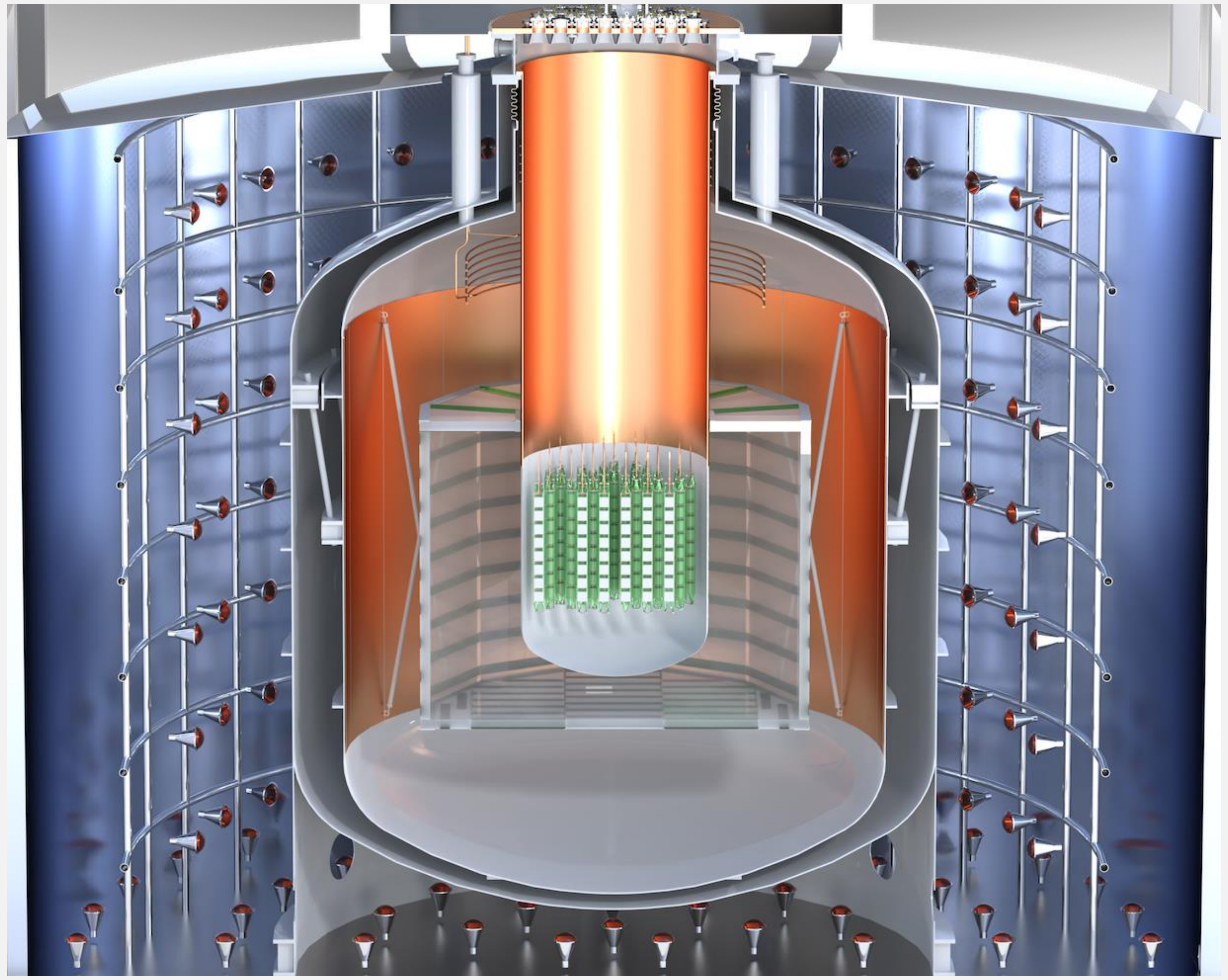
The accuracy of gamma cascades for thermal neutron capture on gadolinium in Geant4

Large Enriched Germanium Experiment for Neutrinoless ββ Decay



Eric Esch
University Tübingen

Vienna Workshop on Simulations
27.04.2024

Usage of gadolinium

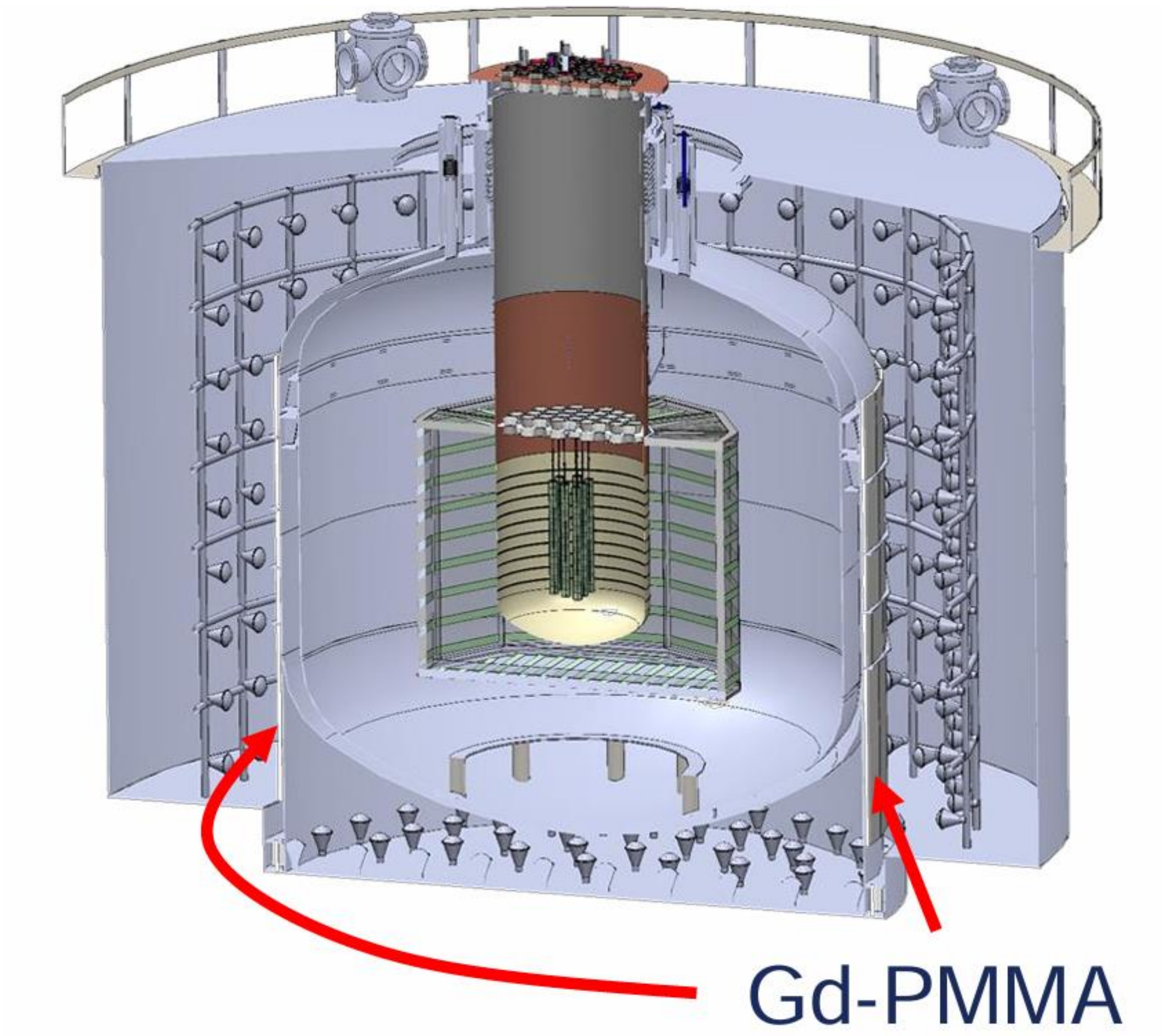
Interactions of interest for neutron detection and counting.

Interaction	Energy T_n	Cross section (b)	Q-value (MeV)	Products
$^{1}H(n, n')$	100 keV – 10 MeV	0.7–28	–	proton
$^{3}He(n, p)$	Thermal	5330	0.764	proton, triton
$^{10}B(n, \alpha)$	Thermal	3840	2.792	alpha, lithium ion
$^{6}Li(n, \alpha)$	Thermal	940	4.78	alpha, triton
$^{157}Gd(n, \gamma)$	Thermal	254000	7.937	photons, electrons
$^{155}Gd(n, \gamma)$	Thermal	60900	8.536	photons, electrons
$^{113}Cd(n, \gamma)$	Thermal	20600	9.04	photons, electrons

J. Dumazert et al. “Gadolinium for neutron detection in current nuclear instrumentation research: A review”. doi: https://doi.org/10.1016/j.nima.2017.11.032.

