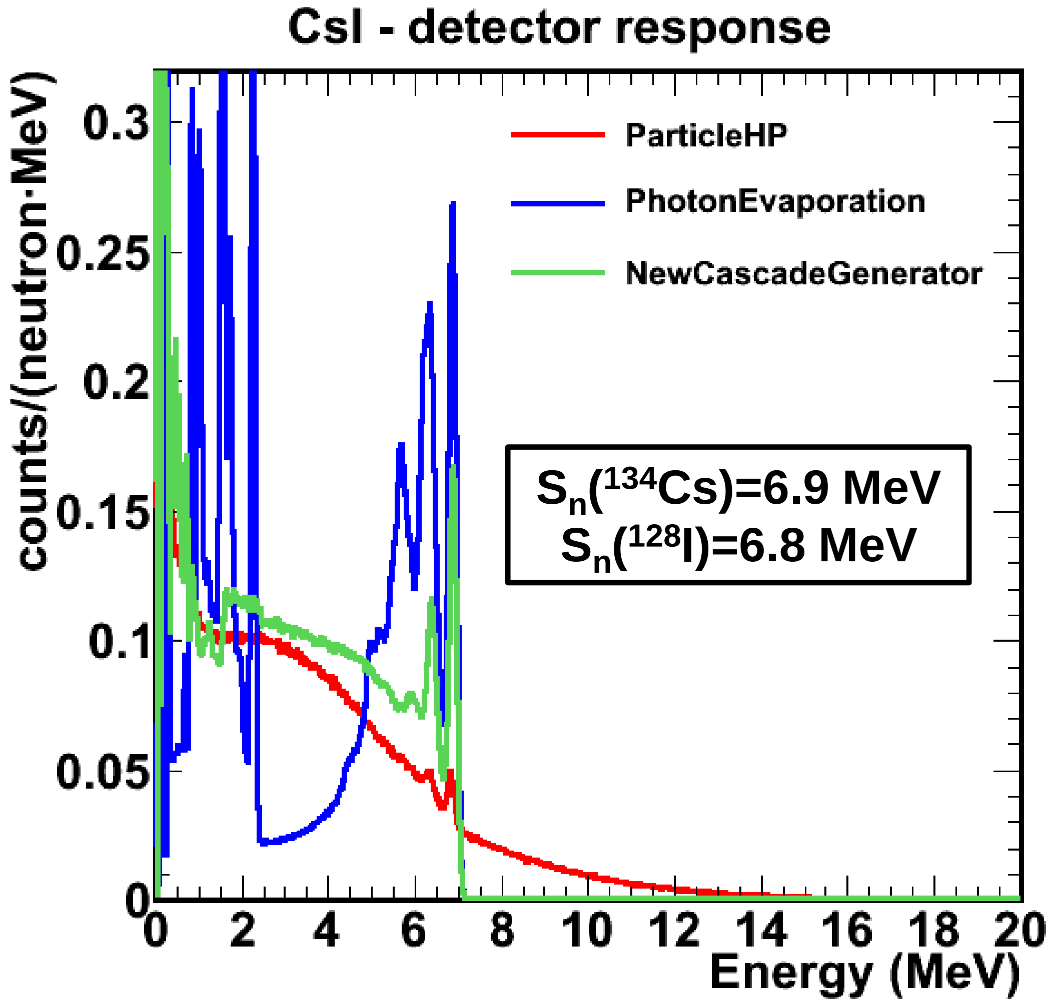


$n + {}^{A}X \rightarrow {}^{A+1}X$

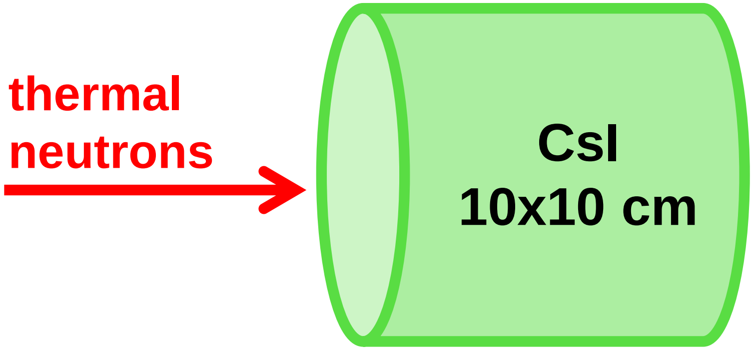
Examples


thermal
neutrons
CsI
10x10 cm

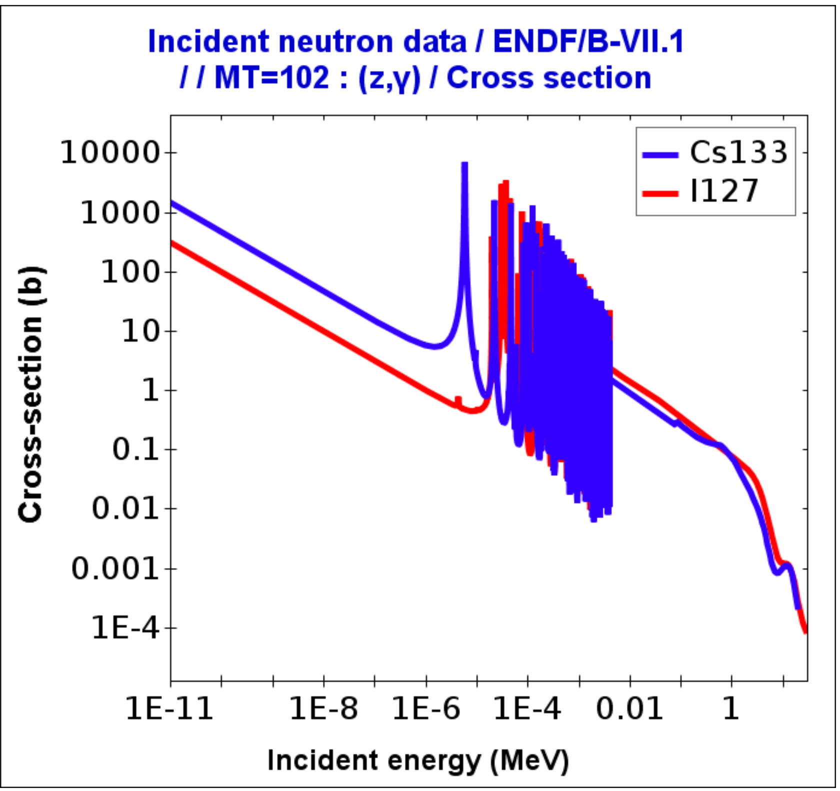

Incident neutron data / ENDF/B-VII.1
/ / MT=102 : (z,γ) / Cross section
Cs133
I127
Cross-section (b)
10000
1000
100
10
1
0.1
0.01
0.001
1E-4
1E-11
1E-8
1E-6
1E-4
0.01
1
Incident energy (MeV)


CsI - detector response
ParticleHP
PhotonEvaporation
NewCascadeGenerator
$S_n(^{134}Cs)$=6.9 MeV
$S_n(^{128}I)$=6.8 MeV
counts/(neutron·MeV)
0.3
0.25
0.2
0.15
0.1
0.05
0
0
2
4
6
8
10
12
14
16
18
20
Energy (MeV)

