Modeling γ-rays from the thermal neutron capture on gadolinium based on JPARC-ANNRI data

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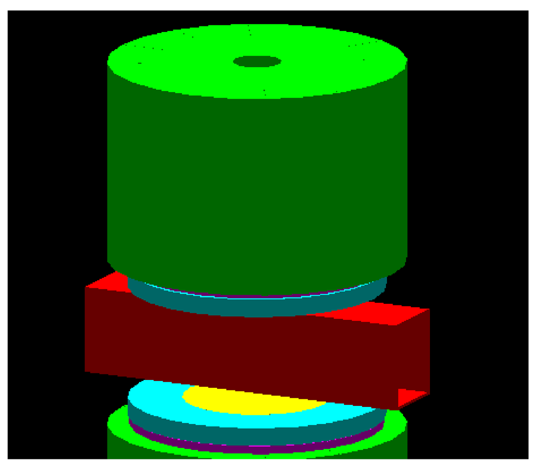
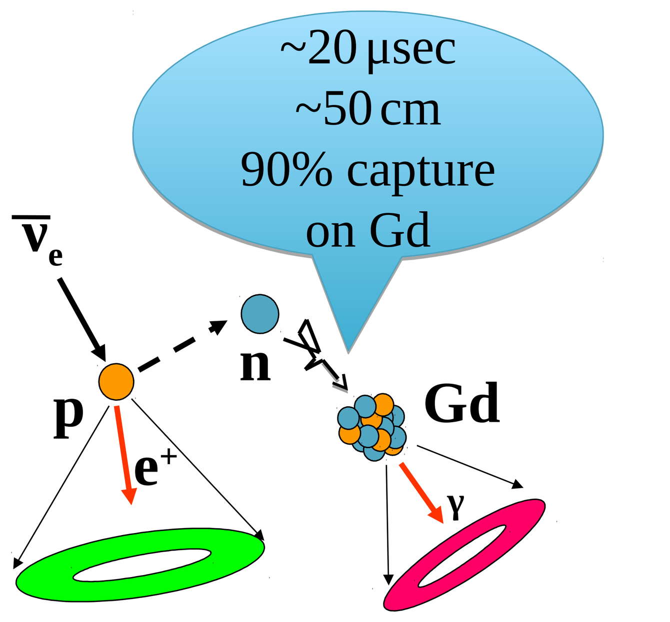


1. Introduction

Gadolinium (Gd, Z=64) has the largest thermal neutron capture cross-section among all stable nuclei. Moreover, the capture reaction emits several γ-rays with ~8 MeV total energy. This makes Gd a good material to enhance the tagging of neutrons from the common *inverse beta decay* (IBD) detection reaction $\bar{\nu}_e + p \rightarrow n + e^+$.



Present and future neutrino experiments using Gd

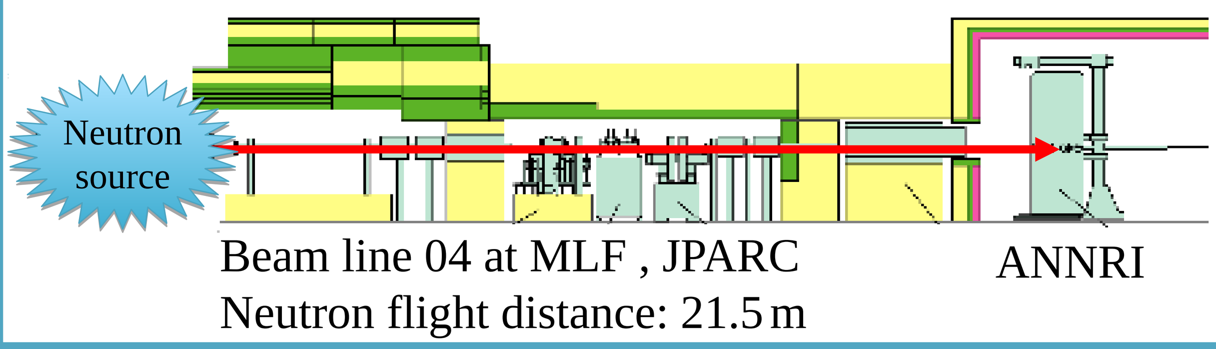
Technology	Experiment (Measurement)
Water Cherenkov	*SK-Gd* (~2018; SRN, SN ν, Solar ν, Atm. ν, p+ decay), *EGADS* (R&D for SK-Gd), *ANNIE* (ν interaction and neutron yield studies), *PANDA* (reactor monitoring)
Liquid scintillator	*Daya Bay, RENO, Double Chooz* (Mixing angle θ_{13})