- Highest neutron capture (NC) cross section of all (stable) natural occuring elements!
- 8 MeV gamma cascade easy detectable

Usage of gadolinium



- Neutron tagger for LEGEND-1000 (and other low background experiments)
- Requires exact simulations to estimate the performance and optimize the setup
- Cherenkov-Veto!
  -> Exact Gamma lines & Energy required

Geant4 Status 2015[1)]

Final state model

- Sample **uncorrelated** gammas from the individual gamma spectrum
- Respects gamma line intensity
- Does not conserve Q-value

Photon evaporation model

- Does not respect gamma line intensity and multiplicites
- Conserves Q-value

We need realistic gamma line cascades conserving the Q-value!

1) Y. Chen, Gadolinium neutron-capture gammas in Geant4, AARM Workshop 2015, Syracuse, Italia 2015

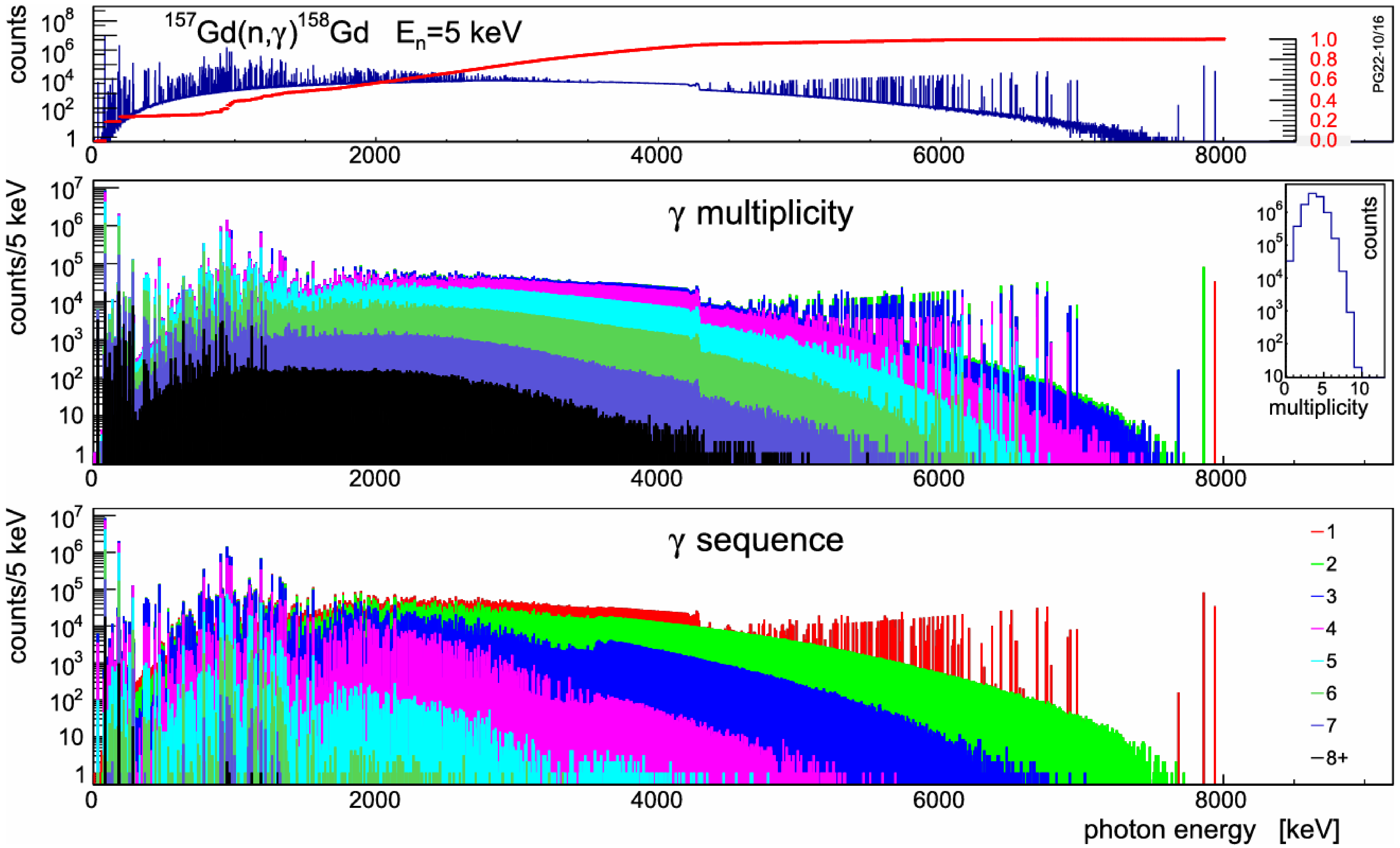
Gamma cascade modeling by Peter Grabmayr

Peter Grabmayr[1] used MAURINA[2] to calculate the cross sections and gamma lines according to the Hauser-Feshbash model

- Published by the EPJC

  Peter Grabmayr. “Gamma Cascades in Gadolinium Isotopes”. In: Eur. Phys. J. C (2023) 83:444
  doi: [10.1140/ epjc/s10052-023-11602-y](https://doi.org/10.1140/epjc/s10052-023-11602-y).

- Gd published, Ge submitted



1) Physikalisches Institut, Eberhard Karls Universität Tübingen, Auf der Morgenstelle 14, 72076 Tübingen, Germany.
2) Fortran-IV based code written by Mario Uhl in the Nineties as expansion of the Hauser-Feshbach code STAPRE. Updated 2022 by Peter Grabmayr