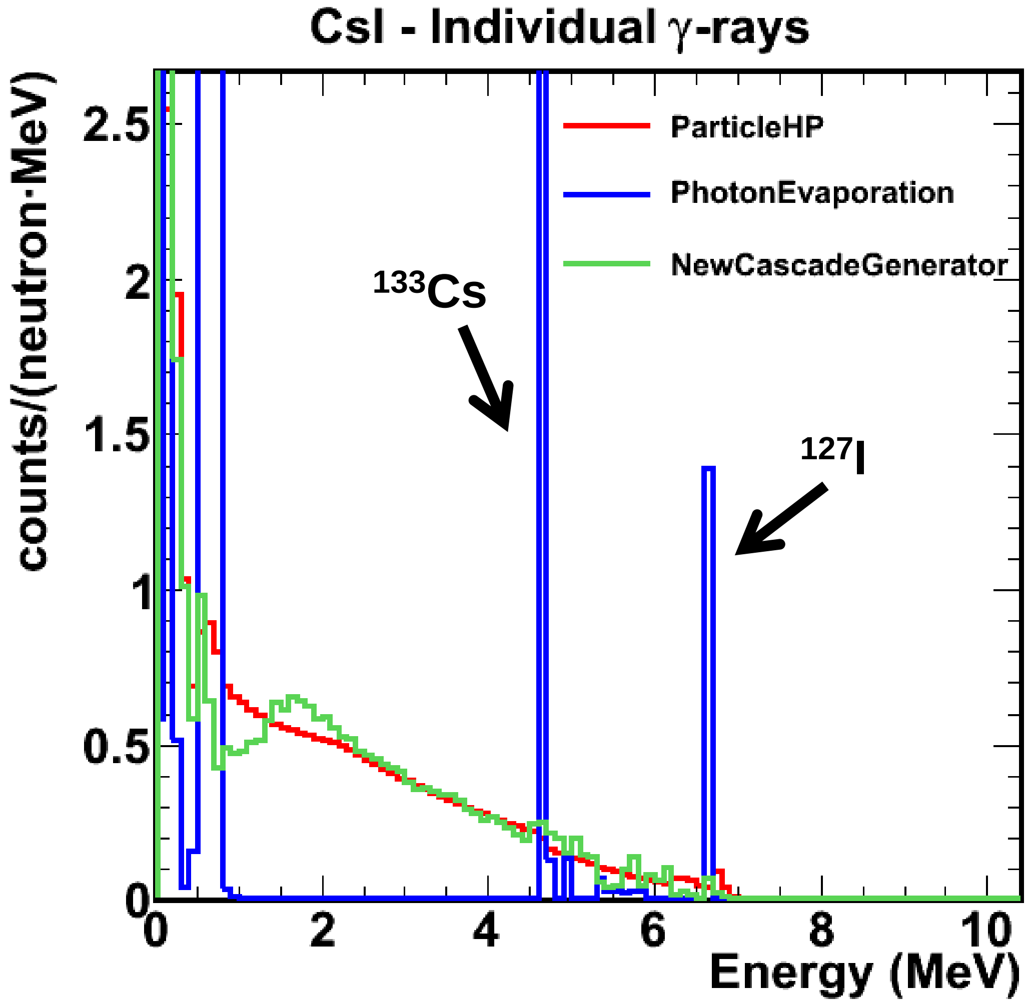
Examples



thermal
neutrons
CsI
10x10 cm

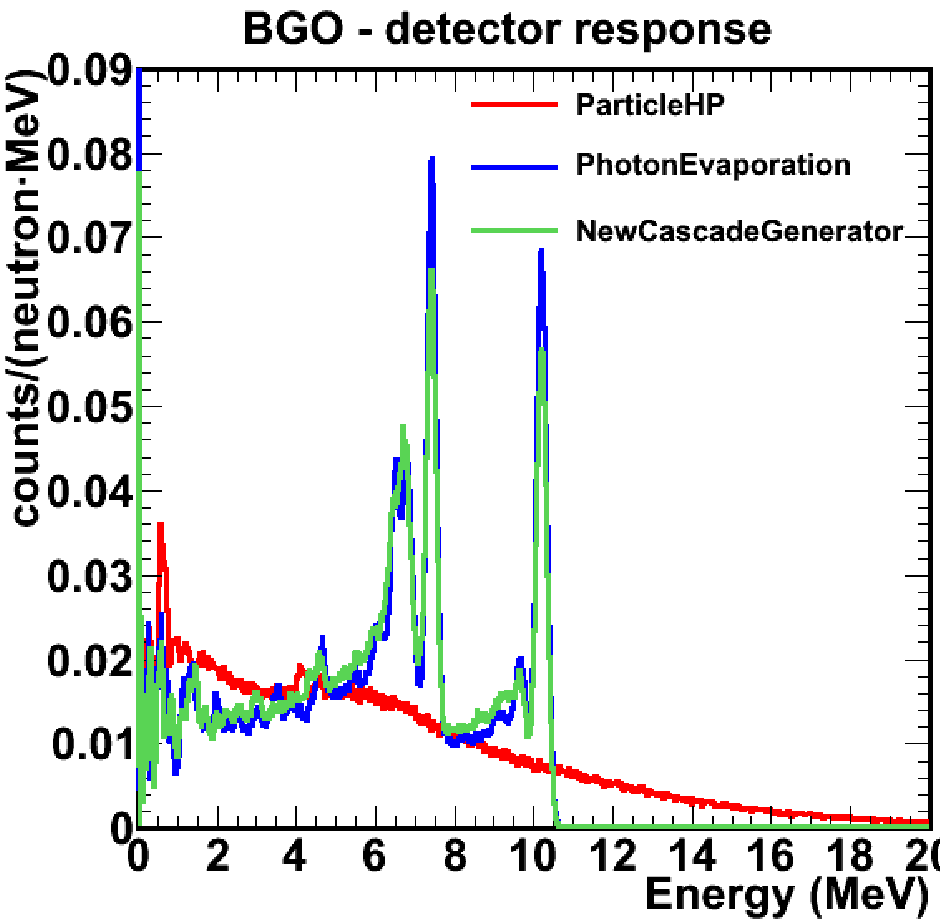


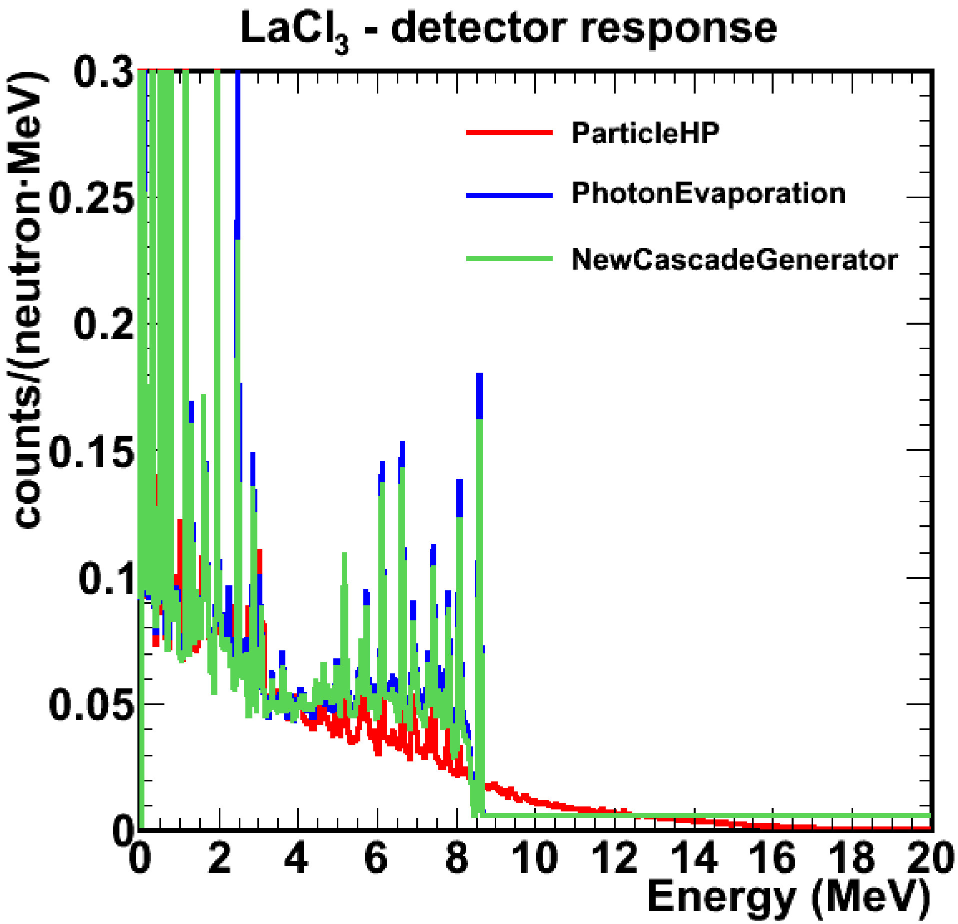
Incident neutron data / ENDF/B-VII.1
/ / MT=102 : (z,γ) / Cross section
Cs133
I127
Cross-section (b)
10000
1000
100
10
1
0.1
0.01
0.001
1E-4
1E-11
1E-8
1E-6
1E-4
0.01
1
Incident energy (MeV)



