Modeling γ-Rays from the Thermal Neutron Capture on Gadolinium based on J-PARC ANNRI Data

- Sebastian Lorenz[1,2] -

on behalf of

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11th International Workshop on Neutrino-Nucleus Scattering in the Few-GeV Region – NuInt 2017

The Fields Institute, University of Toronto, June 30th 2017

Outline

- Motivation
- GARNET with ANNRI at J-PARC
- Data Analysis and Model Building
- Summary

Motivation
Delayed Coincidence Technique for Inverse Beta Decay

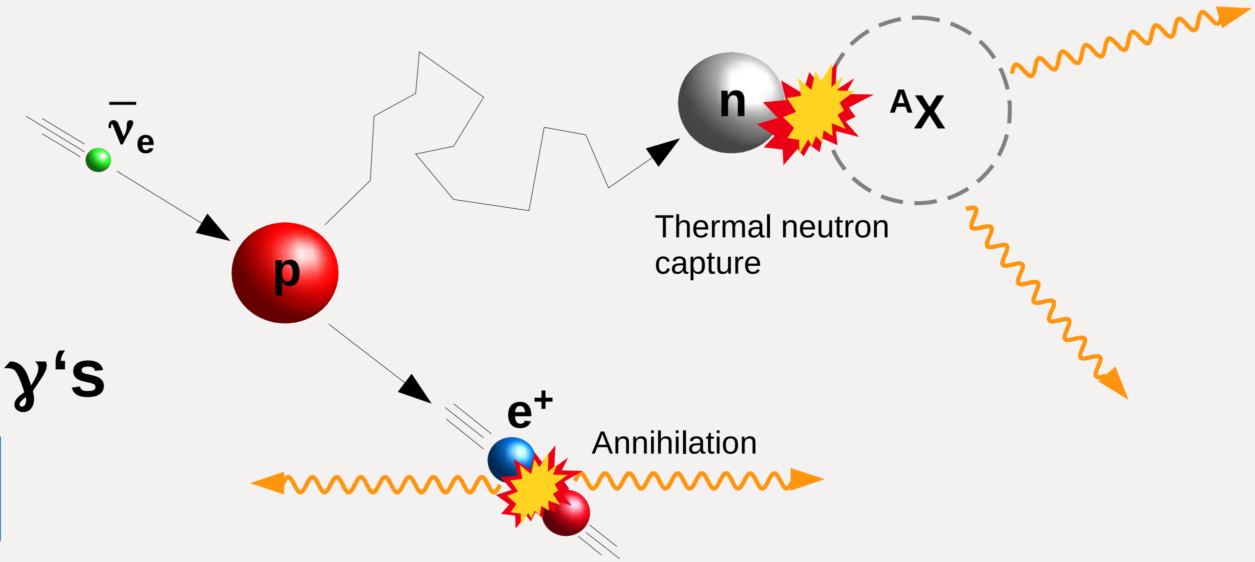
- A common technique for low-energy (few MeV) $\bar{\nu}_e$ detection: Exploit delayed coincidence of signals from inverse beta decay reaction products

$$\bar{\nu}_e + p \rightarrow n + e^+$$

(1) $e^+ + e^- \rightarrow \gamma + \gamma$

(2) $n + {}^{A}X \rightarrow {}^{A+1}X + \gamma\text{'s}$

$$E_\nu = E_{prompt} + 0.78\ \text{MeV}$$



1) Prompt signal (some ns): positron motion + annihilation
2) Delayed signal (some 10s to 100s of μs): γ-ray(s) from **neutron capture**

- Visibility of delayed (“marker“) signal depends on neutron catcher nucleus
- With respect to background rejection, you want a delayed signal that …
  - … follows shortly after the prompt signal → cross-section; concentration
  - … has a strong signature (in face of a Cherenkov threshold) → Q-value

Motivation
Gadolinium as Neutron Catcher

- ✔ Gadolinium (^{157}Gd) has largest thermal neutron capture cross-section among all stable nuclei due to resonance states in thermal energy region
- ✔ High Q-value of >7.9 MeV
- ✔ Incorporation of gadolinium into common target materials demonstrated
- ✗ Excitation energy often released in multiple γ-rays (cascade)
  - ➔ Some γ-rays can escape detection / be below the Cherenkov threshold

Good modeling of the γ-ray spectrum from thermal Gd(n,γ) is important to make reliable neutron tagging efficiency predictions with MC studies!

Isotope	Thermal neutron capture cross-section [barn]	Q-value [MeV]	N_γ
^{155}Gd	61100	8.5	~3-4
^{157}Gd	254000	7.9	~3-4
^{1}H	0.333	2.2	1
^{12}C	0.004	4.9	~1-2
^{16}O	0.189	4.1	~2-3

Side note: Uncertainty for radiative thermal neutron capture x-sec on Gd is about 10%!
[E.g., see Nuclear Science and Engineering: 177, 219–232 (2014)]

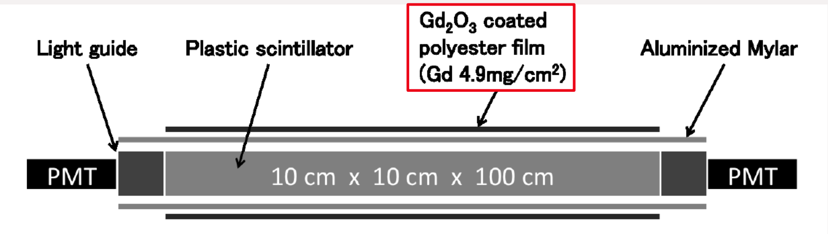
[Neutron News, Vol. 3, No. 3, 1992, pp. 29-37;
Nuclear Data Sheets 141, 1 (2017);
Nuclear Data Sheets 113, 2537 (2012);
TUNL Nuclear Data Evaluation Homepage: www.tunl.duke.edu/nucldata/]

- Gadolinium loading is used in unsegmented ton-scale liquid scintillator $\overline{\nu}_e$ detectors

  Daya Bay, ***Double Chooz***, ***RENO*** (→ θ_{13})

- Gd mass fraction: 0.1% (~1 g per liter)
- Segmented plastic scintillator detectors can put film with Gd-coating between bars

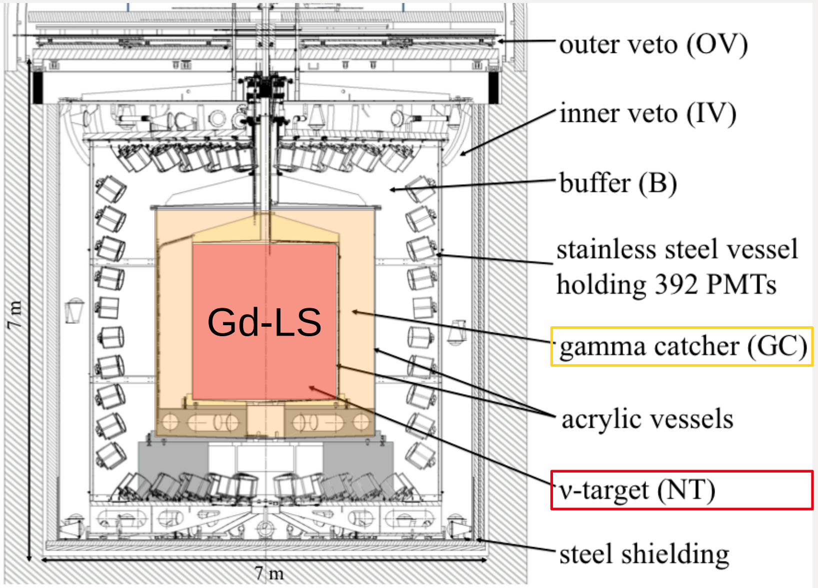
  PANDA (→ reactor monitoring)



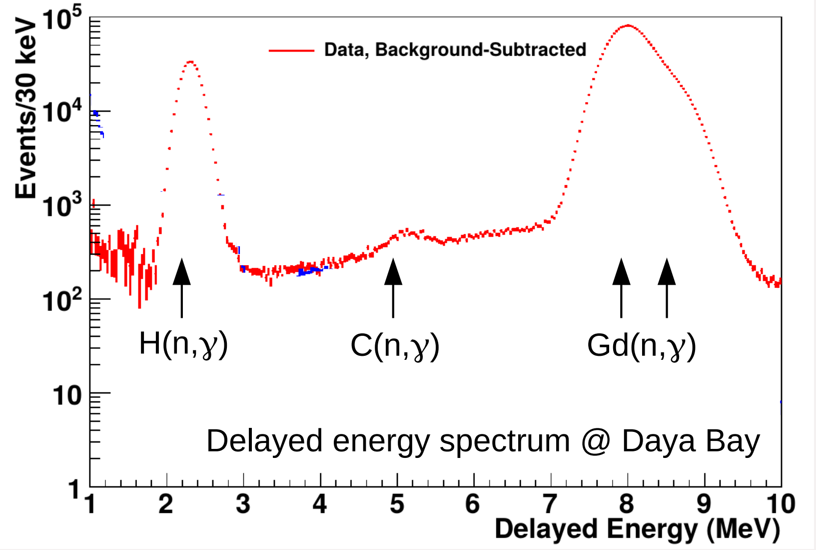
x 10 x 10

[PANDA module schematic; NIM A 757 (2014) 33-39]

- Calorimetric energy measurement
  → **Q-value of n-capture reaction observable if all γ-rays are fully contained**
- Dedicated γ-catcher volume around target or fiducial volume cut!