Gamma cascade modeling by Peter Grabmayr

156Gd-5keV-cascades.txt - Editor

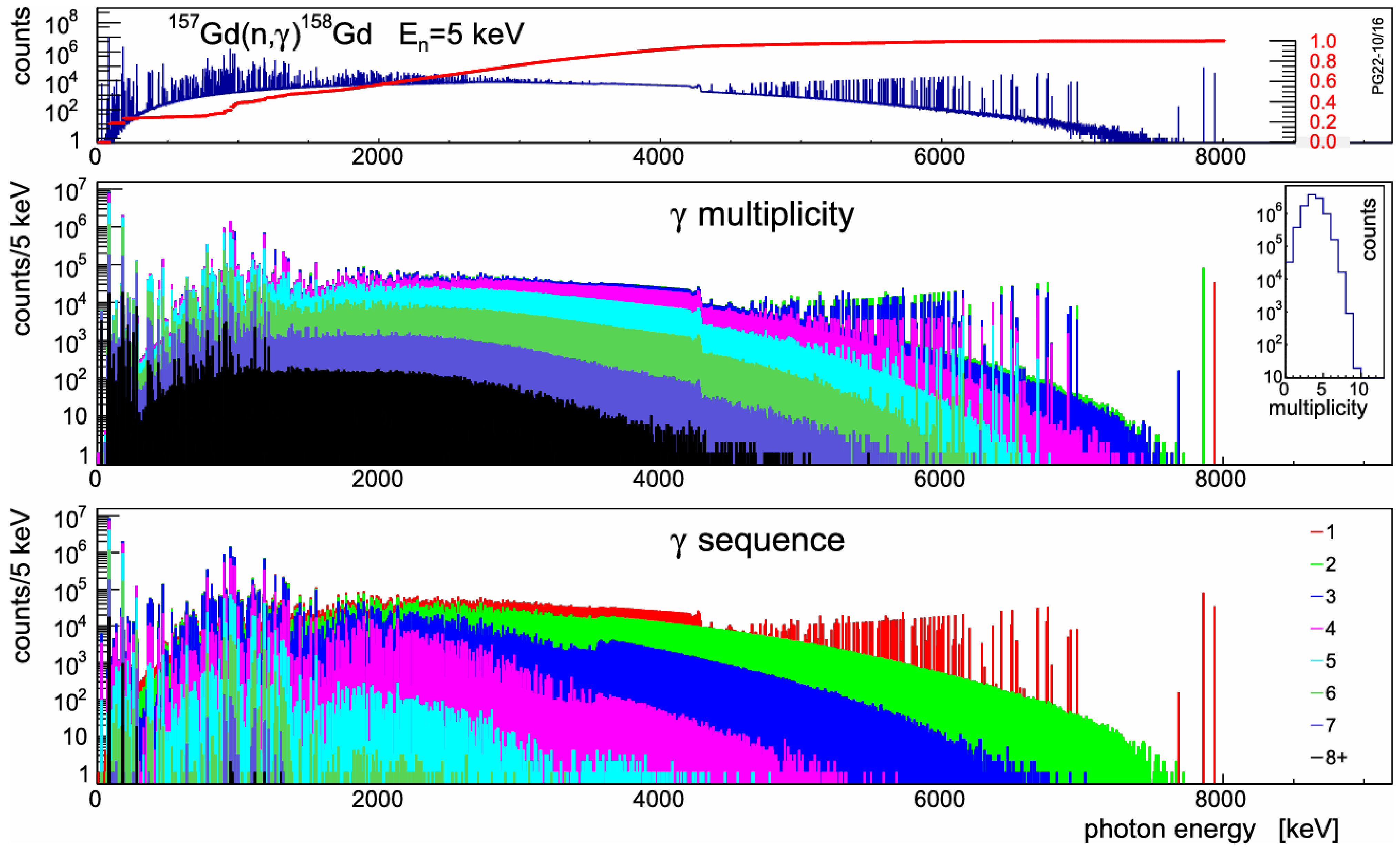
Datei Bearbeiten Format Ansicht Hilfe

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%      listing of gamma cascades by MAURINA/GAMMOC
%%
%%   GD155+N  KRK-D, 3LO GAMMA-RAY STRENGTH FUNCTIONS
%%                                     MATNUM:  15511
%%   E_n= 5 keV
%%
%% date: 20221101 time: 212412.007/pgrabmayr
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% En: neutron energy  [keV]
%% Ex: excitation energy [keV]
%% M:   multiplicity of gamma cascade;    M_max=20