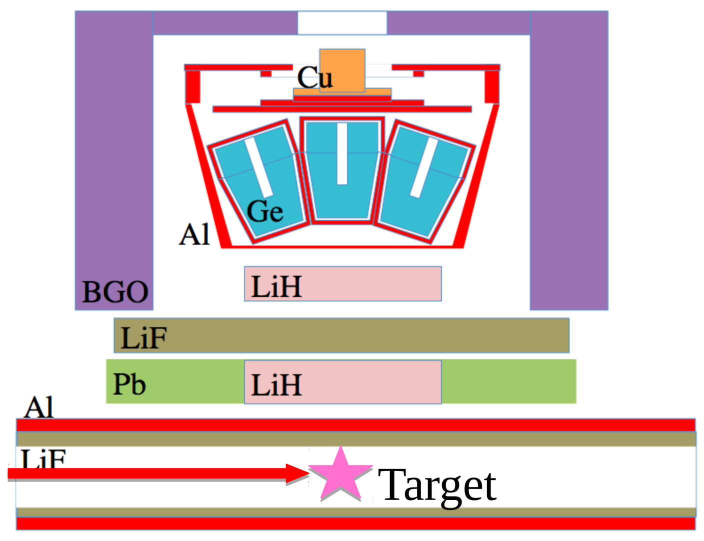
Super-Kamiokande will load $Gd_2(SO_4)_3$ in 2018 (→SK-Gd)!

Precise γ-ray spectrum of Gd(n,γ) reaction is necessary! → We study and model the γ-rays from this reaction based on an experiment.

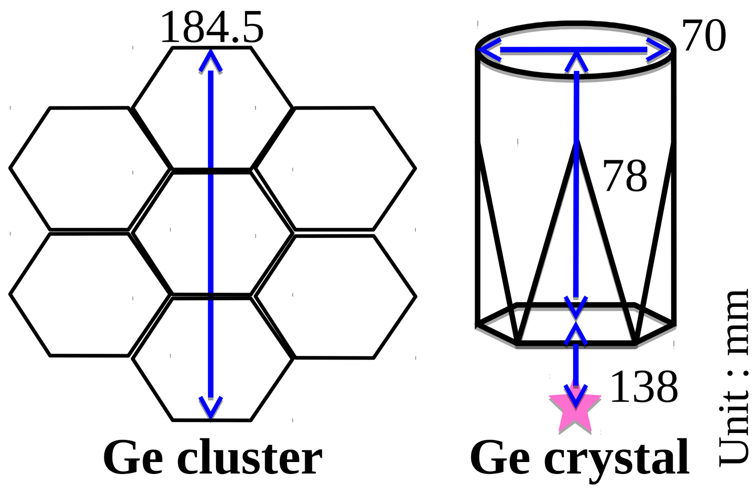
2. ANNRI @ MLF, JPARC

Neutron beam (E_n = 1 meV-10 eV; $\Delta E_n/E_n$ ~1%) to ANNRI. We placed different target materials, nat. Gd (99.99%), enriched ^{155}Gd (91.65%), enriched ^{157}Gd (88.4%) and calibration sources / targets (^{22}Na, ^{60}Co, ^{137}Cs, ^{152}Eu, NaCl(n,γ)), between its two clusters (22% coverage) of seven germanium crystals (ΔE_γ~9 keV @ 1.3 MeV). Each cluster has a BGO veto (55% combined coverage).