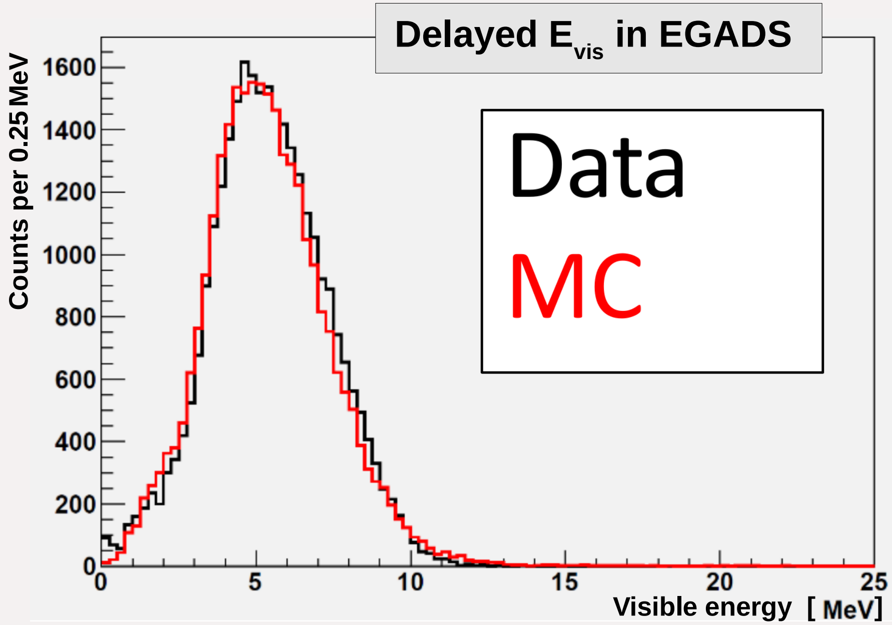
[Double Chooz schematic; Phys.Rev. D86 (2012) 052008]



[Chin.Phys. C41 (2017) no.1, 013002]

Water Cherenkov Detectors

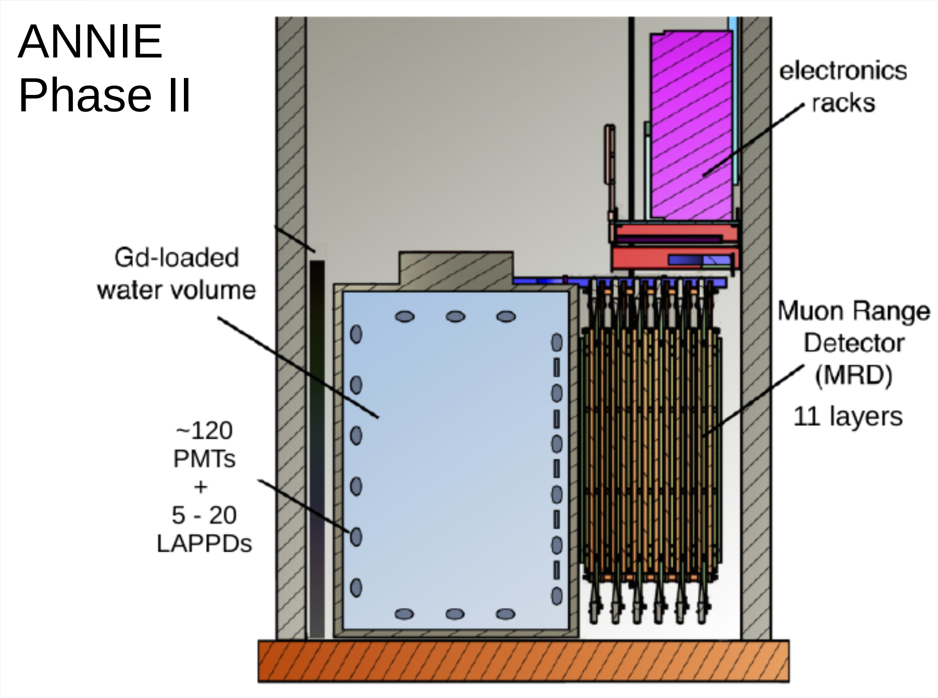
- Neutron tagging with 2.2 MeV γ-rays from $^{1}H(n,\gamma)$ has low efficiency due to Cherenkov threshold → γ's below ~1 MeV produce no Cherenkov light!
- Gd-loading of water would advance this neutrino detector technology → decrease energy threshold for $\bar{\nu}_e$ → e.g., improve SNR-ν flux search
- Sustainable Gd-loading of water was successfully demonstrated by ***EGADS***
- ***Super-K*** will load 100t of $Gd_2(SO_4)_3$ (0.2% concentration) in 2018! → 90% n-capture detection efficiency
- Due to Cherenkov threshold: mean visible energy is below the Q-value of $Gd(n,\gamma)$
- A proper modeling of the energy distribution in the $Gd(n,\gamma)$ cascade is important for MC-based efficiency studies!

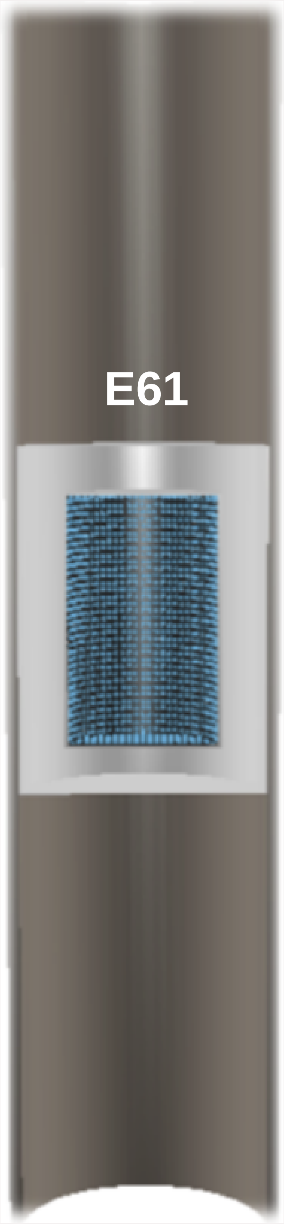


[H.Sekiya (Neutrino 2016)]

Water Cherenkov Detectors – E61 and ANNIE

- Gd will also be used for neutron multiplicity measurements in...
  - the ***E61 JPARC Intermediate Water Cherenkov Detector***
    [Talk by *Blair Jamieson* on Thursday]
  - **ANNIE**
    [Talk by *Marcus O'Flaherty* on Thursday]





GARNET with ANNRI at J-PARC
Overview

- Project: ***GA**mma-**R**ays produced in gadolinium **N**eutron capture **E**xperiment and γ-ray **T**ransition model*
- Measured γ-ray spectra from Gd(n,γ) reaction with thermal neutrons
- Two data-takings with the ***A**ccurate **N**eutron-**N**ucleus Reaction Measurement **I**nstrument* (**ANNRI**) of the ***M**aterials and **L**ife Science Experimental **F**acility* (MLF) at J-PARC
- Neutron targets:
  - Natural Gd film (99.99%), 5 mm x 5 mm x 10, 20 μm
  - Enriched ^{155}Gd (91.65%) / ^{157}Gd (88.4%) in Gd_2O_3 powder
- Development of a Gd γ*-ray* cascade model for GEANT4 with GARNET detector simulation

Composition of natural gadolinium

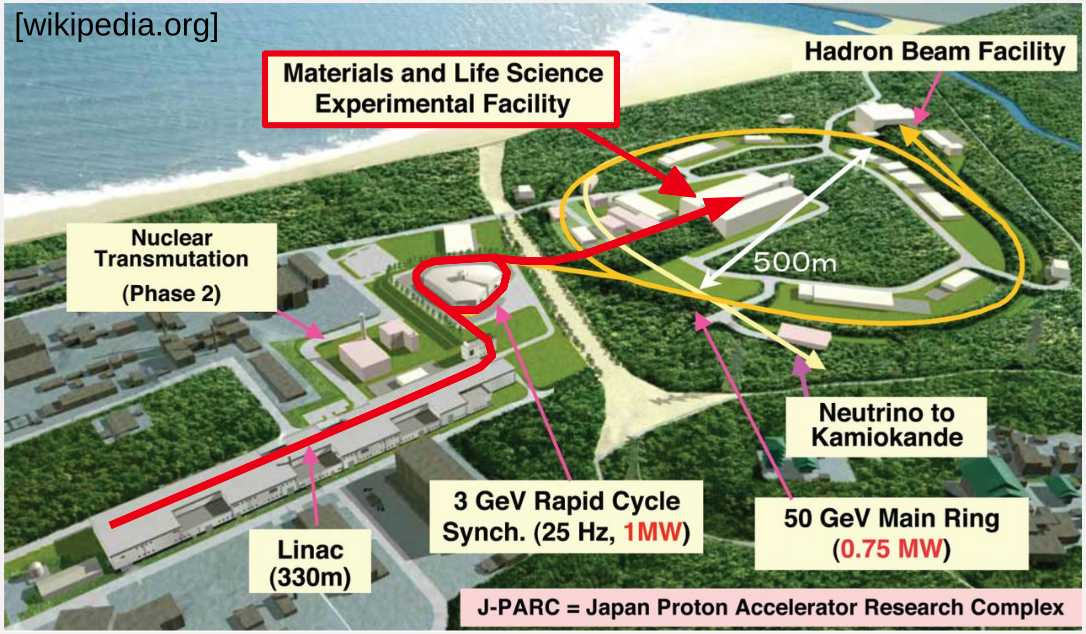
Isotope	Abundance ratio [%]	Thermal capture cross section [barn]
^{152}Gd	0.200	740
^{154}Gd	2.18	85.8
^{155}Gd	14.80	61100
^{156}Gd	20.47	1.81
^{157}Gd	15.65	254000
^{158}Gd	24.84	2.22
^{160}Gd	21.86	1.42