%% Em: missing energy [keV]
%%              :=0 ground state after capture
%%              :=E_iso isomeric state after capture
%%   & M=M_max  :=E_left  left out due too many gammas
%% Eg1: energy of first photon [keV]
%% Eg2: energy of 2nd photon [keV] .....  EgM
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% variables:
%% En/keV Ex/kev  M  Em/keV Eg1/keV Eg2/kev Eg3/kev etc.. EgM
%% format   :
%%  i6    i6 i3    i6    i6    i6    i6    i6    i6    i6    i6    i6
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
     5  8540  6     0  1895  1065  2233  1980  1278    89
     5  8540  5     0   992  5156  1025  1278    89
     5  8540  4     0  2765  2985  2701    89
     5  8540  3     0  3360  3938  1242
     5  8540  4     0  1800  3485  3166    89
     5  8540  1     0  8540
     5  8540  4     0  5310  1988  1153    89
     5  8540  3     0  3262  2361  2917
     5  8540  4     0  1700  5711  1040    89
     5  8540  4     0  1618  3282  3551    89
     5  8540  6     0  1516  3285  1805   780  1065    89
     5  8540  4     0  4097  2252  1037  1154
     5  8540  4     0  3600  3664  1187    89
```

- Files are publicly available to manually include into the Geant4 simulation!

  https://doi.org/10.5281/zenodo.7458654

- Read in during run-time and either use as generator or manipulate events during tracking!

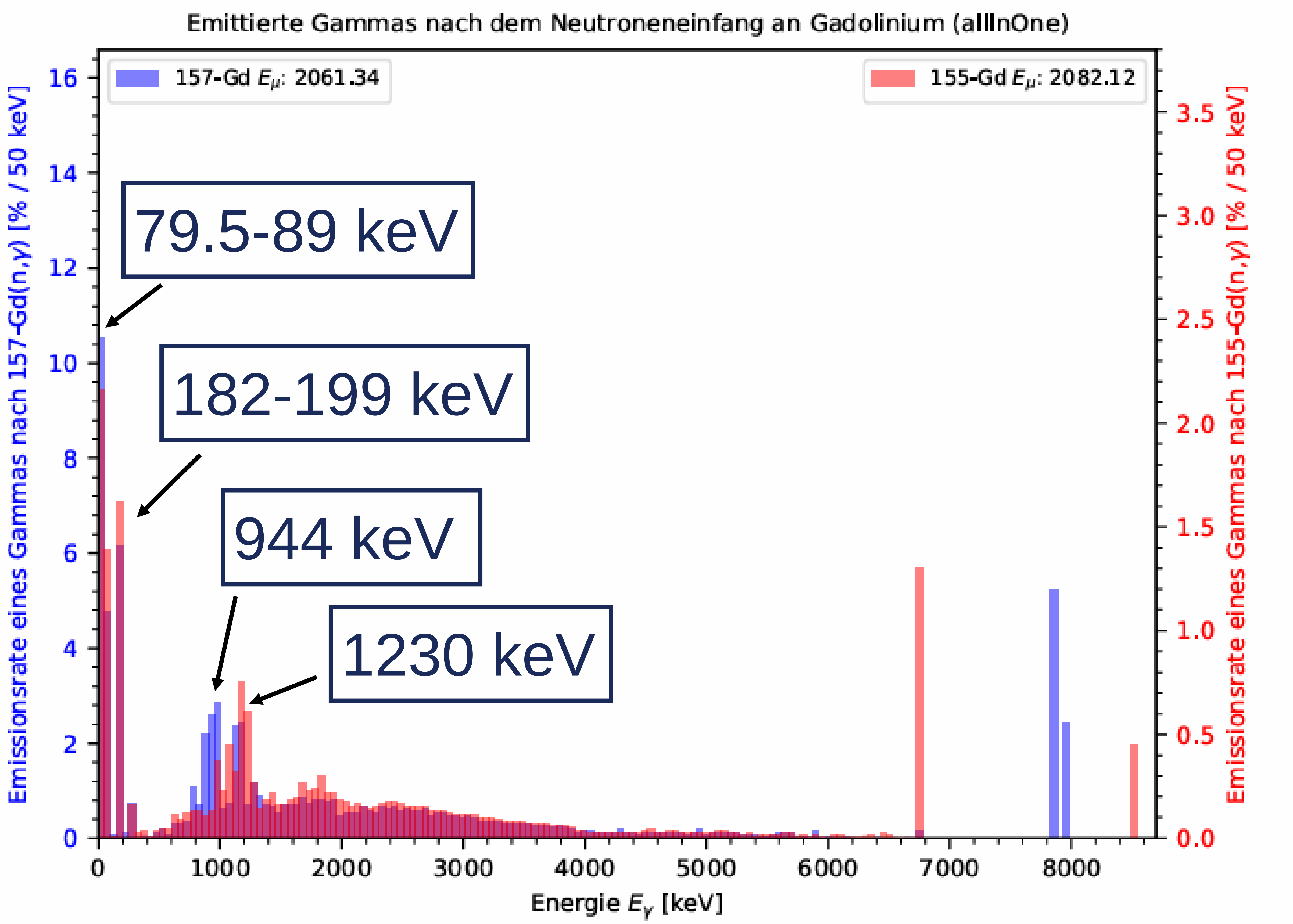


Investigate Geant4s behaviour

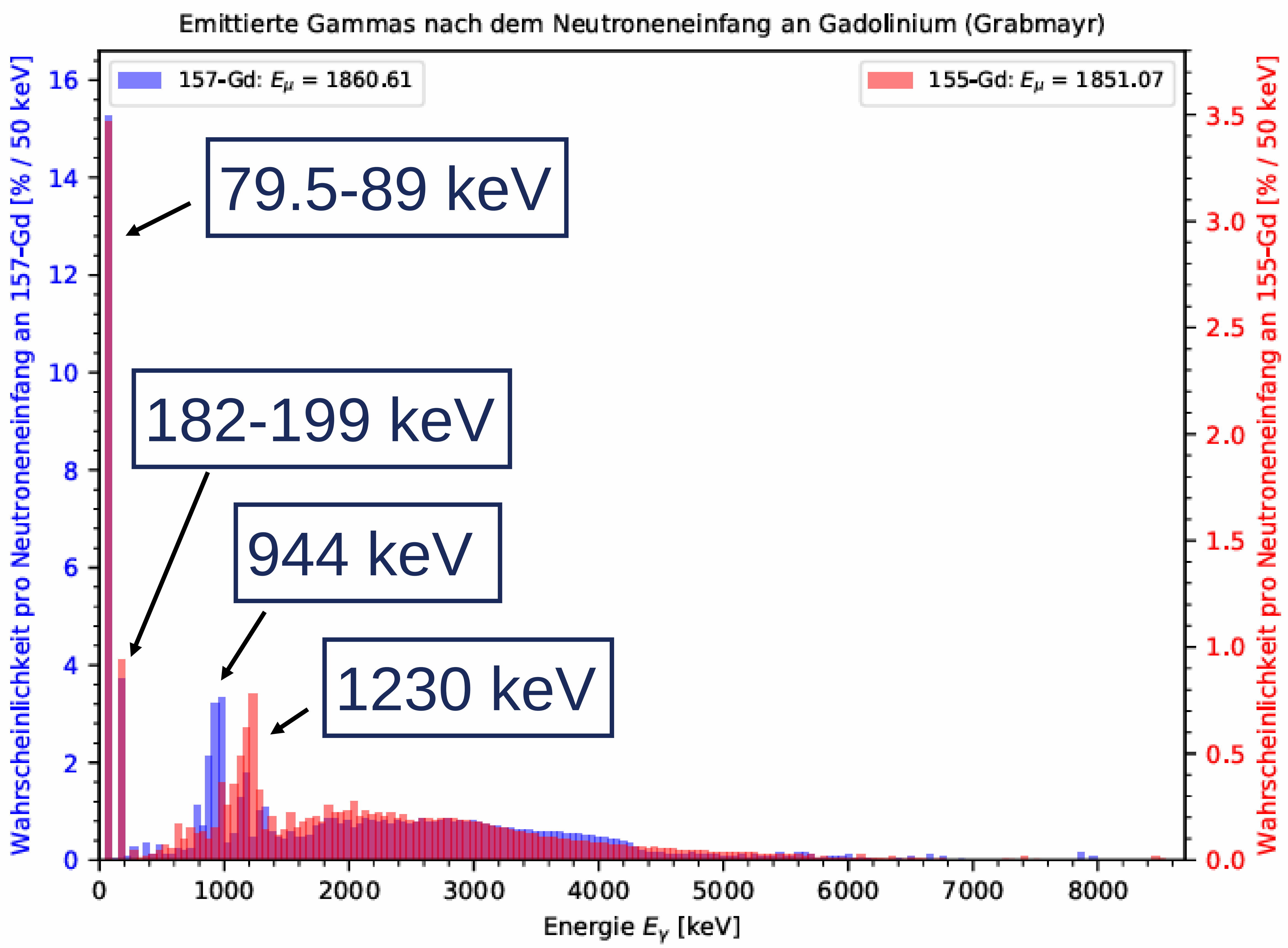
Bachelor Student Loris Steinhart investigated:

1e6 simulated neutrons

Geant4v11.0.3 “Shielding“

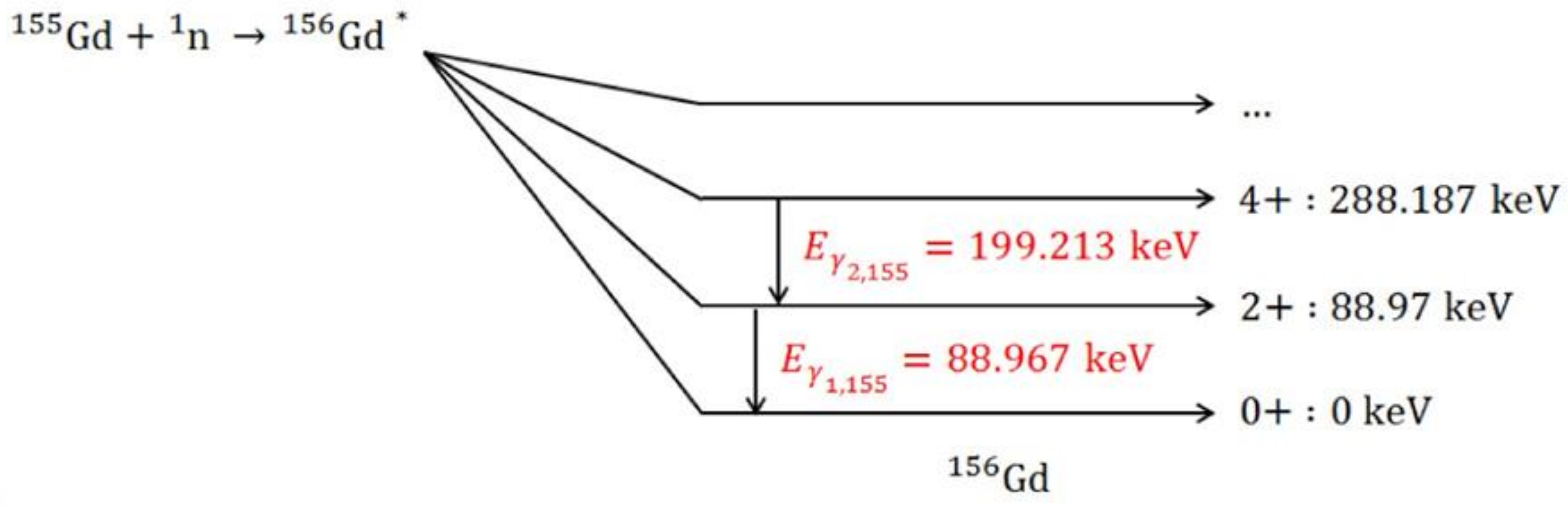


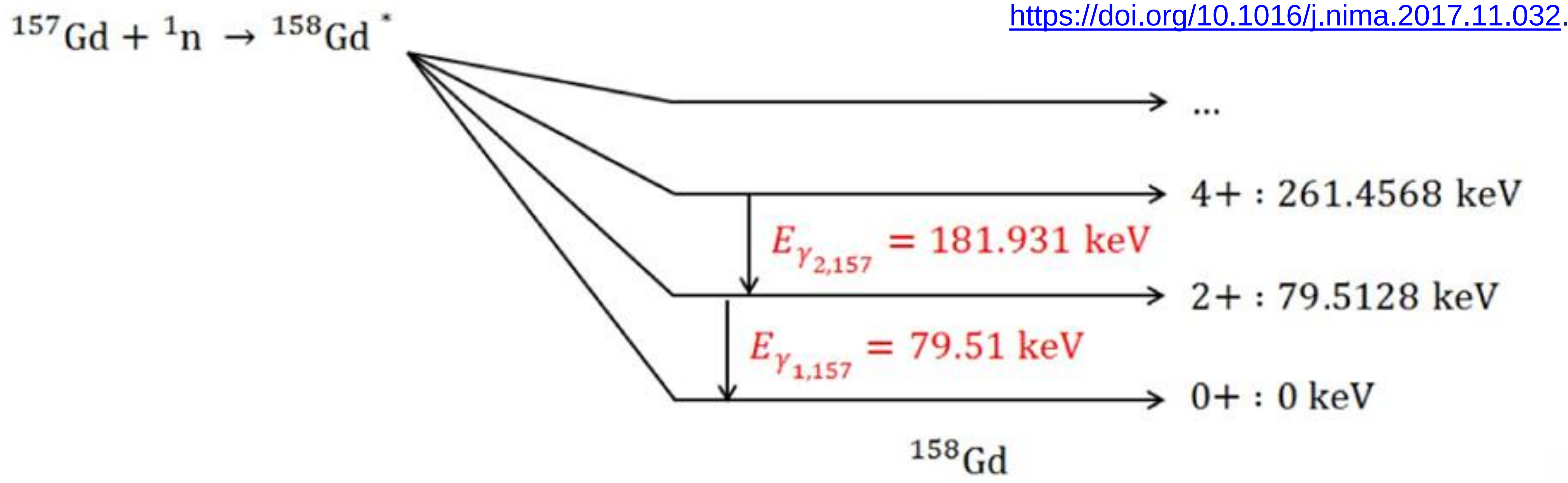
Grabmayr

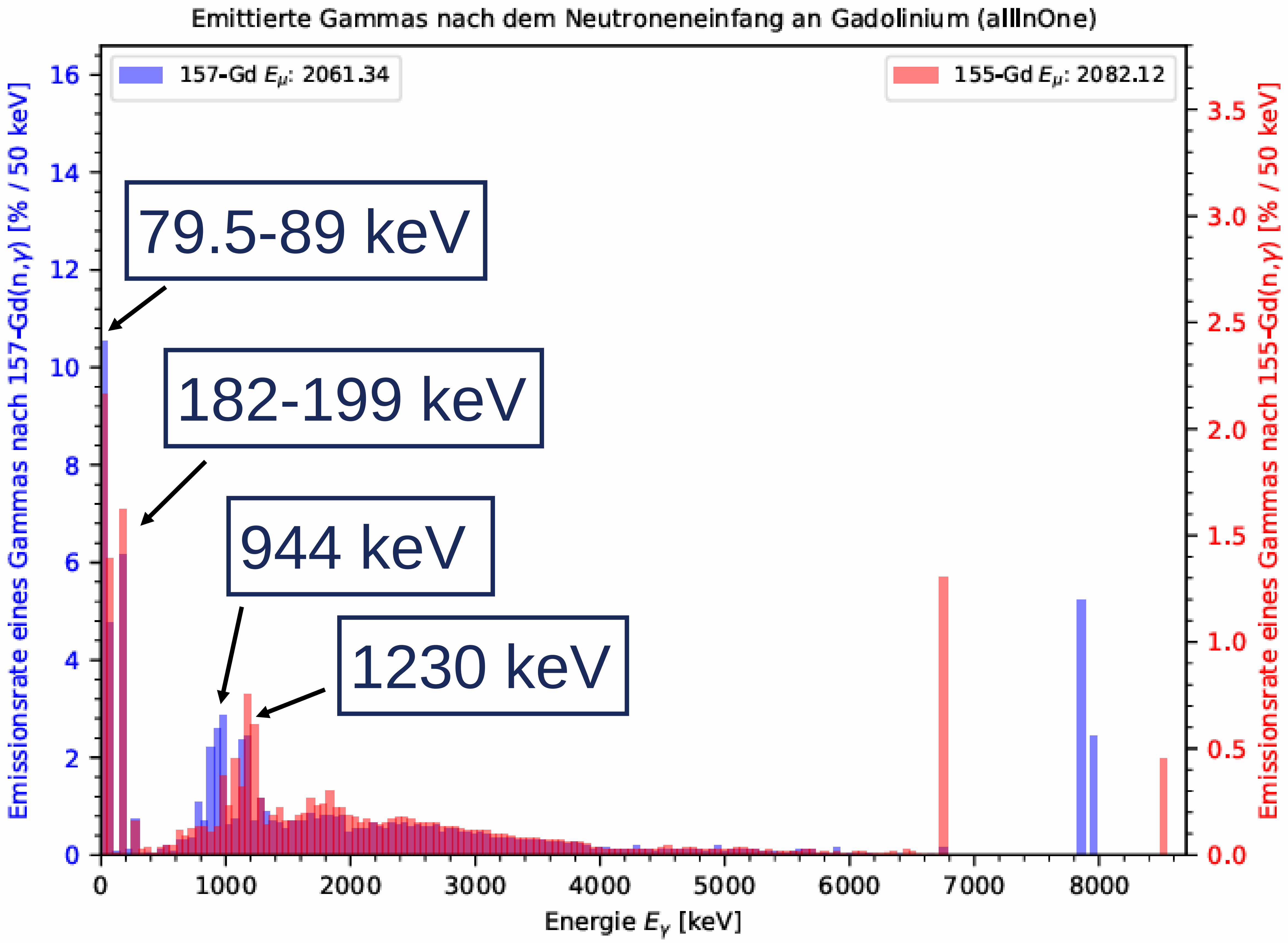