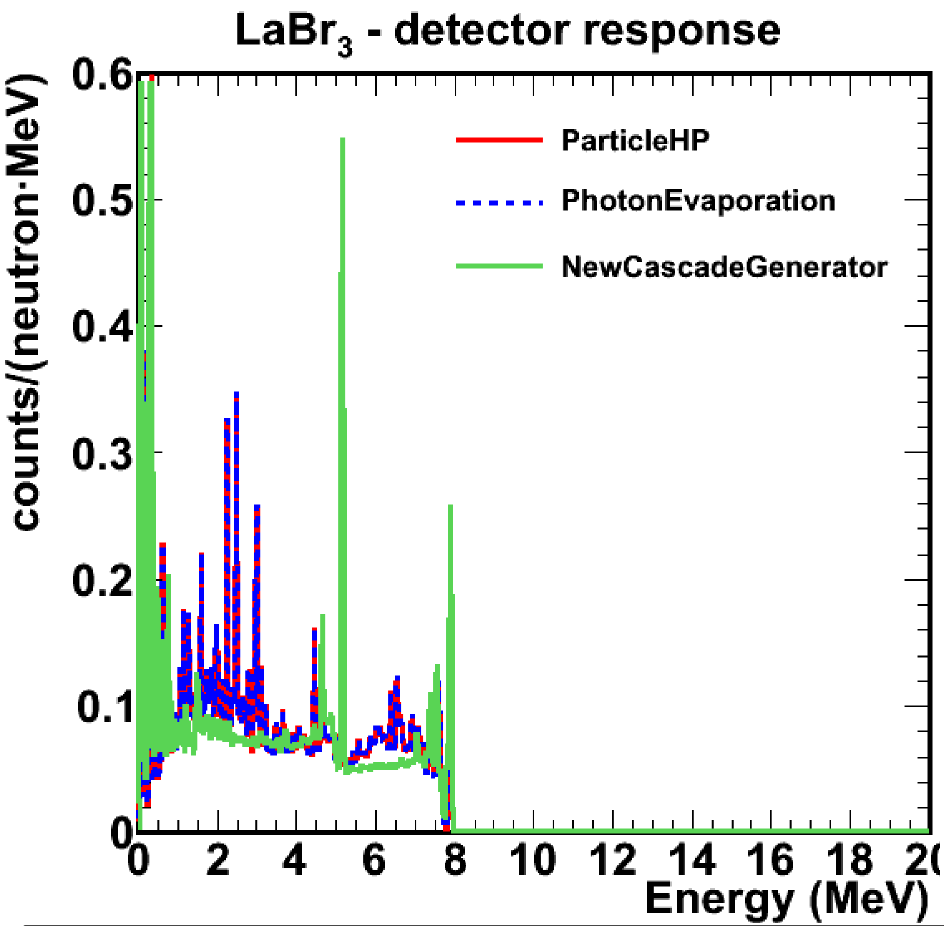
CsI - Individual γ-rays
ParticleHP
PhotonEvaporation
NewCascadeGenerator
133Cs
127I
counts/(neutron·MeV)
2.5
2
1.5
1
0.5
0
2
4
6
8
10
Energy (MeV)

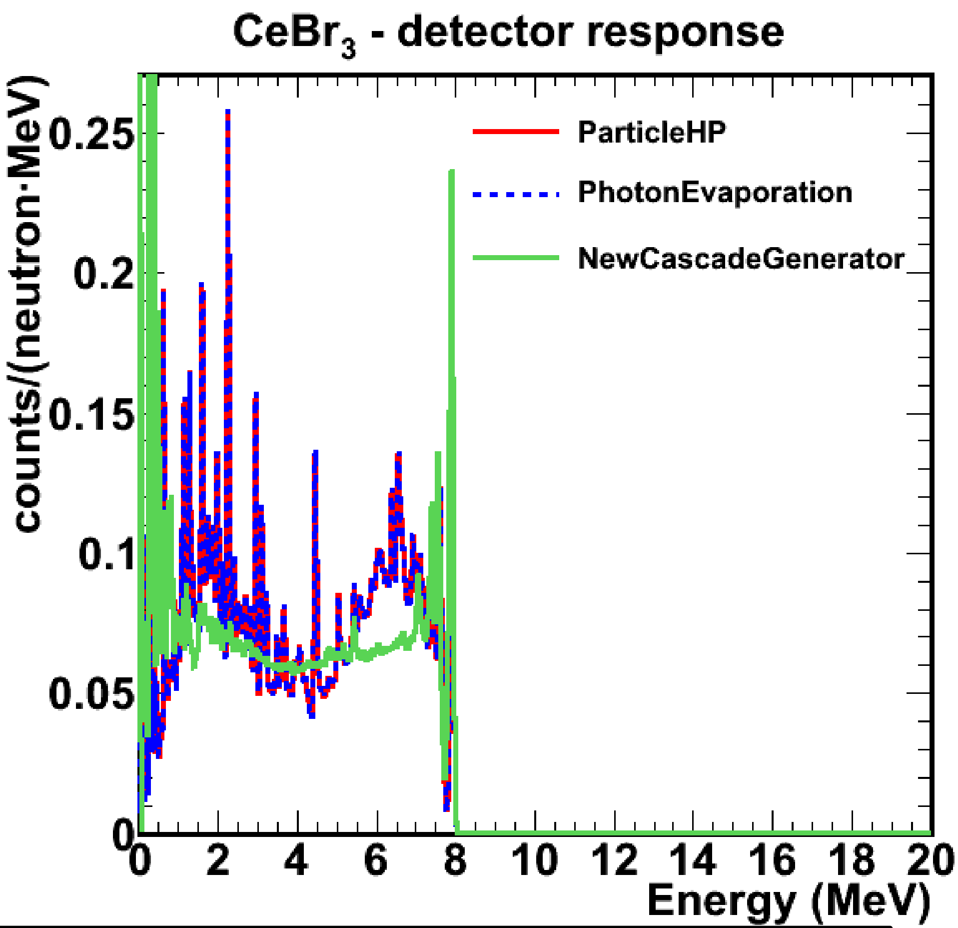
Examples


BGO - detector response
counts/(neutron·MeV)
ParticleHP
PhotonEvaporation
NewCascadeGenerator
Energy (MeV)