at 25 meV neutron energy

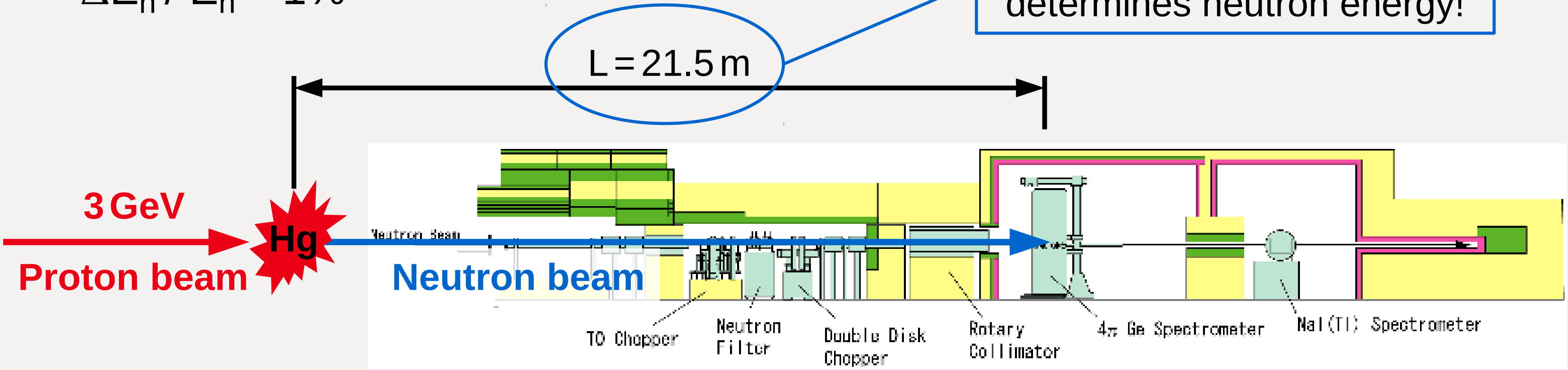
- First measurement of γ-ray spectrum from Gd(n,γ) in [0.1, Q-val] MeV with large statistics, small background (<1%) and excellent energy resolution

ANNRI at MLF

- ANNRI is located at beamline 04 of MLF
- Neutron source:
  - 3 GeV protons on Hg target
  - about 300 kW proton power
  - intensity at Gd target: 1.3×10^{11} n/(s m²) in $E_n = [1.5, 25]$ meV range
  - $\Delta E_n / E_n \sim 1\%$

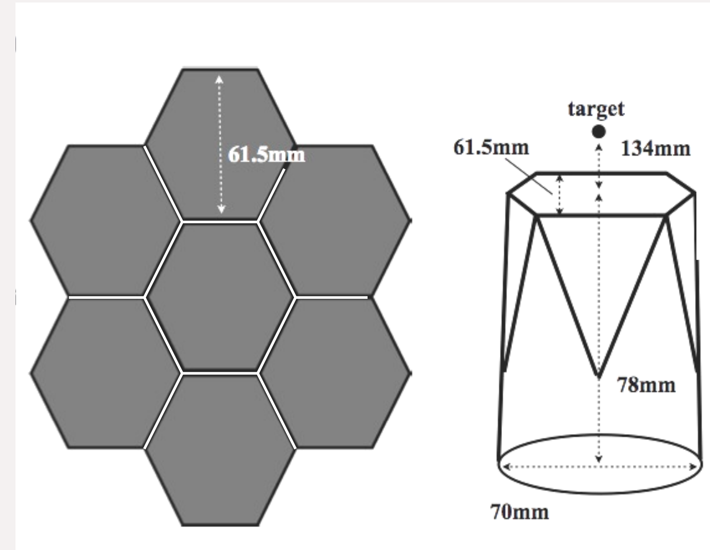


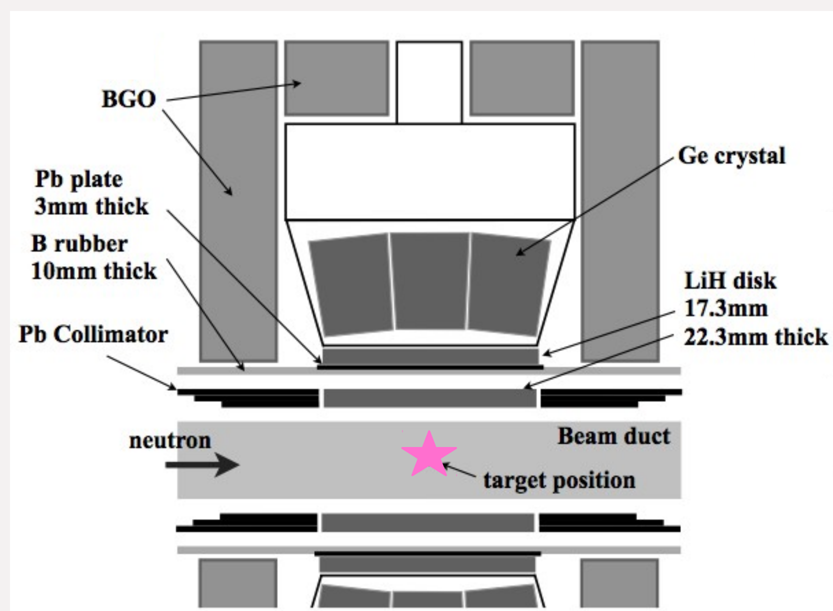
Neutron time-of-flight along L determines neutron energy!

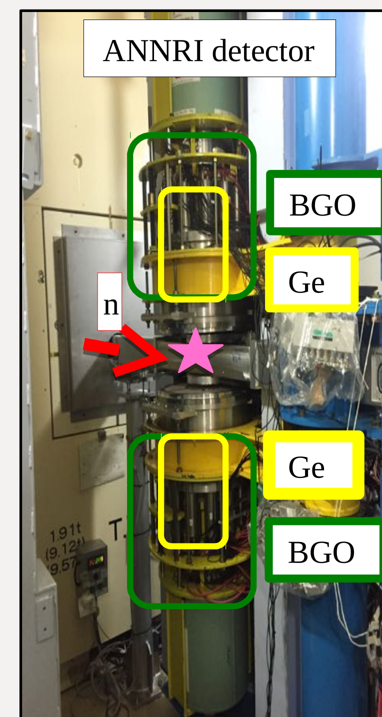


ANNRI – Germanium Spectrometer

- Used instrumentation:
  - 2 Ge clusters (2 x 7 hexagonal crystals)
  - 2 BGO veto shields
- Energy calibration / efficiency determination:
  - Sources: ^{22}Na, ^{60}Co, ^{137}Cs, ^{152}Eu,
  - Targets: NaCl(n,γ); empty target holder for background measurement
- Energy resolution of one Ge crystal:
  ~9.2 keV (FWHM) @ 1.3 MeV
- Full-energy peak efficiency:
  2.2% @ 1.3 MeV
  (all 14 Ge crystals combined)
- Solid angle coverage:
  - 2 Ge clusters: 22%
  - 2 BGO vetoes: 55%







Data Analysis and Model Building

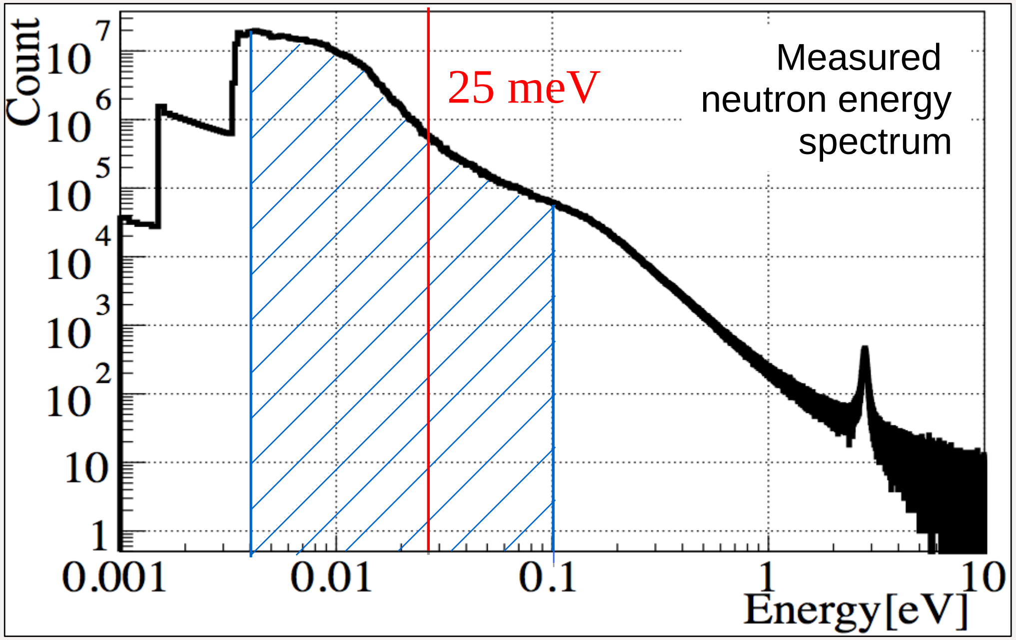
Event selection / Multiplicity Assignment / γ-Ray Energy

- **Event selection:**
  Only events in the thermal neutron energy range 4-100 meV