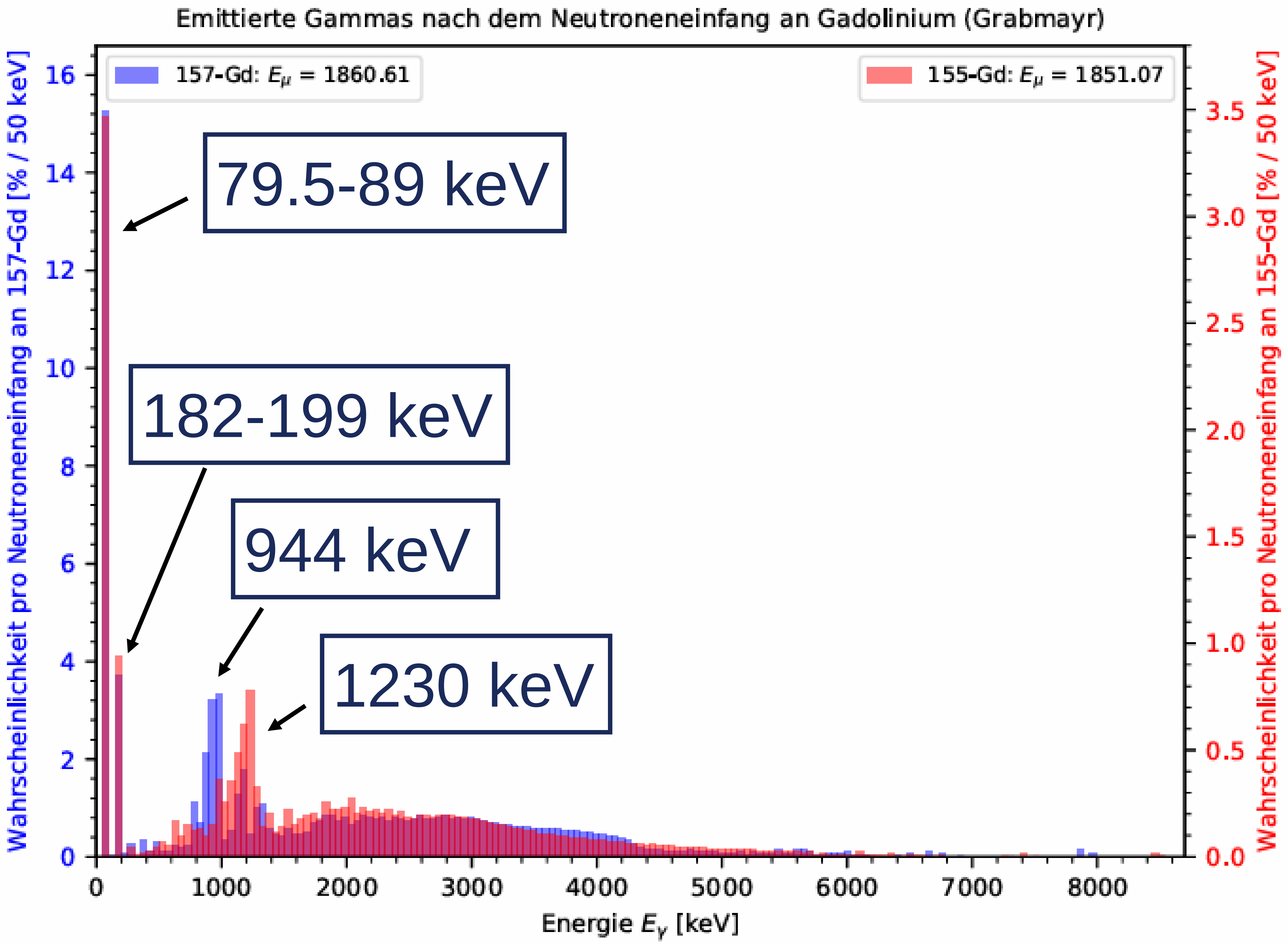
Investigate Geant4s behaviour

Illustration from J. Dumazert et al. doi: https://doi.org/10.1016/j.nima.2017.11.032.









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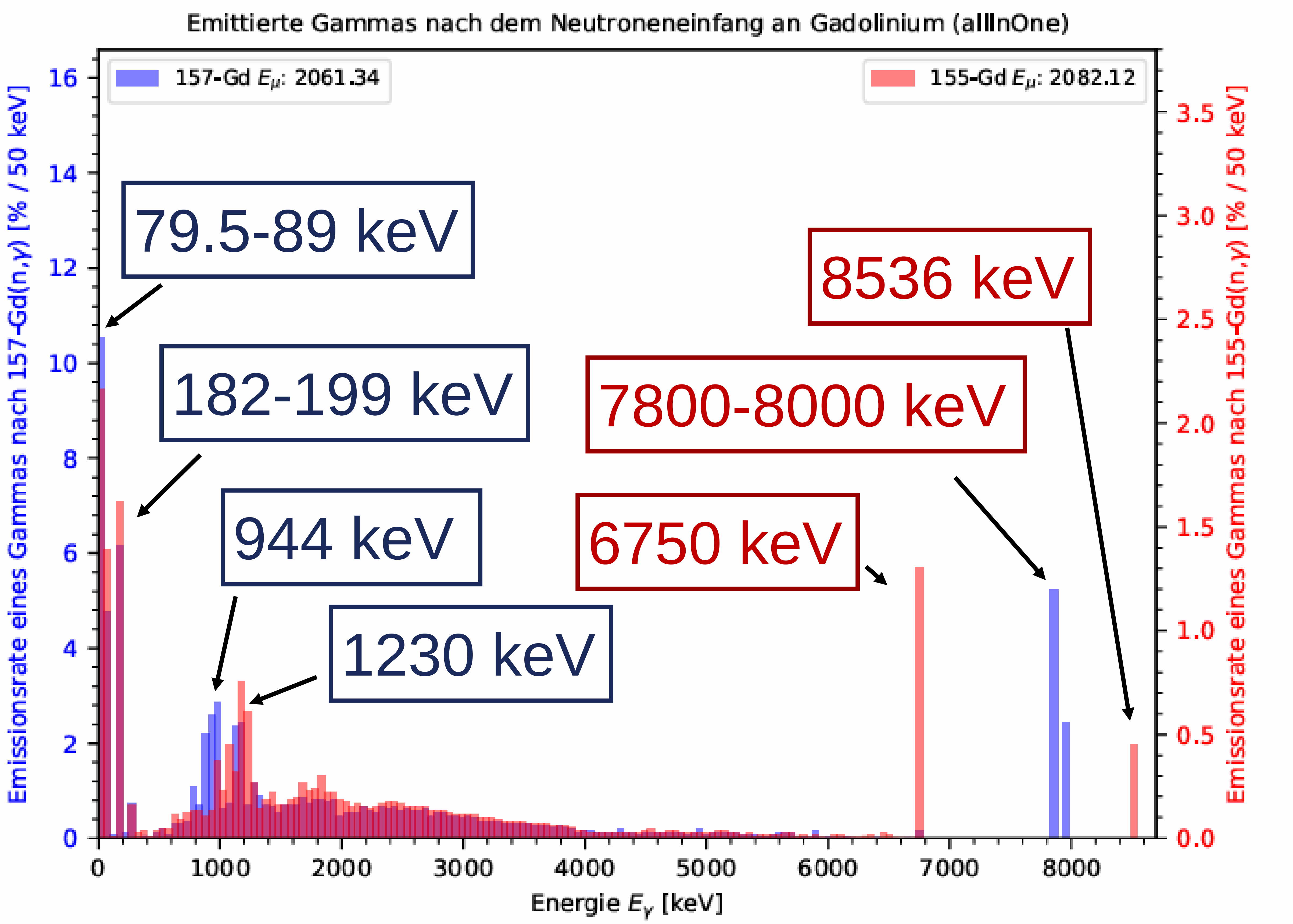
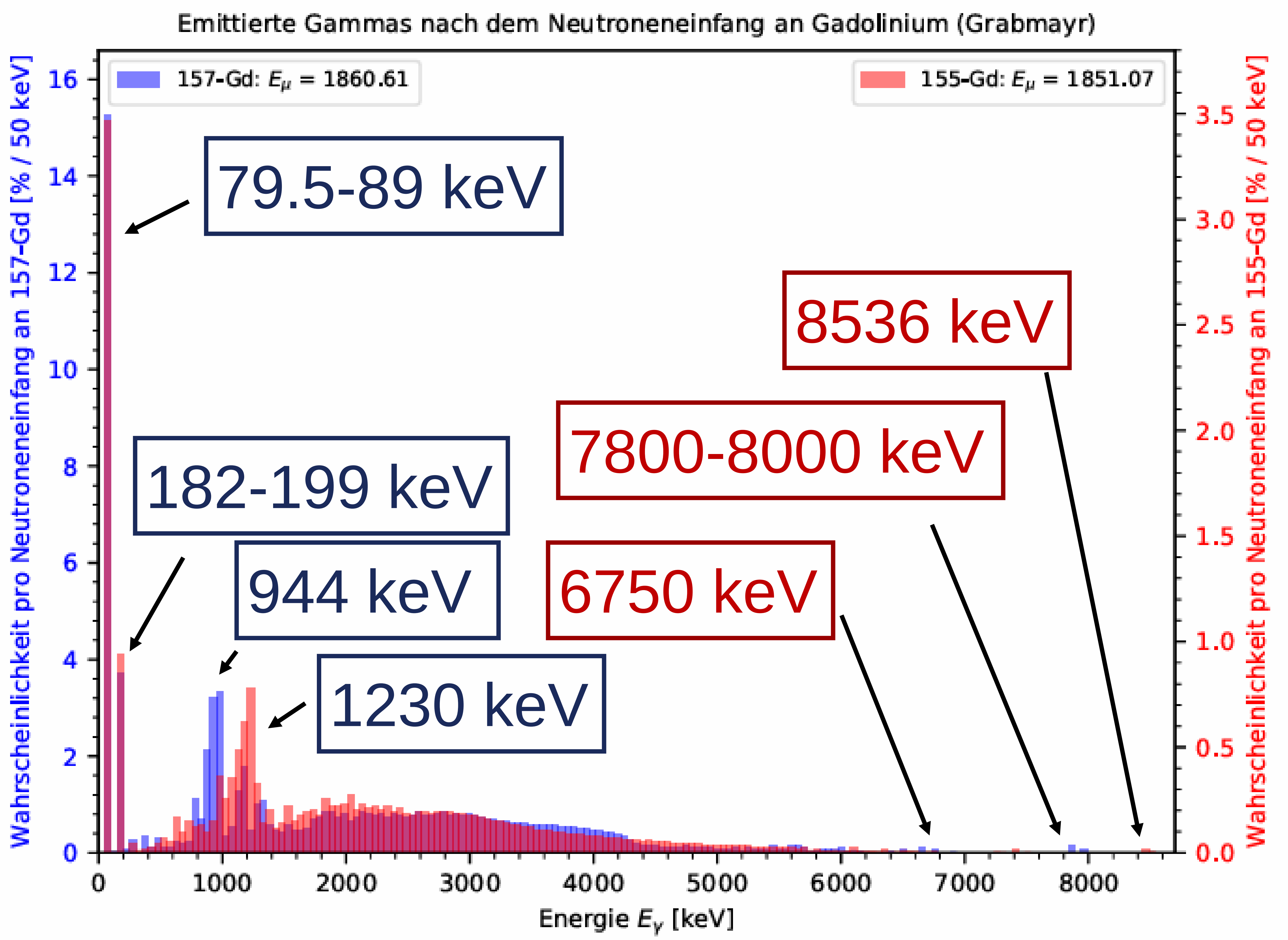
Geant4v11.0.3 “Shielding“



Grabmayr

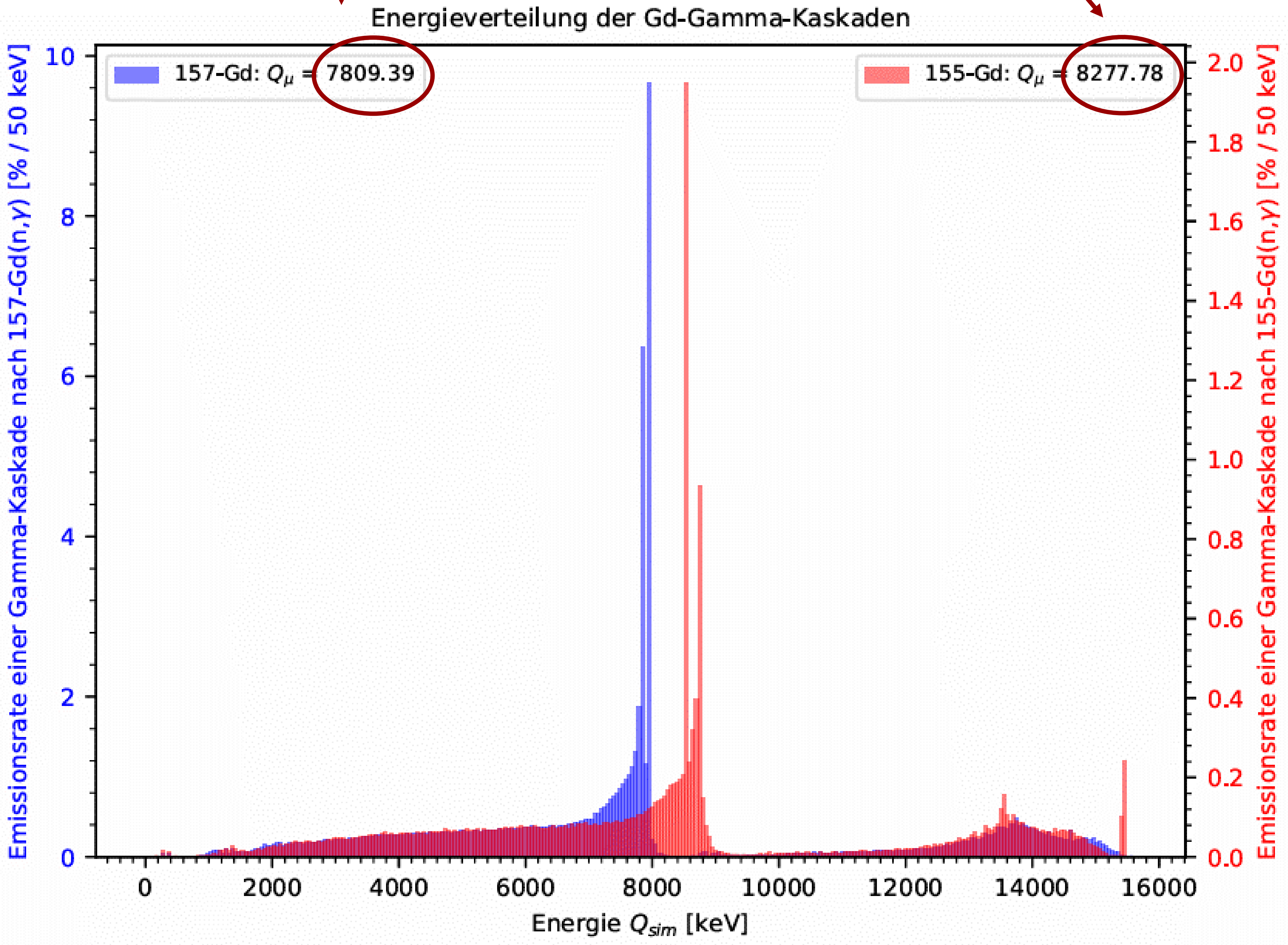


Investigate Geant4s behaviour

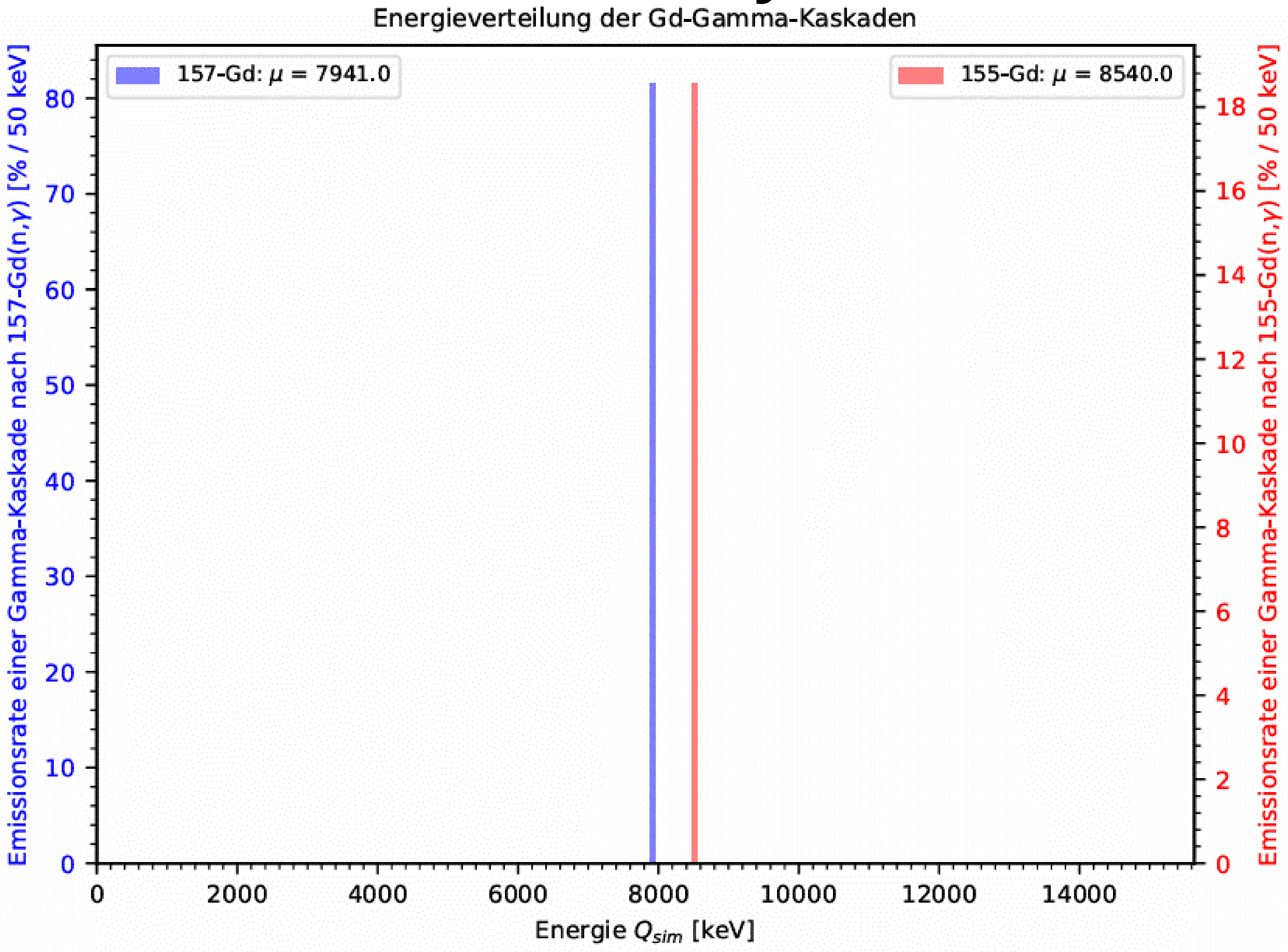
Q-Values are not conserved!

Average Q-Value lower?

Geant4v11.0.3

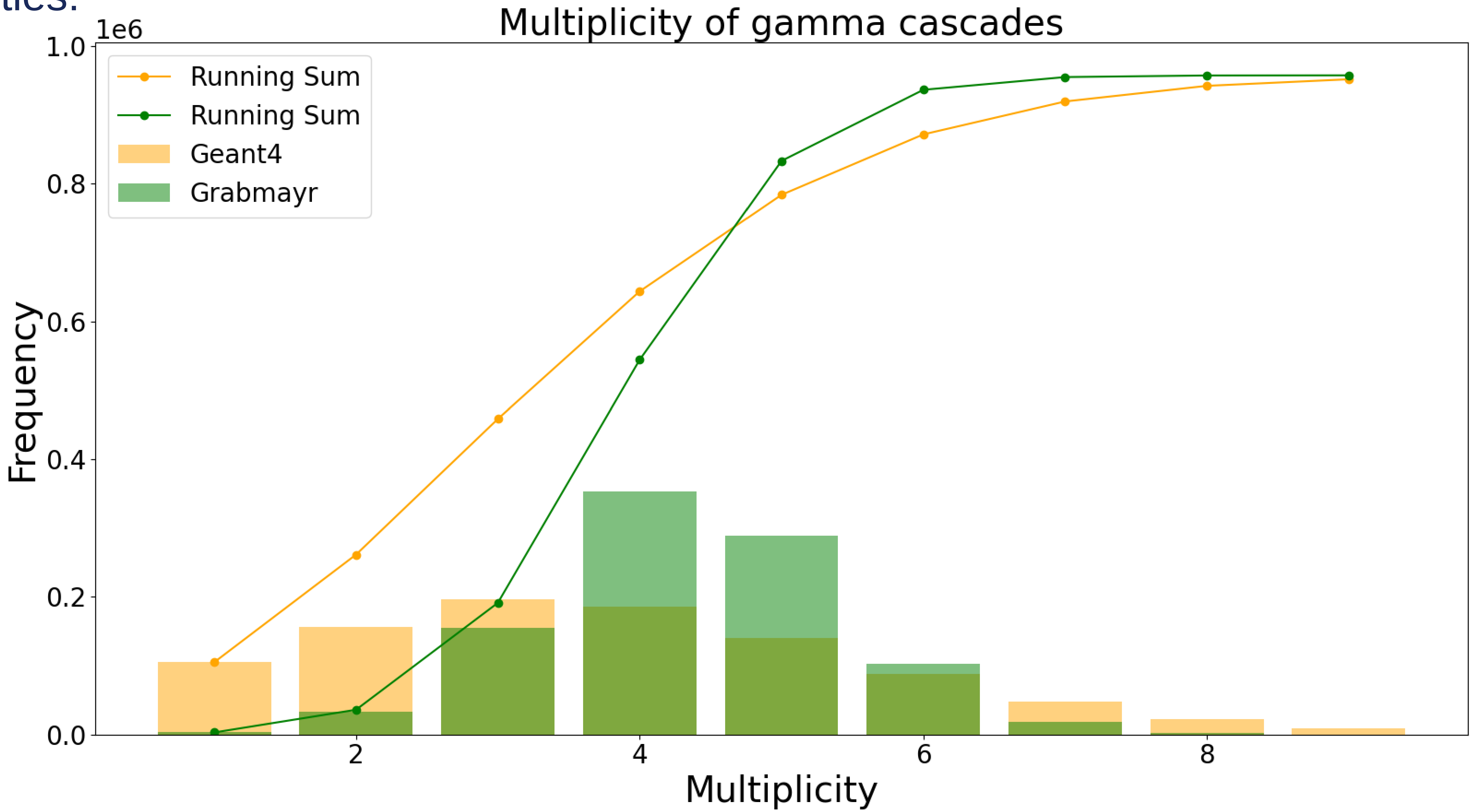