LaCl$_3$ - detector response
counts/(neutron·MeV)
ParticleHP
PhotonEvaporation
NewCascadeGenerator
Energy (MeV)

Examples





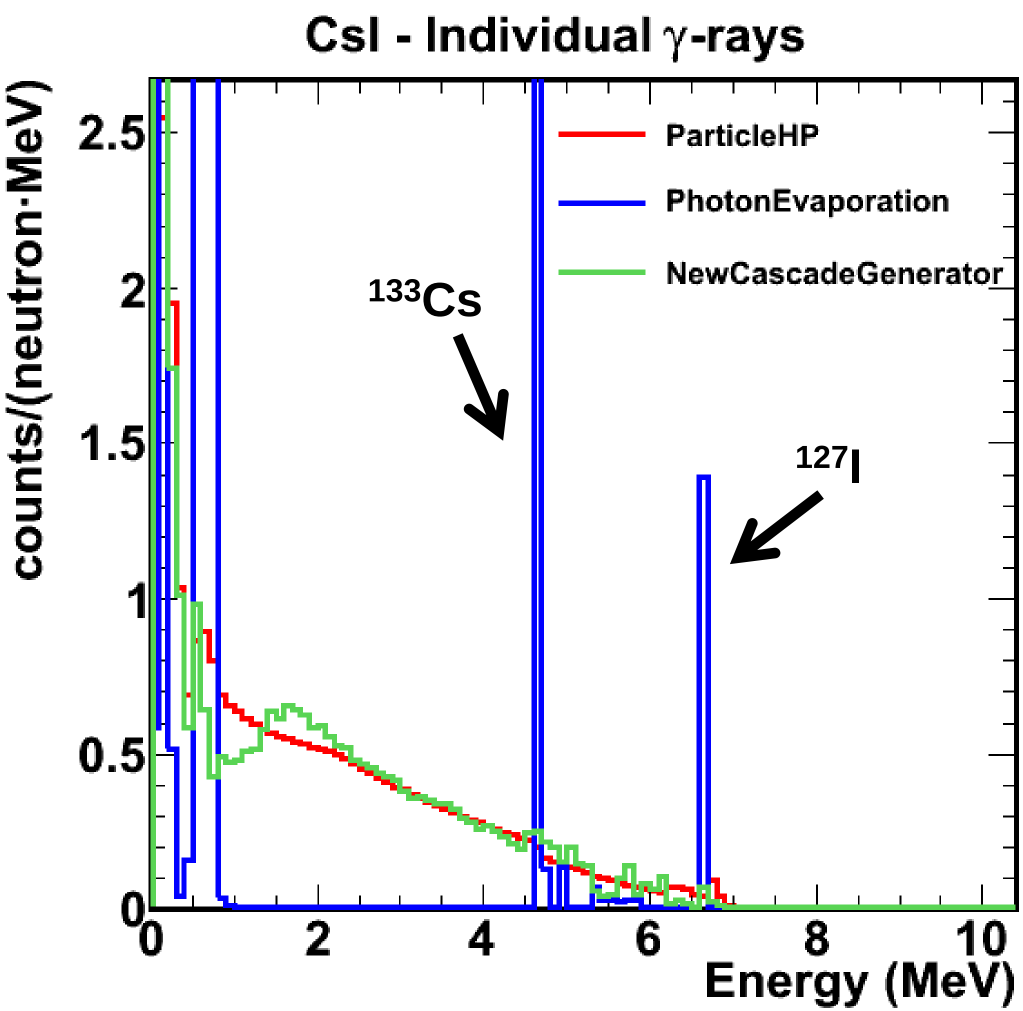
Note: no photon data in $LaBr_3$ and $CeBr_3$ in G4NDL4.5 → G4ParticleHP same as G4PhotonEvaporation.

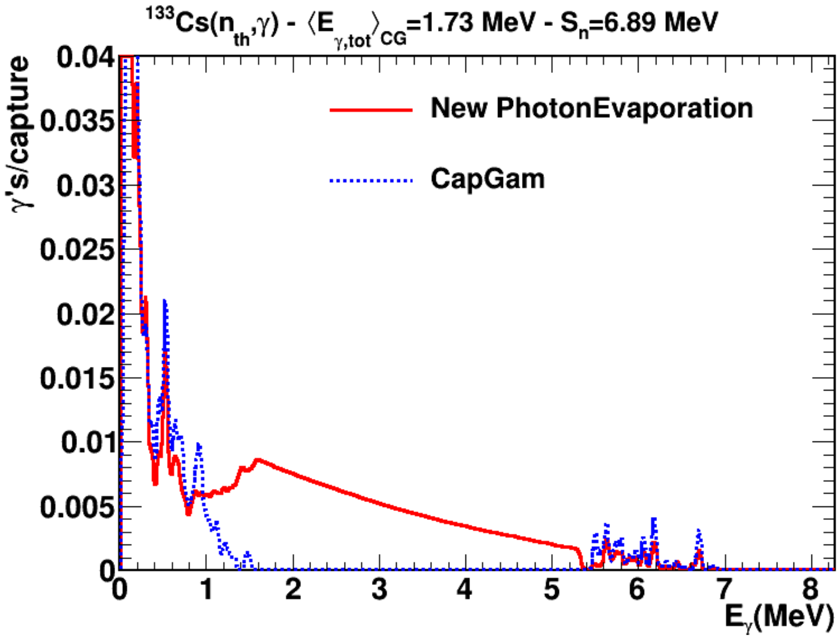
Example

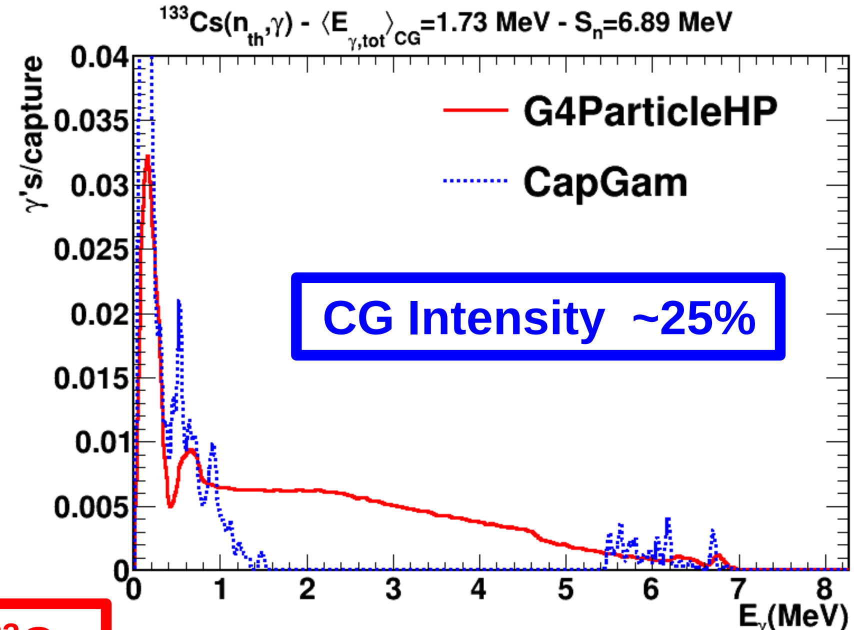
To check γ-ray intensities from (thermal) neutron capture:

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

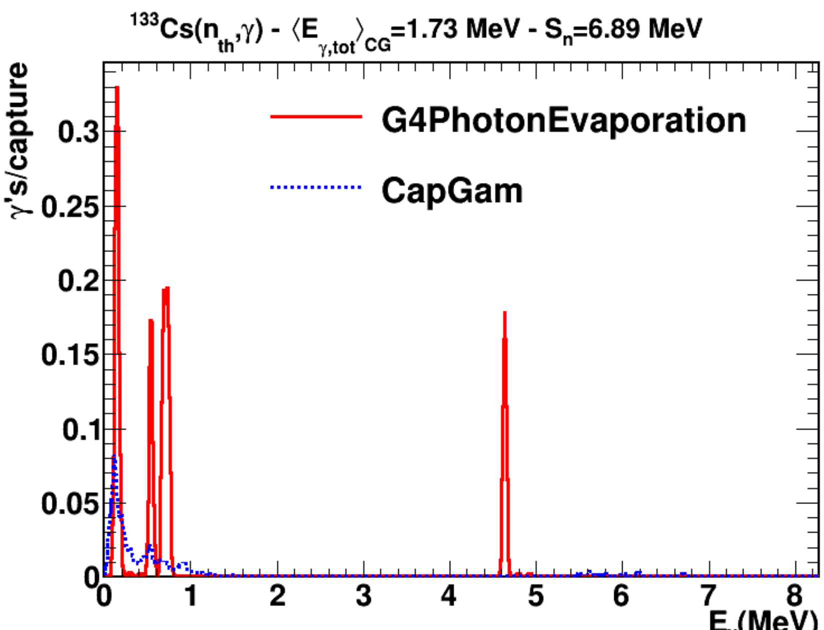
IAEA-Database for Prompt Gamma-ray Neutron Activation Analysis:
https://www-nds.iaea.org/pgaa/

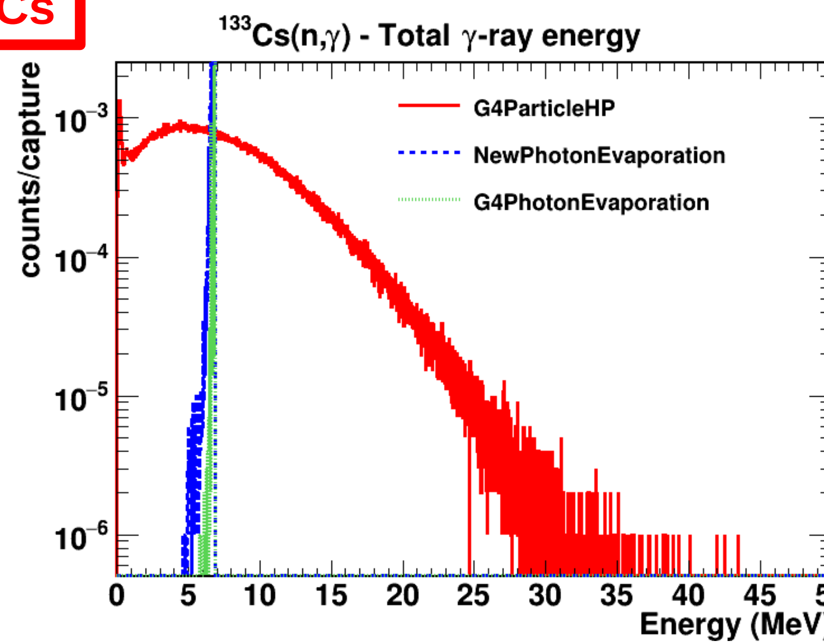


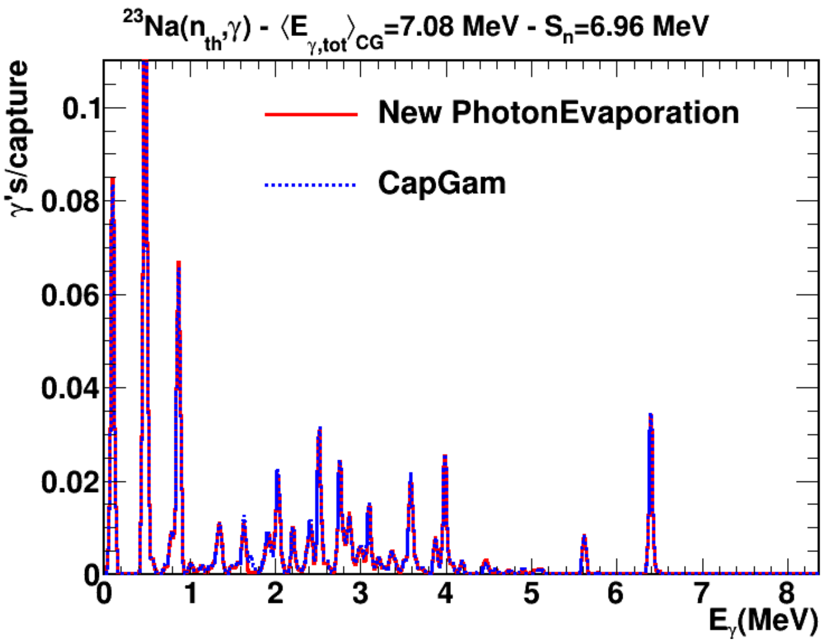

^{133}Cs(n_{th},γ) - ⟨$E_{\gamma,tot}$⟩$_{CG}$=1.73 MeV - S_n=6.89 MeV
γ's/capture
E_γ(MeV)
New PhotonEvaporation
CapGam


^{133}Cs(n_{th},γ) - ⟨$E_{\gamma,tot}$⟩$_{CG}$=1.73 MeV - S_n=6.89 MeV
γ's/capture
E_γ(MeV)
G4ParticleHP
CapGam
CG Intensity ~25%