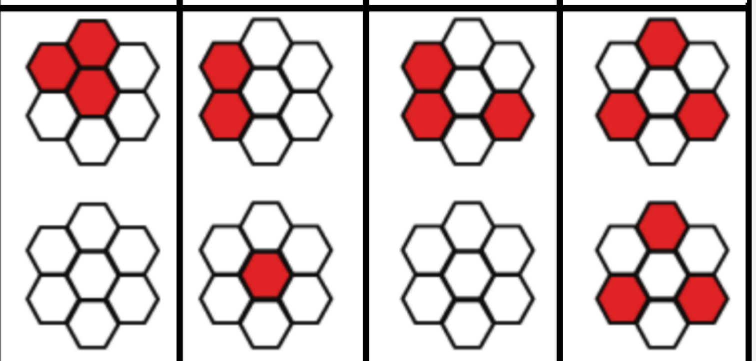
- **γ-ray multiplicity M:**
  - Number of disconnected crystal sub-clusters over both Ge clusters
  - $M \leq$ true γ-ray multiplicity due to
    - ➔ limited solid angle coverage
    - ➔ Compton scattering over multiple crystals

- **Hit count H:** number of hit crystals

- **Reconstructed γ-ray energy:**
  Amount of deposited energy in sub-cluster



M	1	2	2	6 (MAX)
Up				
Down				
H	3	3	3	6



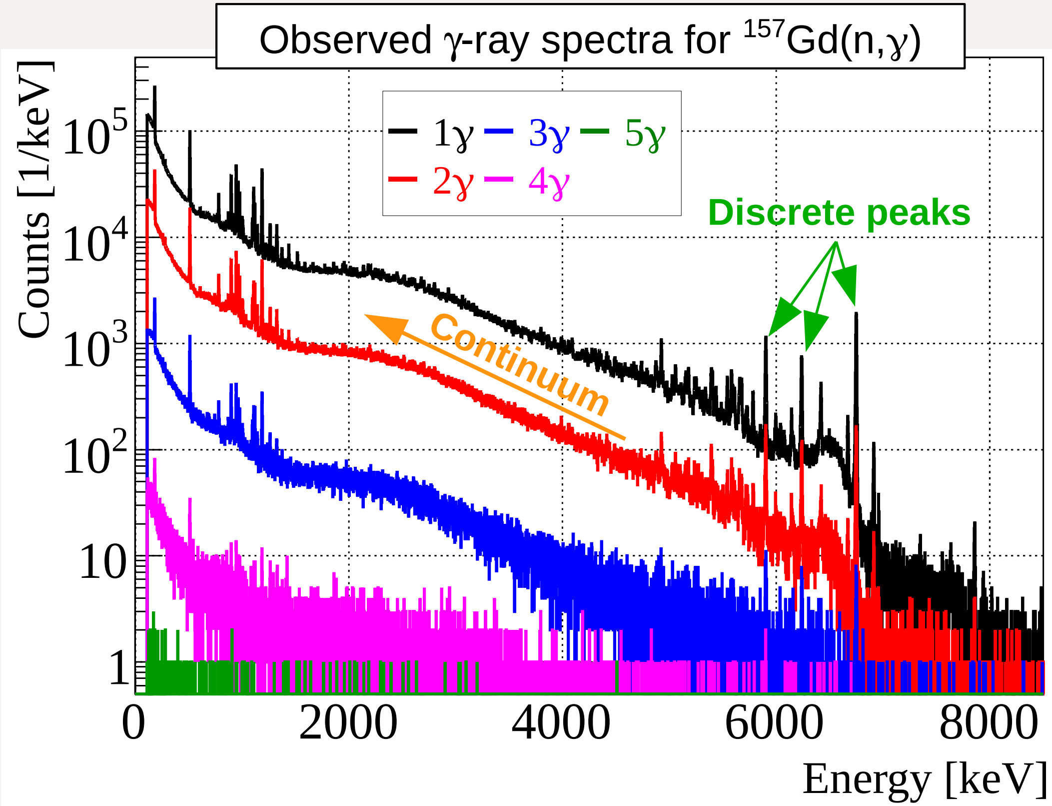
- Large event samples; more than 3×10^9 events per Gd target

Target	Time	Number of Events	Source	Time	Number of Events
Nat. Gd	116 hours	3.5×10^9	^{22}Na	5 minutes	1.5×10^7
$^{155}Gd_2O_3$	38 hours	3.1×10^9	^{60}Co	18 hours	8.8×10^7
$^{157}Gd_2O_3$	55 hours	4.6×10^9	^{137}Cs	30 minutes	2.1×10^6
NaCl	4 hours	1.3×10^8	^{152}Eu	7 hours	2.3×10^7
Empty	6 hours	1.3×10^7			

- Sub-samples for different γ-ray multiplicities
- For MC model building: describe spectrum by two parts
  - **Discrete peaks**
  - **Continuum**

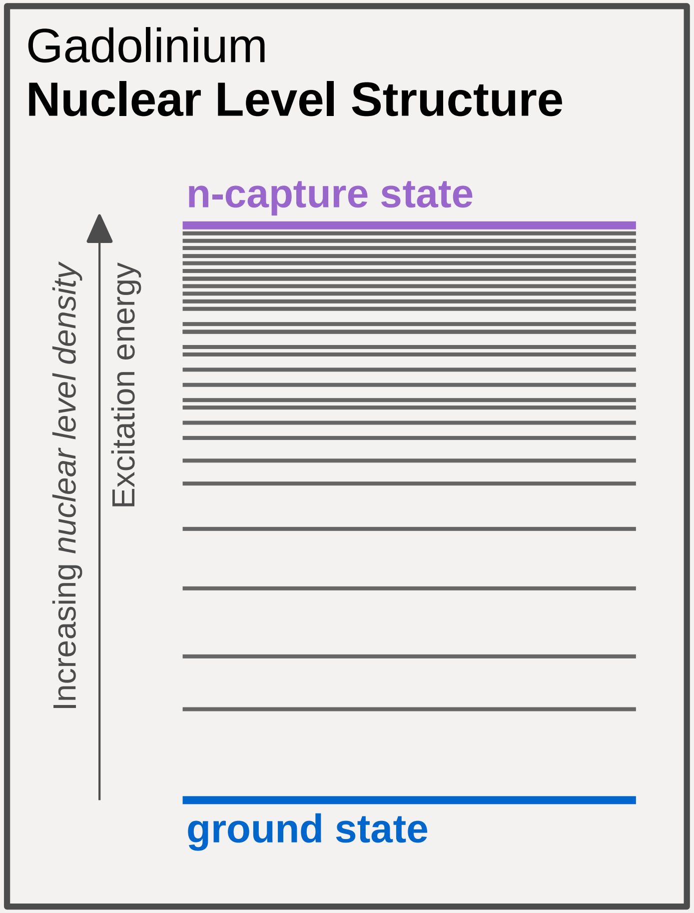
  = same approach GLG4sim[1] uses for GEANT4 simulations

In the following: only ^{157}Gd(n,γ)

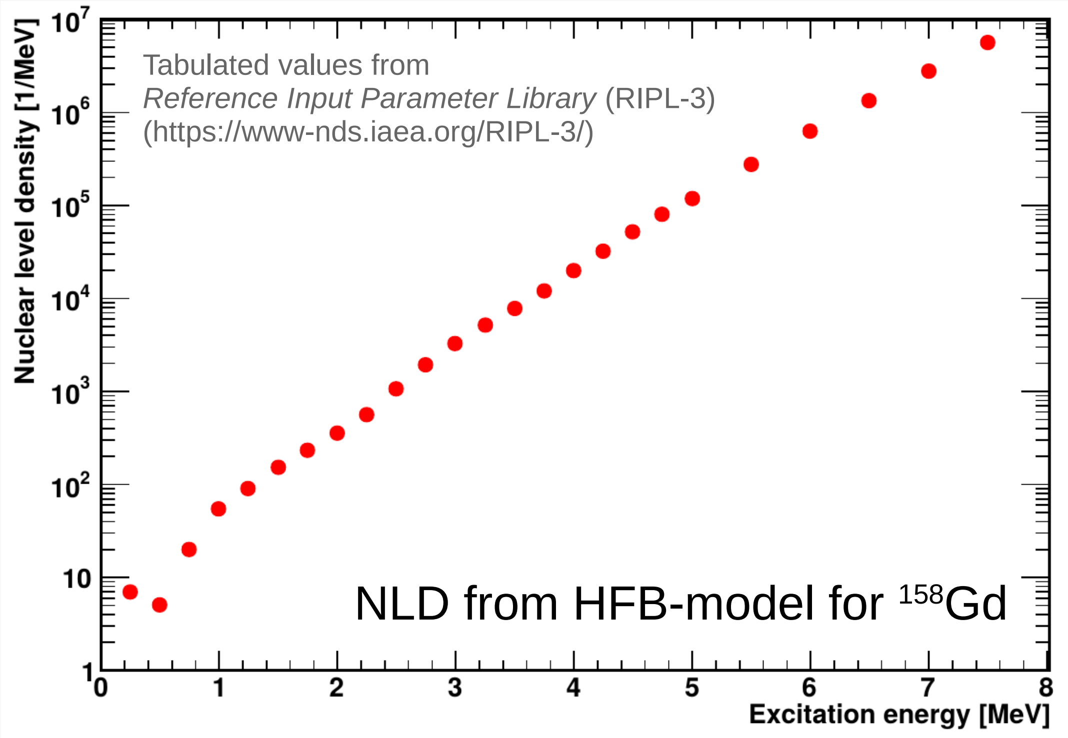


[1] *Generic Liquid-scintillator Anti-Neutrino Detector Geant4 simulation* http://neutrino.phys.ksu.edu/~GLG4sim/ - last updated 2005

- Gadolinum (Z=64; A~152–160 for nat. Gd) has a complex nuclear level structure
- *Nuclear Level Density* (NLD) ρ(E) increases with rising excitation energy
  Discrete nuclear levels → a quasi-continuum of nuclear levels
- Example ^{158}Gd: NNDC[1] lists about 220 discrete levels up to ~4 MeV, but there are many more!