Grabmayr



Investigate Geant4s behaviour

Multiplicities:

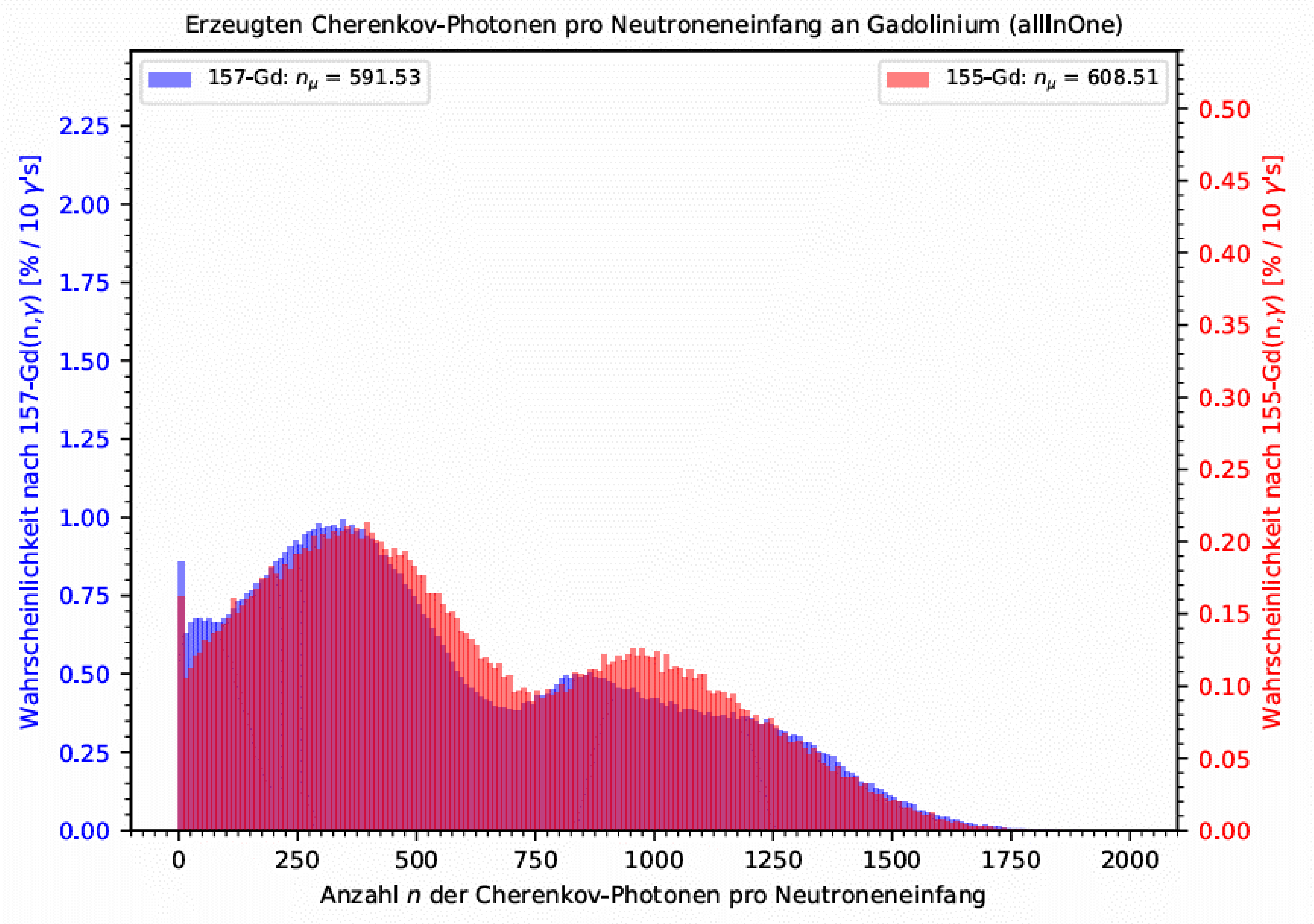


Investigate Geant4s behaviour

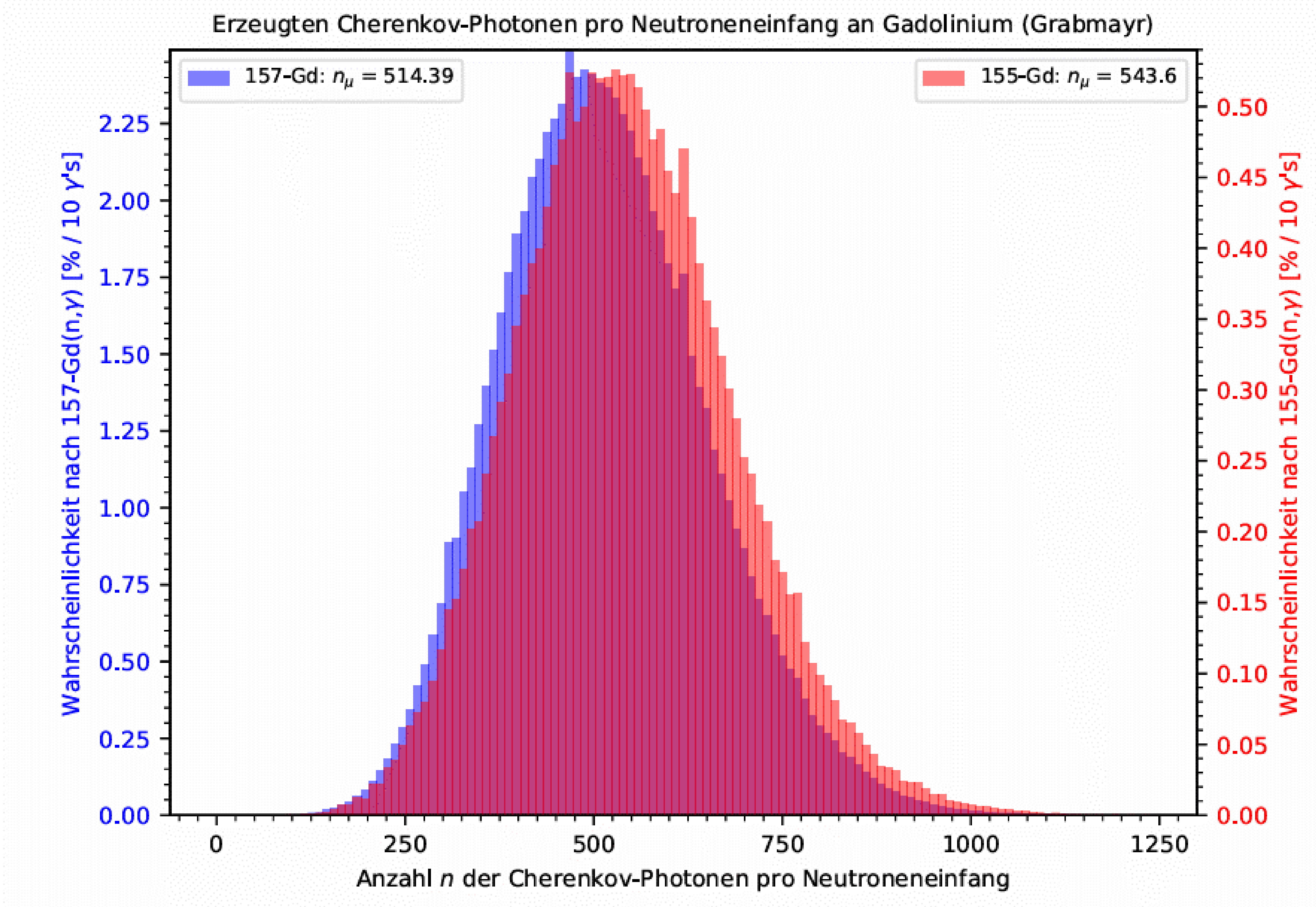
Cherenkov yield:

~ 13% more Cherenkov photons from Geant4

Geant4v11.0.3 “Shielding“



Grabmayr



Conclusion

- Geant4 mean value deviates ~10% from the calculated mean values and prefers lower multiplicites
- Geant4 individual values: 68% outside $\pm$10% of the calculated values
- Geant4 does not conserve energy, therefore we use the Grabmayr version for LEGEND!

BACKUP

Gamma cascades by IAEA