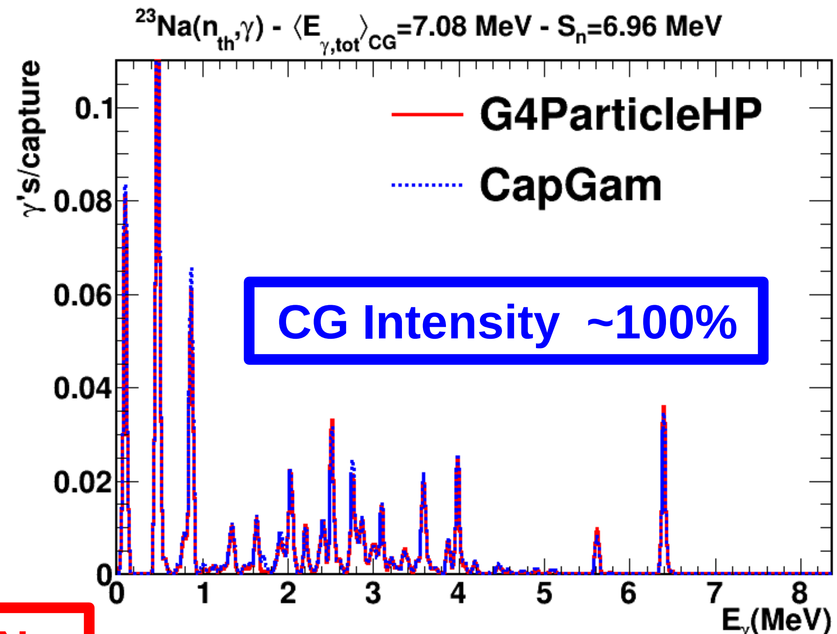
^{133}Cs


^{133}Cs(n_{th},γ) - ⟨$E_{\gamma,tot}$⟩$_{CG}$=1.73 MeV - S_n=6.89 MeV
γ's/capture
E_γ(MeV)
G4PhotonEvaporation
CapGam


^{133}Cs(n,γ) - Total γ-ray energy
counts/capture
Energy (MeV)
G4ParticleHP
NewPhotonEvaporation
G4PhotonEvaporation

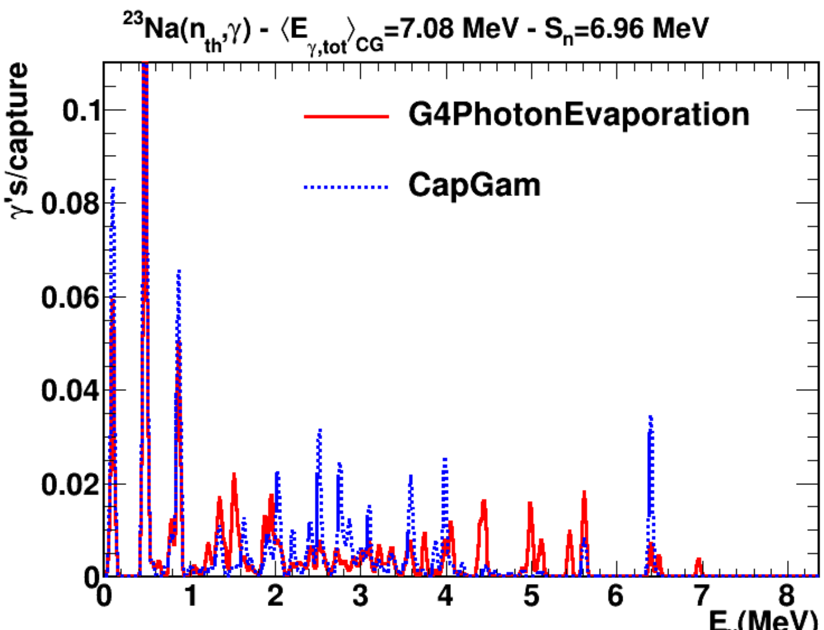


²³Na(n_th,γ) - ⟨E_γ,tot⟩_CG=7.08 MeV - S_n=6.96 MeV
γ's/capture
New PhotonEvaporation
CapGam
E_γ(MeV)

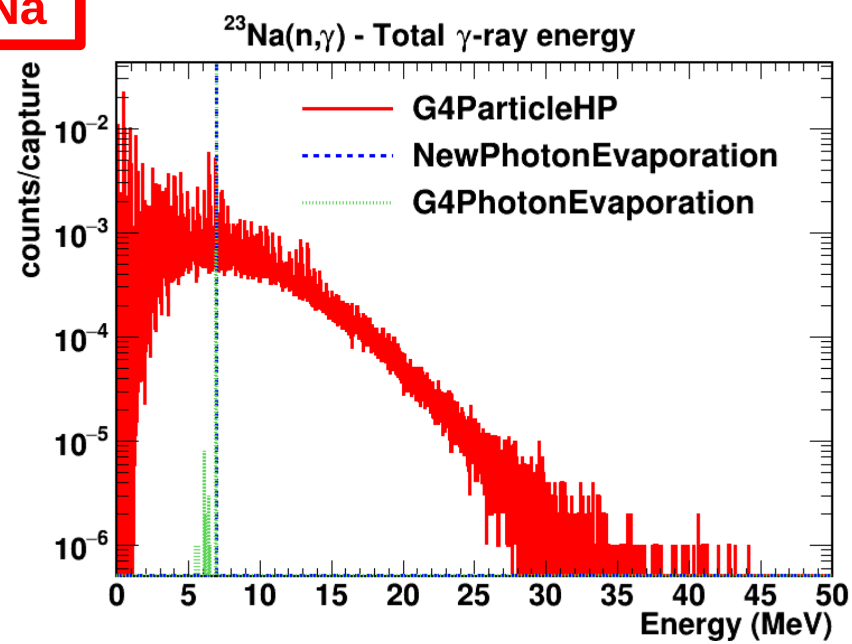


²³Na(n_th,γ) - ⟨E_γ,tot⟩_CG=7.08 MeV - S_n=6.96 MeV
γ's/capture
G4ParticleHP
CapGam
CG Intensity ~100%
E_γ(MeV)