- We use tabulated values of ρ(E) from the Hartree-Fock-Bugoliubov (HFB) model[2]

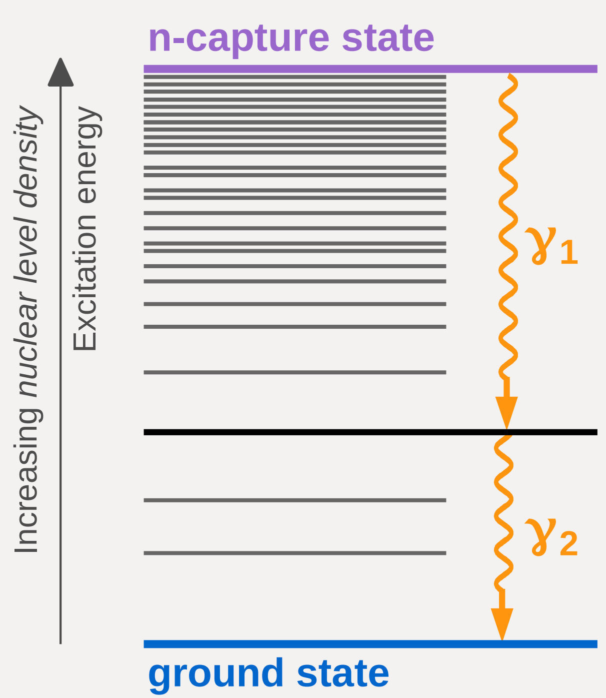


[1] *National Nuclear Data Center* (https://www.nndc.bnl.gov/)
[2] E.g., see Capote et al.: Nuclear Data Sheets 110 (2009) 3107–3214

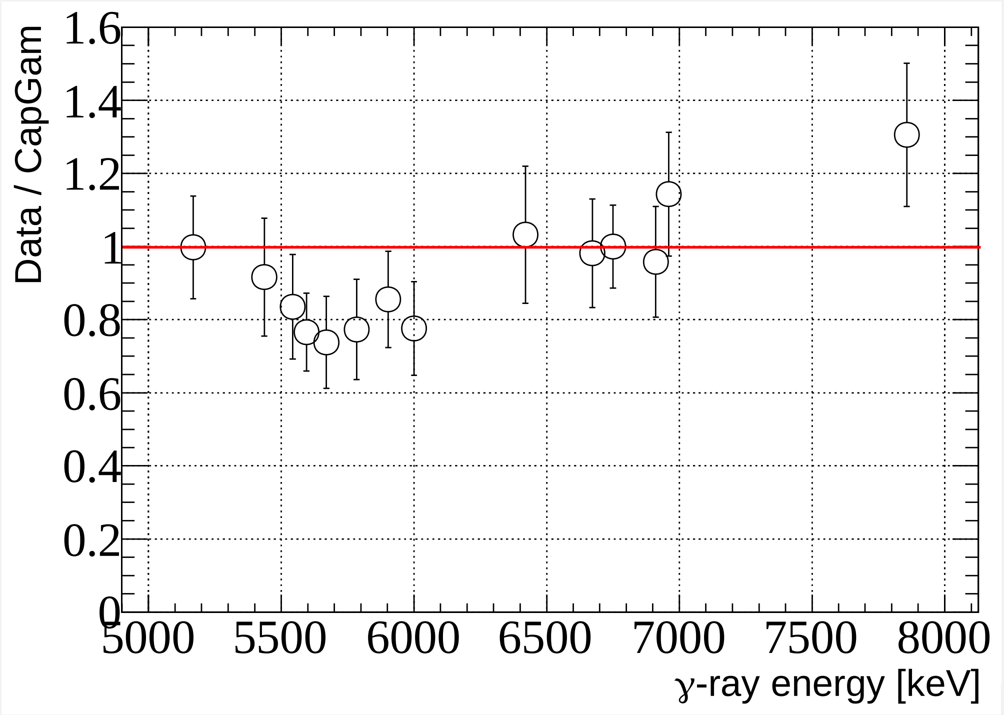
^{157}Gd(n,γ) - Discrete Peaks in γ-Ray Spectrum

- Discrete peaks are fixed, prominent transitions between nuclear levels
- We identified 15 discrete peaks in our data (prompt γ-ray energies from 7937 to 5167 keV)
- They are directly included into our model (GLG4sim uses 6 peaks)
- Their strengths are tuned to match our data
- For E > 110 keV, they contribute (6.8 ± 0.1)% to our data

Gadolinium disexcitation
Discrete Peaks



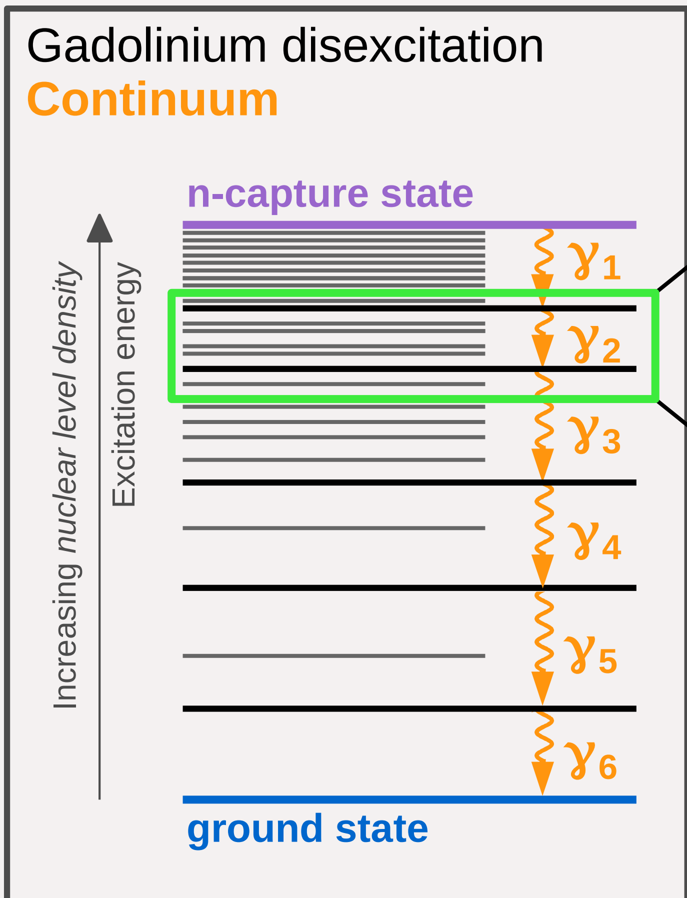
- Our relative intensities of prompt γ-rays agree with *CapGam*[1] values within about ±30%



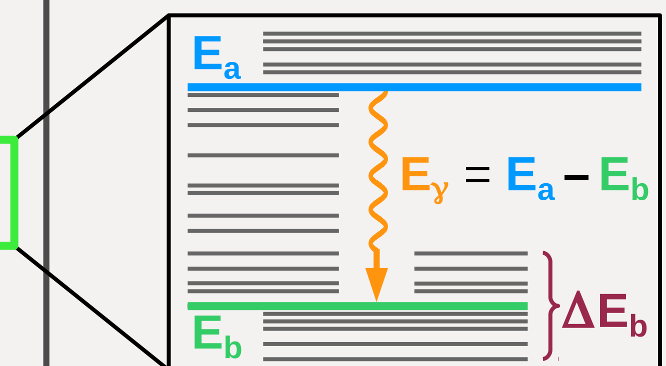
[1] *Thermal Neutron Capture γ's* from NNDC (http://www.nndc.bnl.gov/capgam/)

^{157}Gd(n,γ) – Continuum Spectrum

- Continuum spectrum stems from (numerous) random transitions – especially within the high NLD domain;
- It contributes (93.2 ± 0.1)% to our data (E > 110 keV)



- We use a statistical model to calculate the transition probability P from E_a to E_b based on



- the NLD ρ(E),
- the *Photon Strength Function* (PSF) $f(E_\gamma,T)$:

$$P(E_a,E_b) = \frac{\mathrm{d}P}{\mathrm{d}E}(E_a,E_b)\,\Delta E_b = \frac{T(E_\gamma)\rho(E_b)\Delta E_b}{\int_0^{E_a} T(E_\gamma)\rho(E_b)\mathrm{d}E_b}, \qquad T(E_\gamma) = 2\pi E_\gamma^3 f(E_\gamma,T)$$

Transmission coeff. for E1 transition

- Only E1 transitions considered

$$P(E_a,E_b) = \frac{\mathrm{d}P}{\mathrm{d}E}(E_a,E_b)\,\Delta E_b = \frac{T(E_\gamma)\rho(E_b)\Delta E_b}{\int_0^{E_a} T(E_\gamma)\rho(E_b)\mathrm{d}E_b}, \quad T(E_\gamma) = 2\pi E_\gamma^3 f(E_\gamma,T)$$

Transmission coeff. for E1 transition

- For the PSF of the E1 transitions we use the *Enhanced Generalized Lorentzian* (EGLO) model[1] for a deformed nucleus

$$f(E_\gamma,T) = \sum_{i=1}^{2}\left[\frac{E_\gamma\Gamma_i(E_\gamma,T)}{\left(E_\gamma^2-E_i^2\right)^2 + E_\gamma^2\Gamma_i^2(E_\gamma,T)} + 0.7\frac{\Gamma_i(E_\gamma=0,T)}{E_i^3}\right]\sigma_i\Gamma_i$$