Top half detector



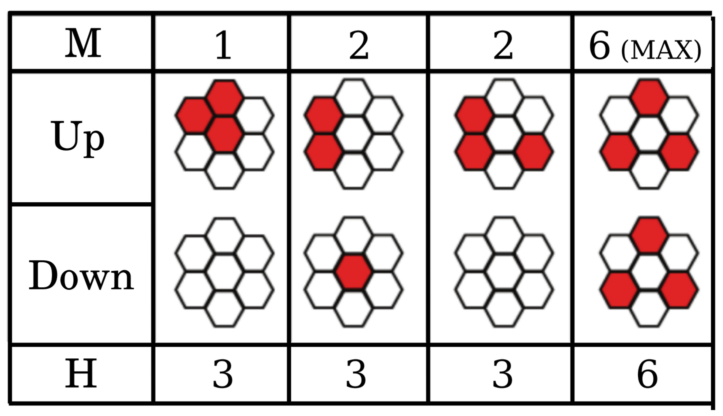
Ge cluster Ge crystal

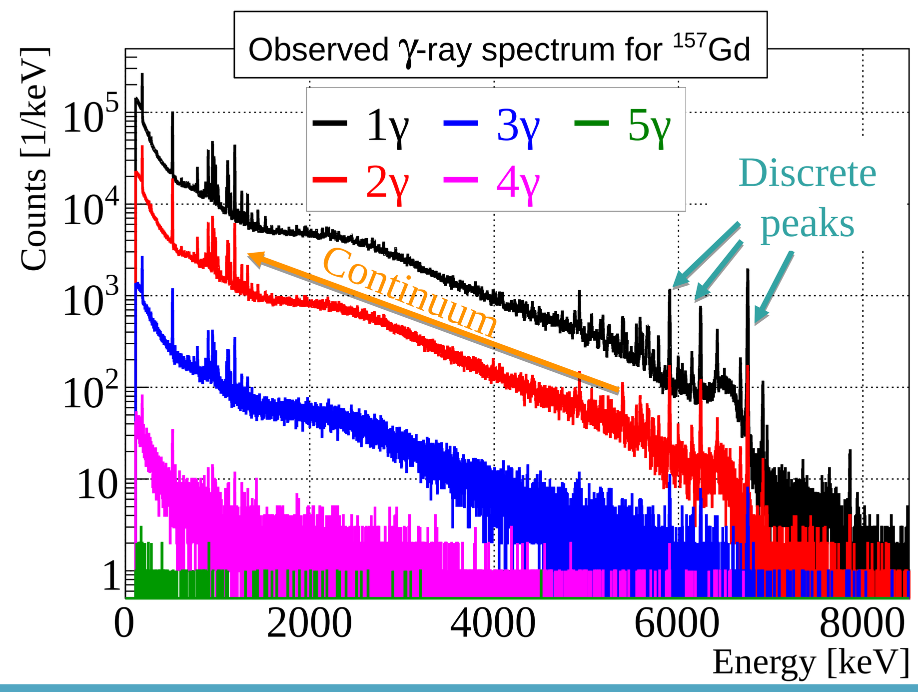
Trigger condition: ≥0.1 MeV in one germanium cluster and <0.1 MeV in corresponding BGO veto; both clusters are independent

Event selection: Neutron energy between 4 and 100 meV; energy in Ge >0.11 MeV

Event classification: Assigned multiplicity value (M: number of disconnected sub-clusters) and hit value (H: number of hit crystals)

γ-ray energy reconstruction: Energy deposition in sub-cluster





3. Results for ^{157}Gd

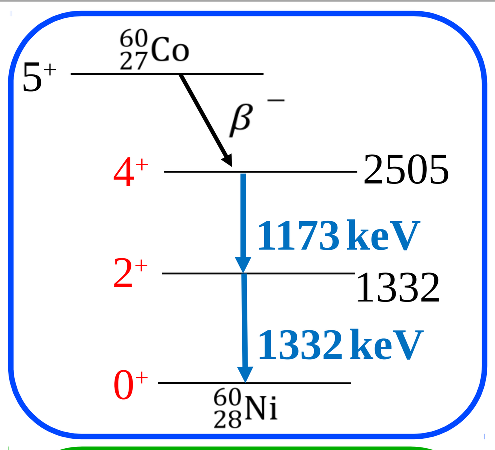
For the ^{157}Gd target, we identified 15 discrete peaks with a total contribution of (6.8±0.1)% to the overall spectrum in our data (E>0.11 MeV). Relative intensities of the prompt γ-rays agree with values from CapGam [NNDC] within 30%. The discrete levels are directly included into our model.