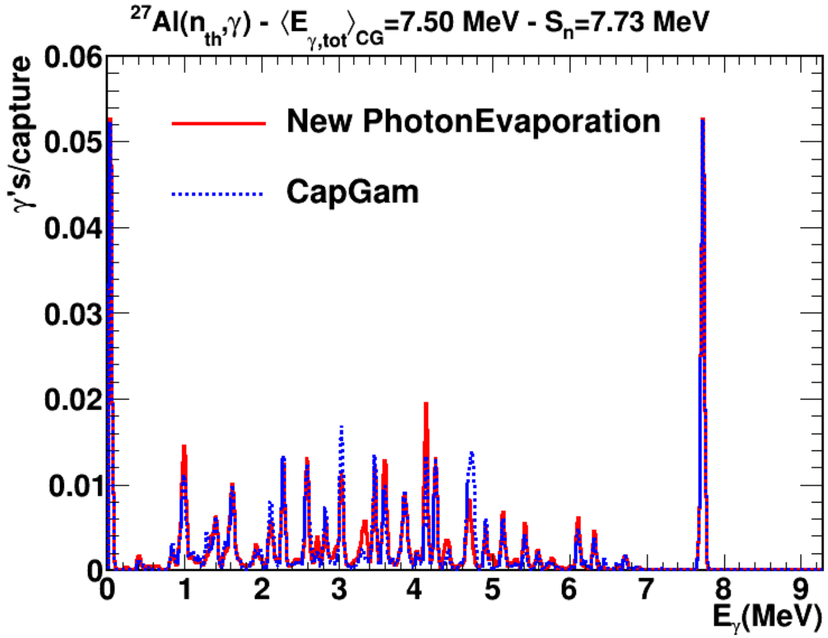
^{23}Na

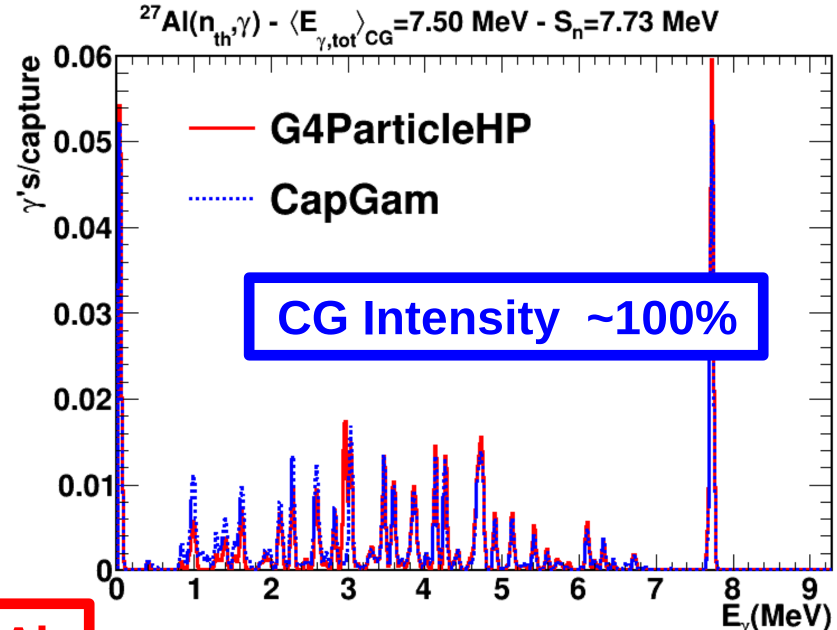


²³Na(n_th,γ) - ⟨E_γ,tot⟩_CG=7.08 MeV - S_n=6.96 MeV
γ's/capture
G4PhotonEvaporation
CapGam
E_γ(MeV)

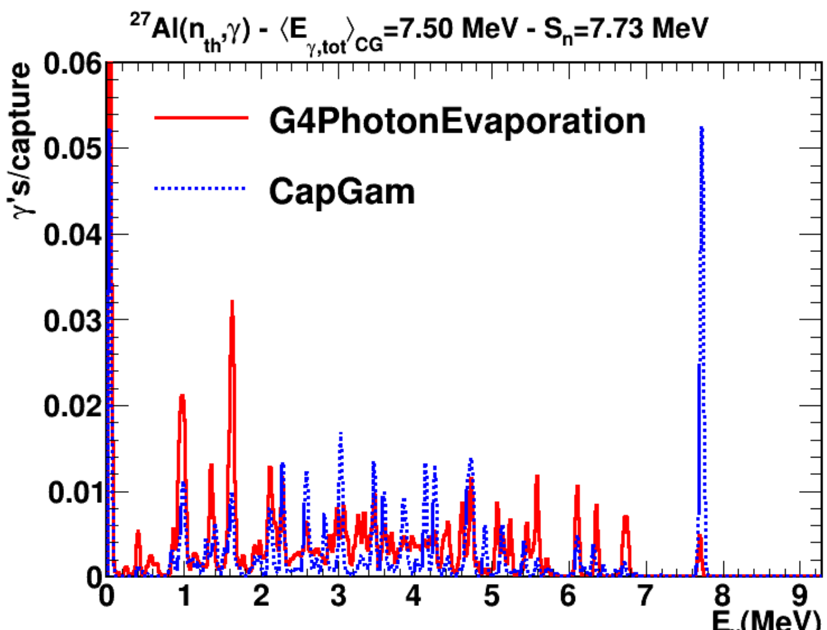


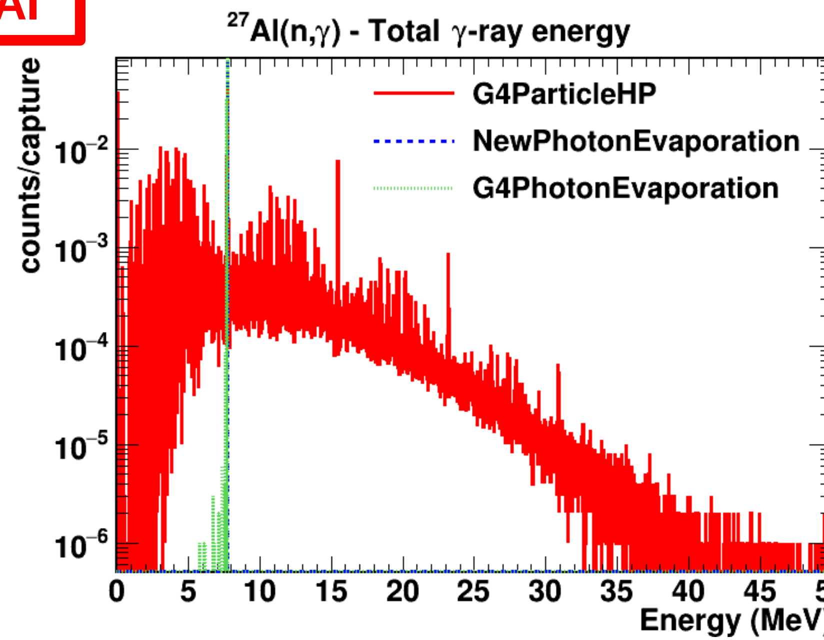
²³Na(n,γ) - Total γ-ray energy
counts/capture
G4ParticleHP
NewPhotonEvaporation
G4PhotonEvaporation
Energy (MeV)

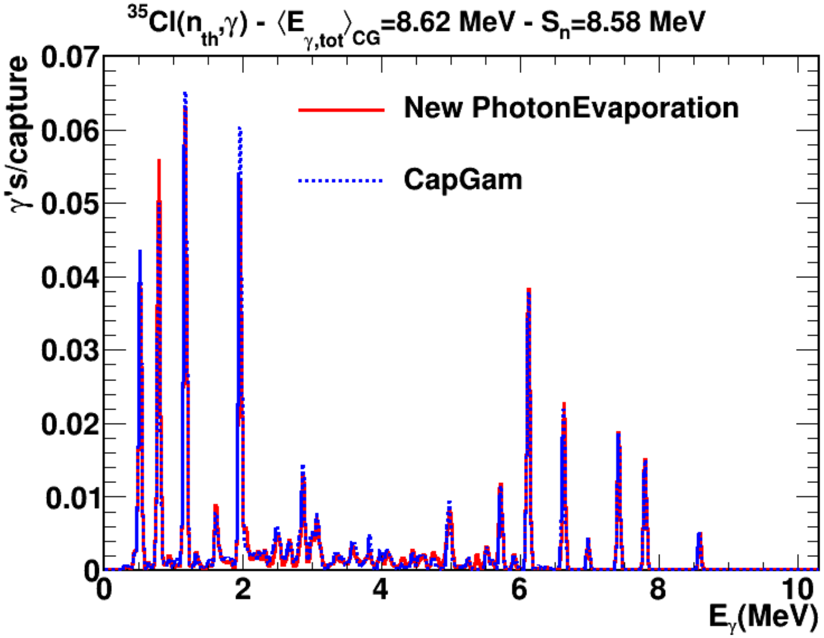

^{27}Al(n$_{th}$,γ) - ⟨E$_{γ,tot}$⟩$_{CG}$=7.50 MeV - S$_n$=7.73 MeV
New PhotonEvaporation
CapGam
γ's/capture
E$_γ$(MeV)