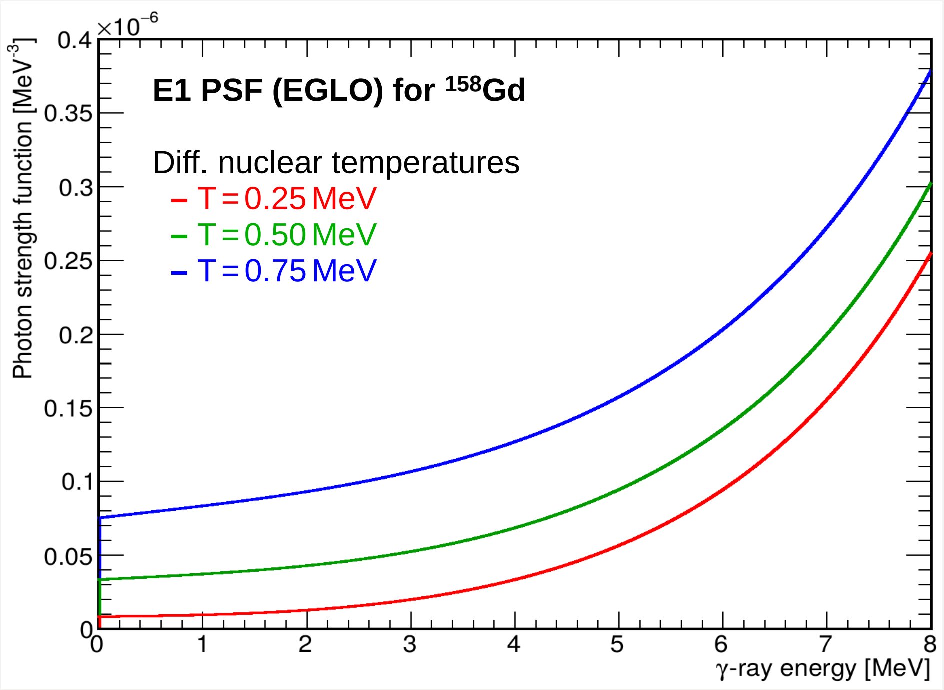
with

$$\Gamma_i(E_\gamma,T) = \left[k_0 + \frac{E_\gamma-\varepsilon_0^\gamma}{E_i-\varepsilon_0^\gamma}(1-k_0)\right]\frac{\Gamma_i}{E_i^2}\left(E_\gamma^2+4\pi^2T^2\right)$$

and the E1 resonance paramters

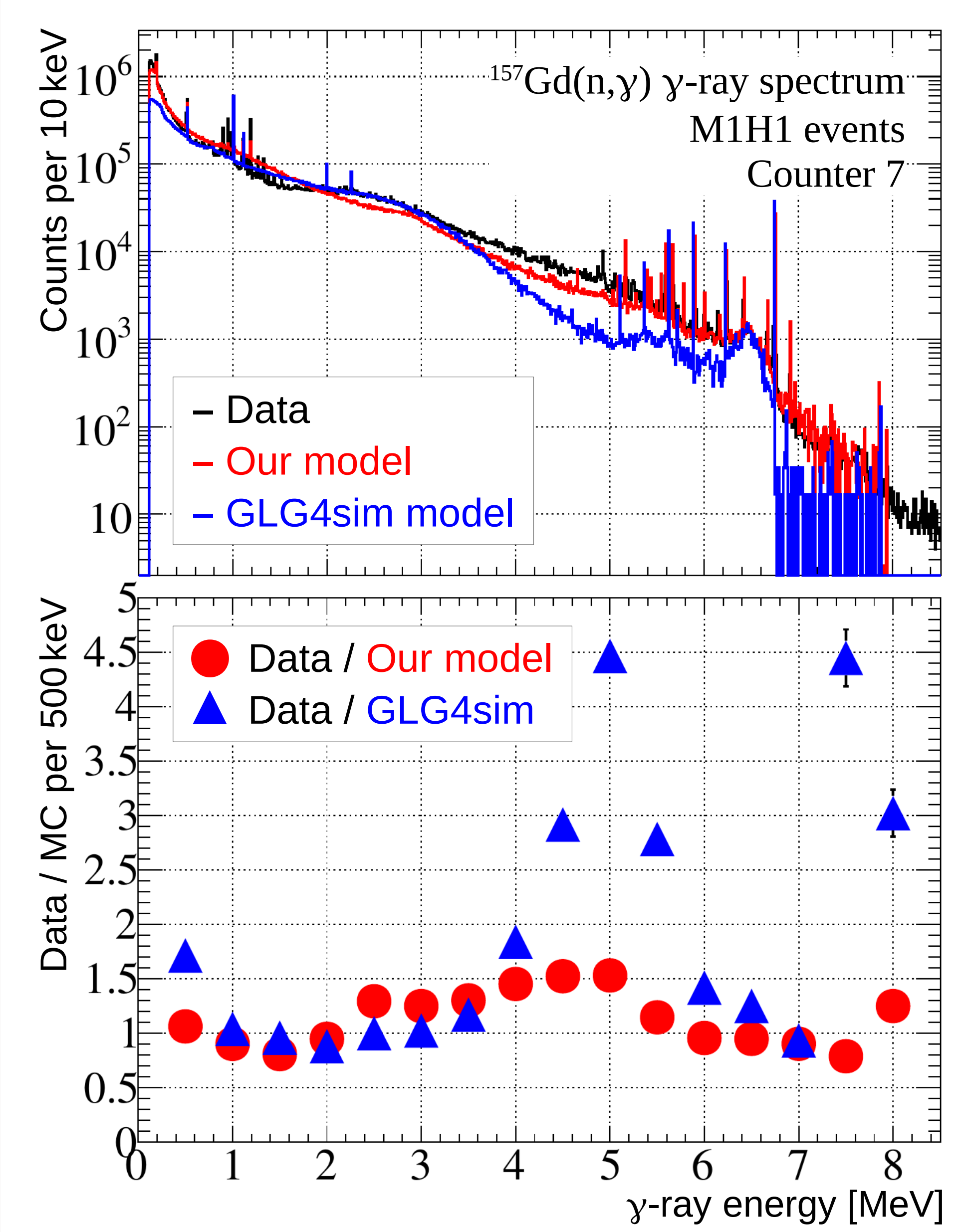
	Energy (E_i) [MeV]	Strength (σ_i) [mb]	Width (Γ_i) [MeV]
^{158}Gd	11.7	165	2.6
	14.9	249	3.8

[From RIPL-2; see also Phys. Rev. C 47, 312]



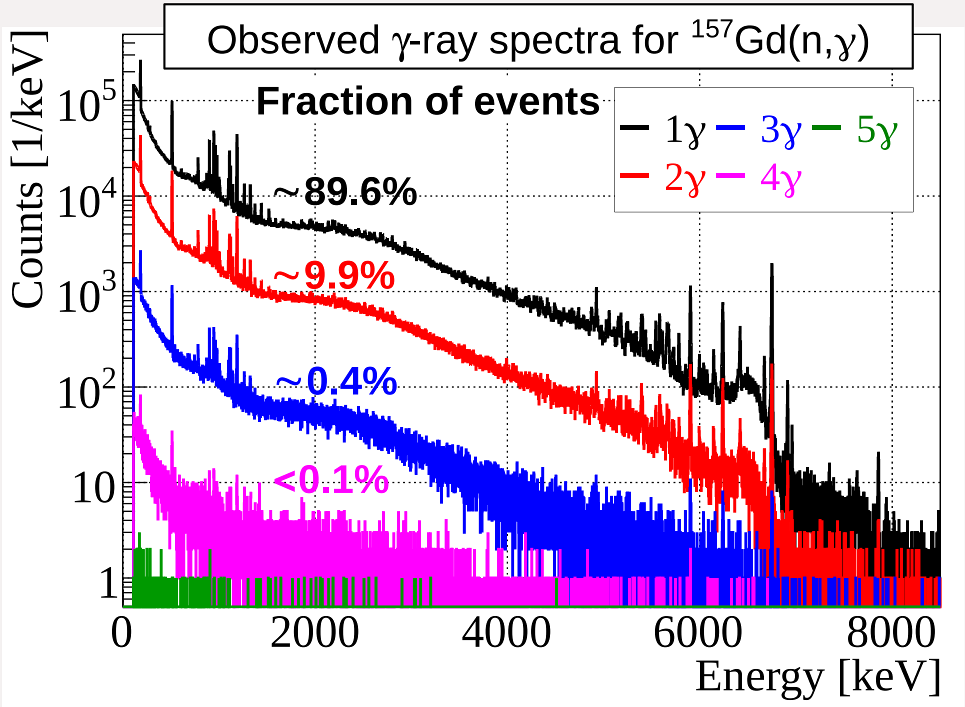
[1] E.g., see Capote et al.: Nuclear Data Sheets 110 (2009) 3107–3214

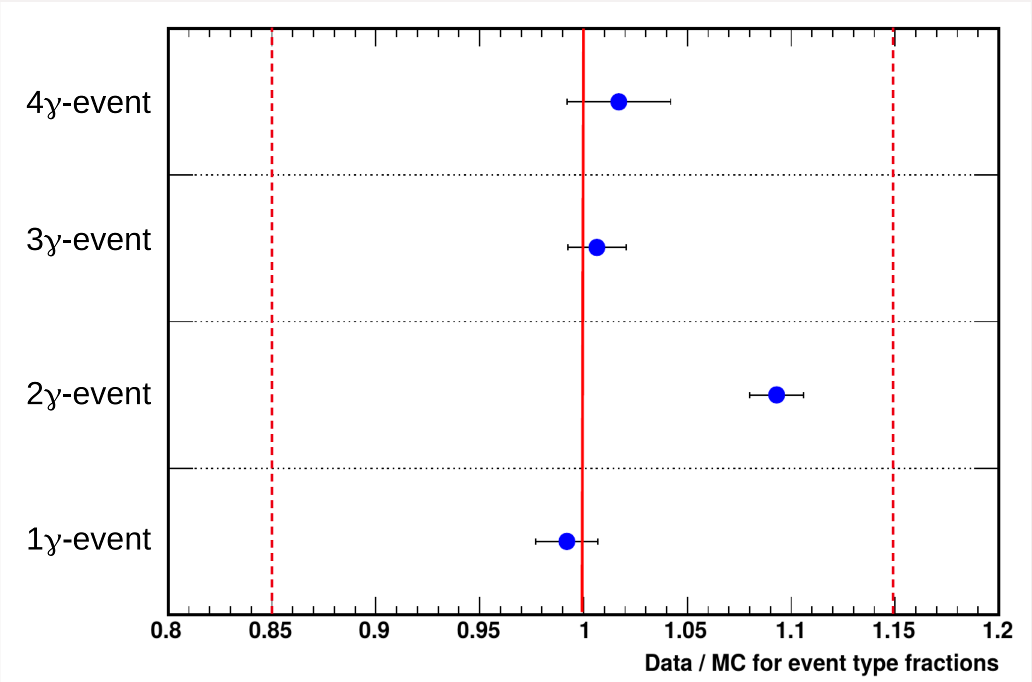
^{157}Gd(n,γ) – Models vs. Data – Spectrum



- Compare full model to data (continuum + discrete peaks)
- For single-γ-ray events (M1H1): agreement within about ±50% at ΔE = 500 keV
- Our model shows a better performance than the GLG4sim model
- Analysis is ongoing!
- Use different models for NLD / PSF

^{157}Gd(n,γ) – Model vs. Data – Event Class Fractions





- We also compare the fractions of the different event classes (γ-ray multiplicities) in data and MC
- For the considered event classes, the agreement between data and MC is well within ±15%

Summary

- Gadolinium is a popular additive in neutrino detectors to enhance the delayed neutron capture signal of an IBD event
- Precise knowledge of the γ-ray spectrum from Gd(n,γ) is important to assess neutron tagging efficiencies with MC simulations
- We precisely measured the γ-ray spectra from thermal ^{Nat,155,157}Gd(n,γ) reactions with the ANNRI germanium spectrometer at J-PARC
- Based on the data, we build a model for the spectrum to generate the γ-rays in a MC simulation (GEANT4); 15 discrete peaks for ^{157}Gd(n,γ) included and tuned to data; contiuum part bases on statistical modeling
- Spectrum model and data currently agree within about ±50% ($\Delta E = 500\,keV$) for single-γ-ray events; our model reproduces the different γ-ray multiplicities with below 15% deviation from our data

Summary

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- Spectrum model and data currently agree within about ±50% ($\Delta E = 500$ keV) for single-γ-ray events; our model reproduces the different γ-ray multiplicities with below 15% deviation from our data

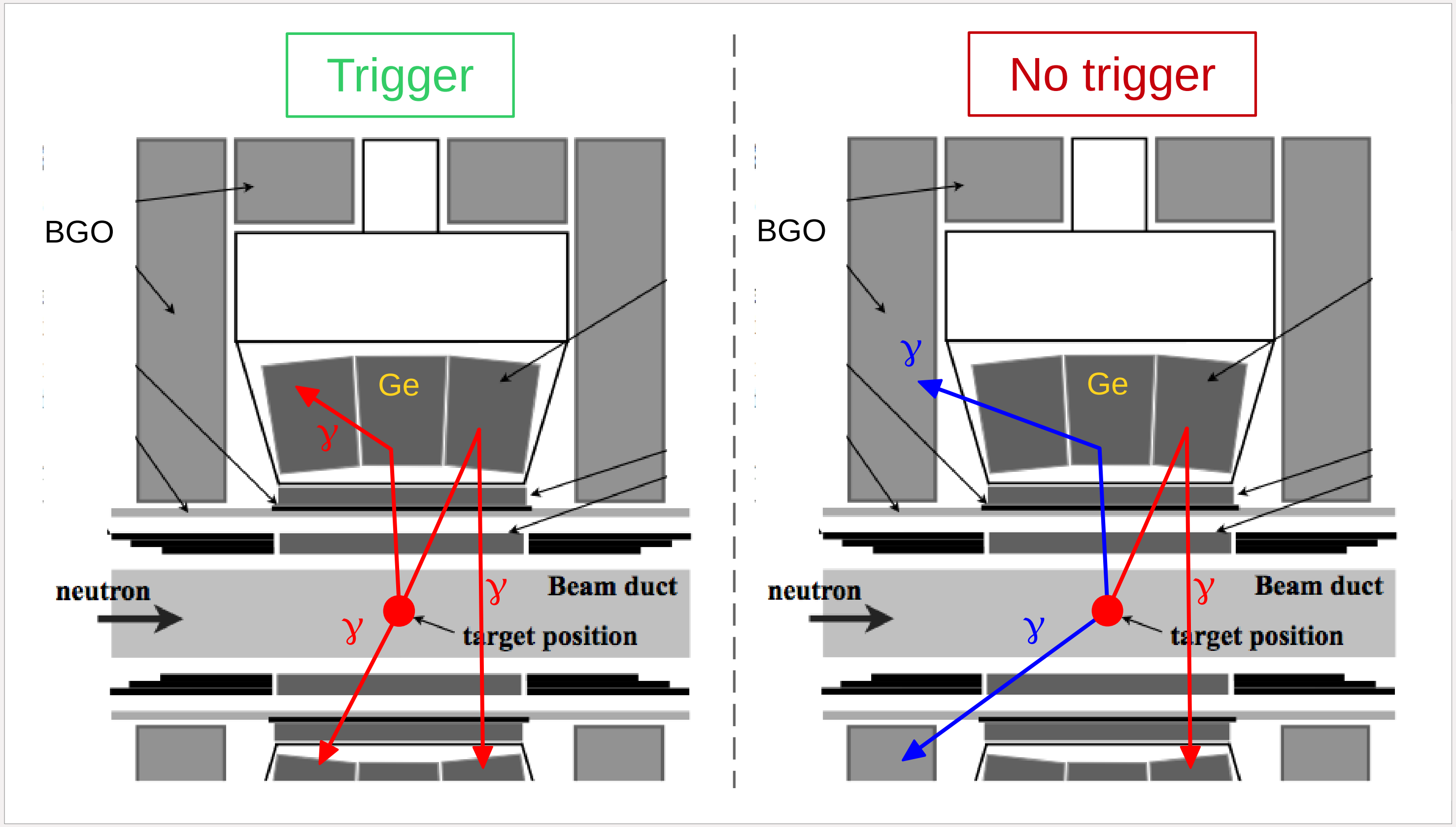
Thank you very much for your kind attention!

FURTHER INFORMATION

Trigger Conditions

- Trigger conditions:
  1) At least one Ge crystal has E > 0.1 MeV
  2) The surrounding BGO has E < 0.1 MeV

→ upper and lower cluster independent!