^{27}Al(n$_{th}$,γ) - ⟨E$_{γ,tot}$⟩$_{CG}$=7.50 MeV - S$_n$=7.73 MeV
G4ParticleHP
CapGam
CG Intensity ~100%
γ's/capture
E$_γ$(MeV)

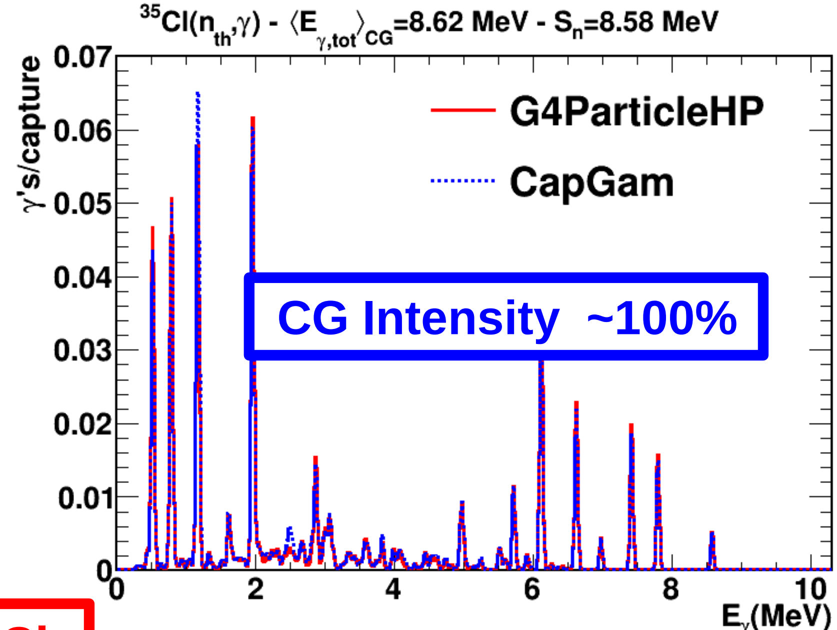
^{27}Al


^{27}Al(n$_{th}$,γ) - ⟨E$_{γ,tot}$⟩$_{CG}$=7.50 MeV - S$_n$=7.73 MeV
G4PhotonEvaporation
CapGam
γ's/capture
E$_γ$(MeV)


^{27}Al(n,γ) - Total γ-ray energy
G4ParticleHP
NewPhotonEvaporation
G4PhotonEvaporation
counts/capture
Energy (MeV)

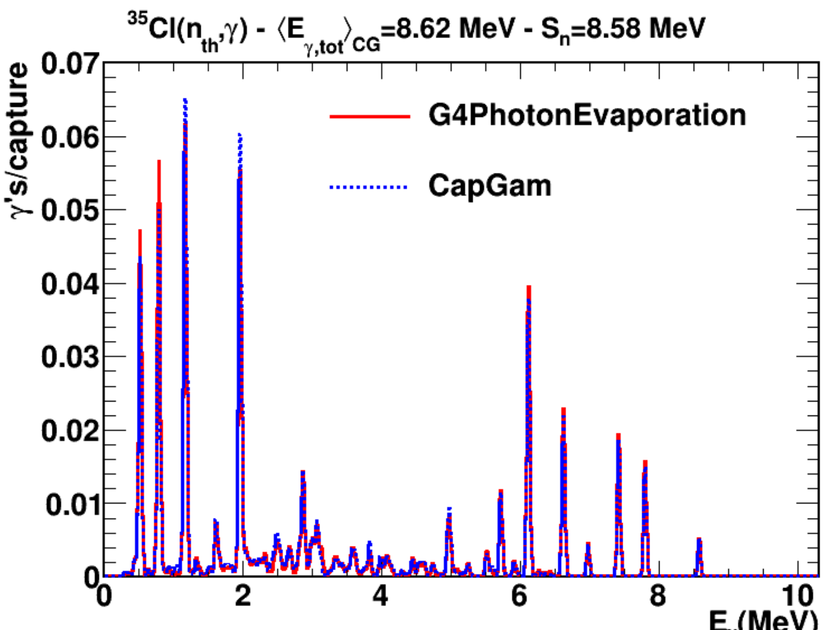


^{35}Cl(n$_{th}$,γ) - ⟨E$_{γ,tot}$⟩$_{CG}$=8.62 MeV - S$_n$=8.58 MeV
γ's/capture
New PhotonEvaporation
CapGam
E$_γ$(MeV)

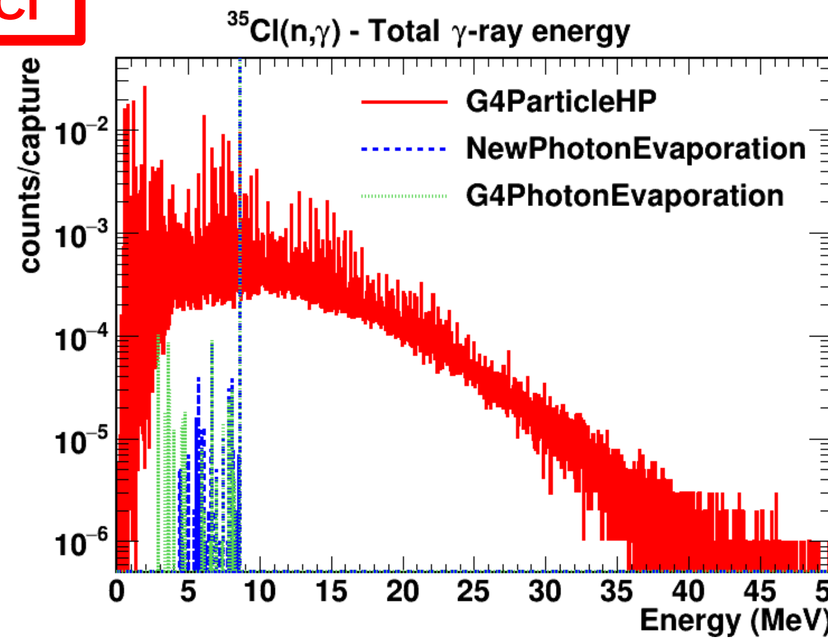


^{35}Cl(n$_{th}$,γ) - ⟨E$_{γ,tot}$⟩$_{CG}$=8.62 MeV - S$_n$=8.58 MeV
γ's/capture
G4ParticleHP
CapGam
CG Intensity ~100%
E$_γ$(MeV)

^{35}Cl



^{35}Cl(n$_{th}$,γ) - ⟨E$_{γ,tot}$⟩$_{CG}$=8.62 MeV - S$_n$=8.58 MeV
γ's/capture
G4PhotonEvaporation
CapGam
E$_γ$(MeV)



^{35}Cl(n,γ) - Total γ-ray energy
counts/capture
G4ParticleHP
NewPhotonEvaporation
G4PhotonEvaporation
Energy (MeV)

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** → 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.