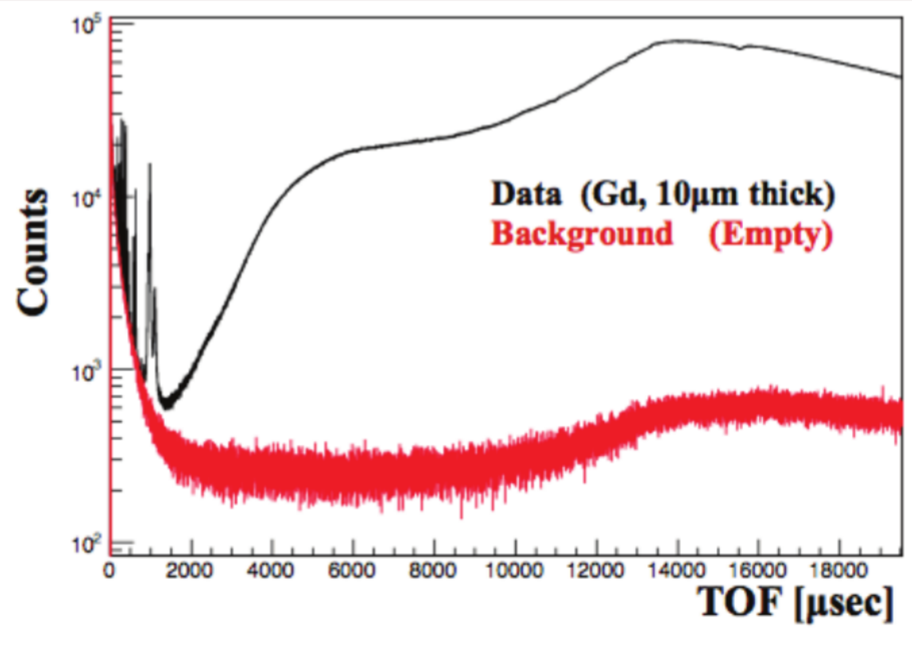


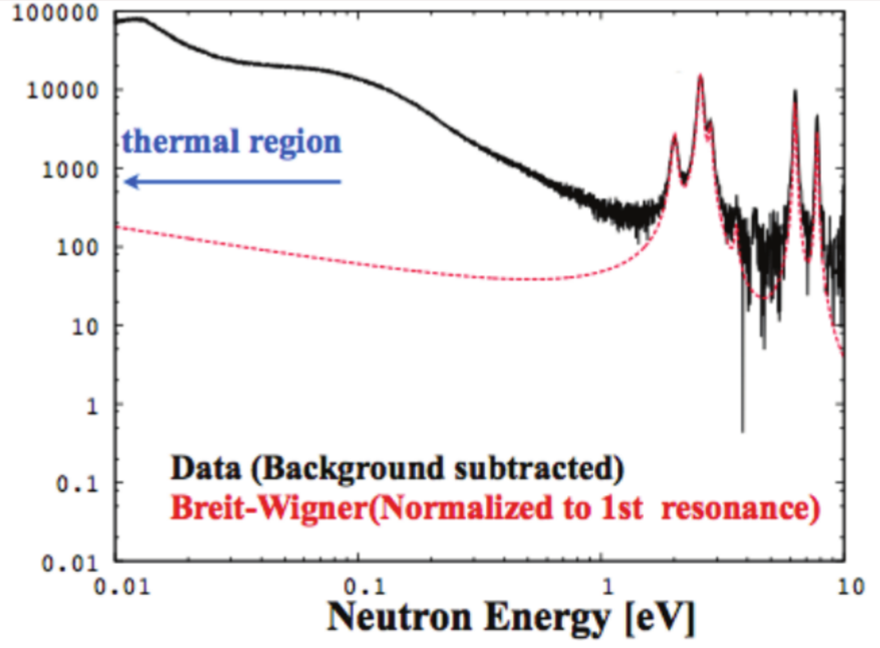
Detected Neutron Energy Spectrum

- With known distance (L=21.5 m) between n-source and detector one can calculate the energy E_n of the thermal neutron with mass m_n from its time of flight T for the distance L with the classical formula

$$E_n = m_n (L/T)^2 / 2$$

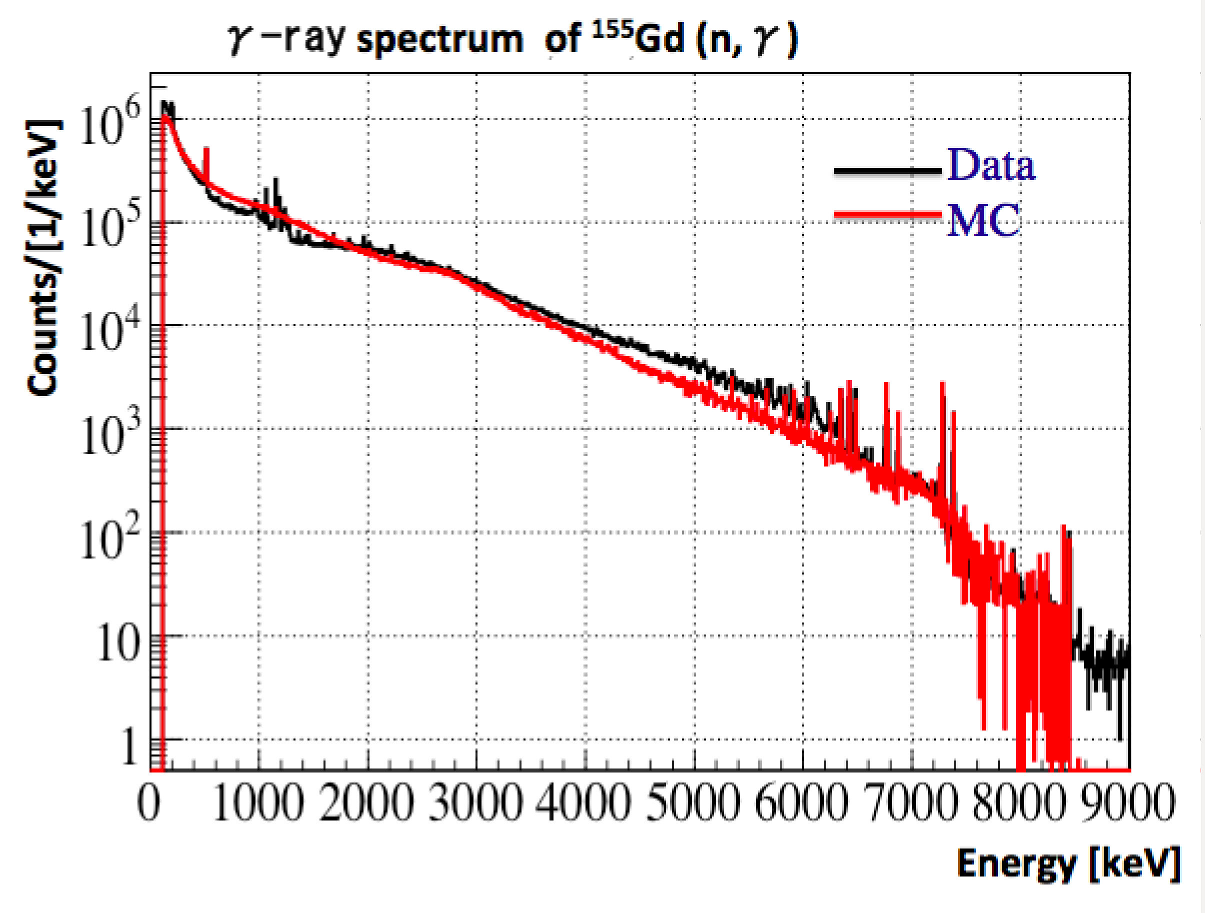
- Resonances of ^{155}Gd and ^{157}Gd in detected neutron energy spectrum between 1 and 10 eV
  - ✔ Good agreement with calculated expectations
  - ✔ Reasonable isotope abundances in nat. Gd and good energy calibration





Further Information
^{155}Gd(n,γ) – Data vs. MC

- Comparison of full model to data for ^{155}Gd(n,γ)



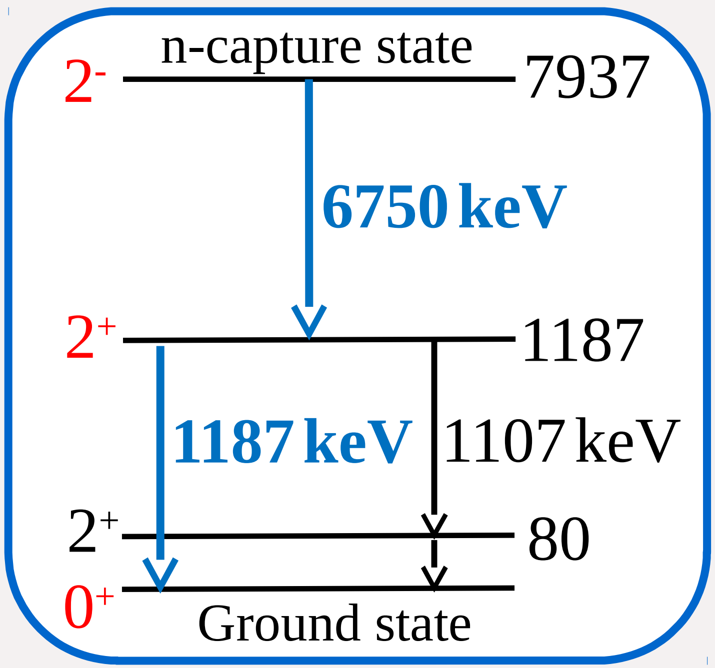
Angular Correlations

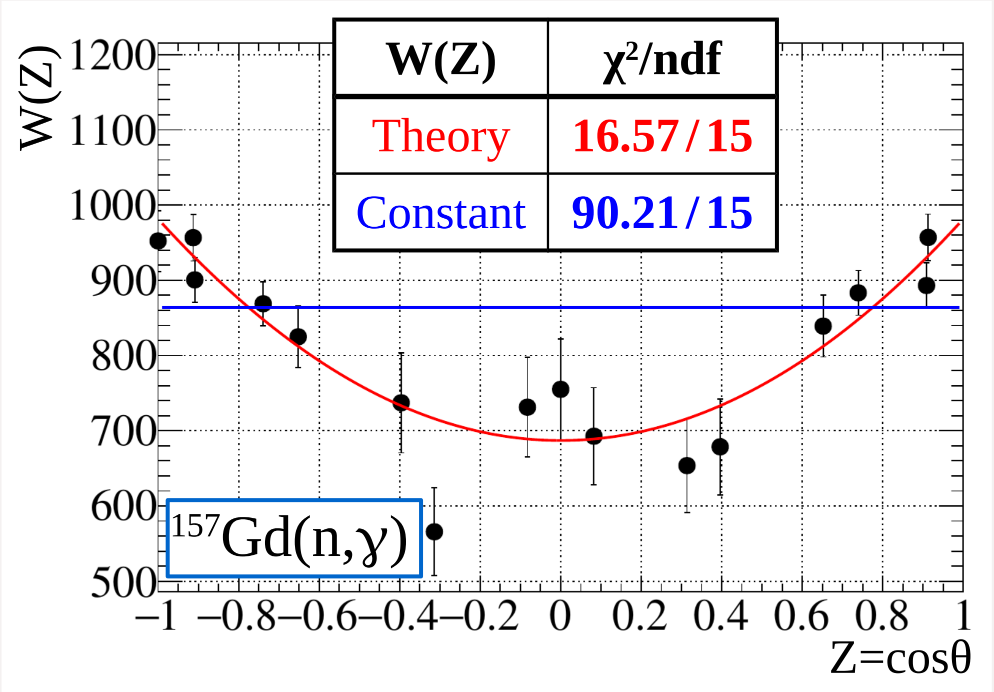
- We see the angular correlation of γ-rays from ^{157}Gd(n,γ)
- For the shown γ-ray lines it agrees with the theory[1]

$$W(Z) = A\left(1 + \frac{3}{7}Z^2\right)$$

for dipole-quadrupole transitions.

- Future: Study angular correlations with 8 additional co-axial counters.





[1] Physical Review 78, 5 (1950) p. 558-566