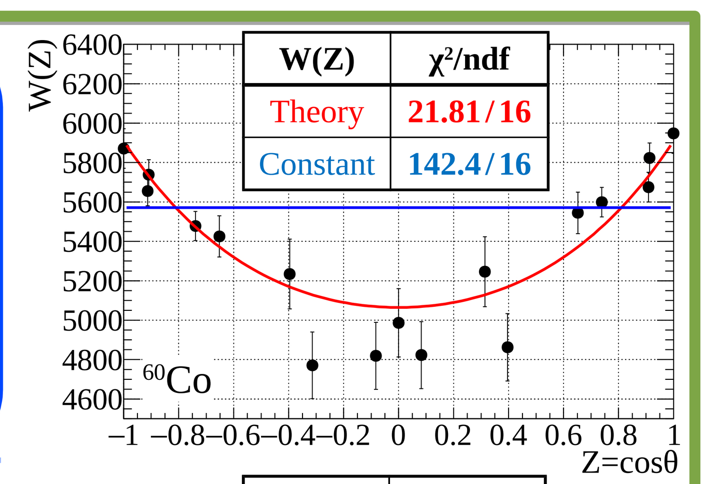
No.	γ-ray energies [keV] 1st	2nd	3rd	4th	5th	Our absolute intensity [%]
1	7937	–	–	–	–	(5.3±0.4)×10^{-3}
2	7857	80	–	–	–	(2.3±0.1)×10^{-2}
3	6960	–	–	–	–	(2.0±0.1)×10^{-2}
4	6914	944	80	–	–	0.13±0.06
5	6750	1187	–	–	–	1.19±0.07
		1107	80	–	–	1.19±0.07
6	6672	1187	80	–	–	0.16±0.02
		1004	182	80	–	(2.8±0.6)×10^{-2}
7	6420	1517	–	–	–	0.12±0.01
		1438	80	–	–	0.13±0.01
		1256	182	80	–	0.06±0.01
8	6601	–	–	–	–	(15.4±0.7)×10^{-2}
9	5903	1010	944	80	–	0.46±0.03
		875	898	182	80	0.29±0.03
		769	1186	80	–	0.25±0.03
		676	1097	182	80	0.15±0.01
10	5784	–	–	–	–	(19.2±0.8)×10^{-2}
11	5669	–	–	–	–	0.62±0.02
12	5595	–	–	–	–	0.65±0.02
13	5543	–	–	–	–	(23.1±0.9)×10^{-2}
14	5436	–	–	–	–	(15.7±0.6)×10^{-2}
15	5167	–	–	–	–	0.58±0.02

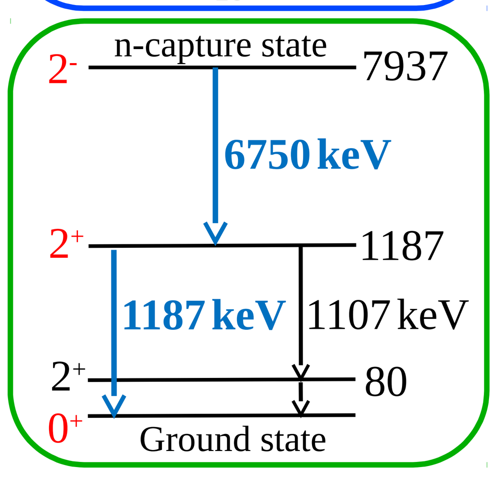
We study the angular correlation W(Z), Z=cosθ, of γ-rays with given energies E_1, E_2 from ^{60}Co decay and ^{158}Gd disexcitation using two-γ-ray events. For a given Ge crystal pair (i,j) with intermediate angle θ and efficiencies $\varepsilon_i(E)$, $\varepsilon_j(E)$, the number of events is $N_{ij} = N_0\,\varepsilon_i(E_1)\,\varepsilon_j(E_2)\,W(Z)$.

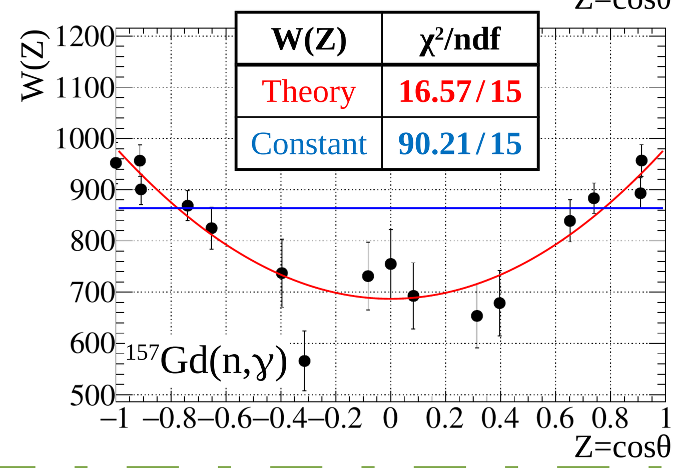
We find good agreement with the theoretical predictions for quadrupole-quadrupole and dipole-quadrupole transitions [PR 78, 5],

$$W(Z) = A\left(1+\frac{1}{8}Z^2+\frac{1}{24}Z^4\right) \quad \text{and} \quad W(Z) = A\left(1+\frac{3}{7}Z^2\right).$$









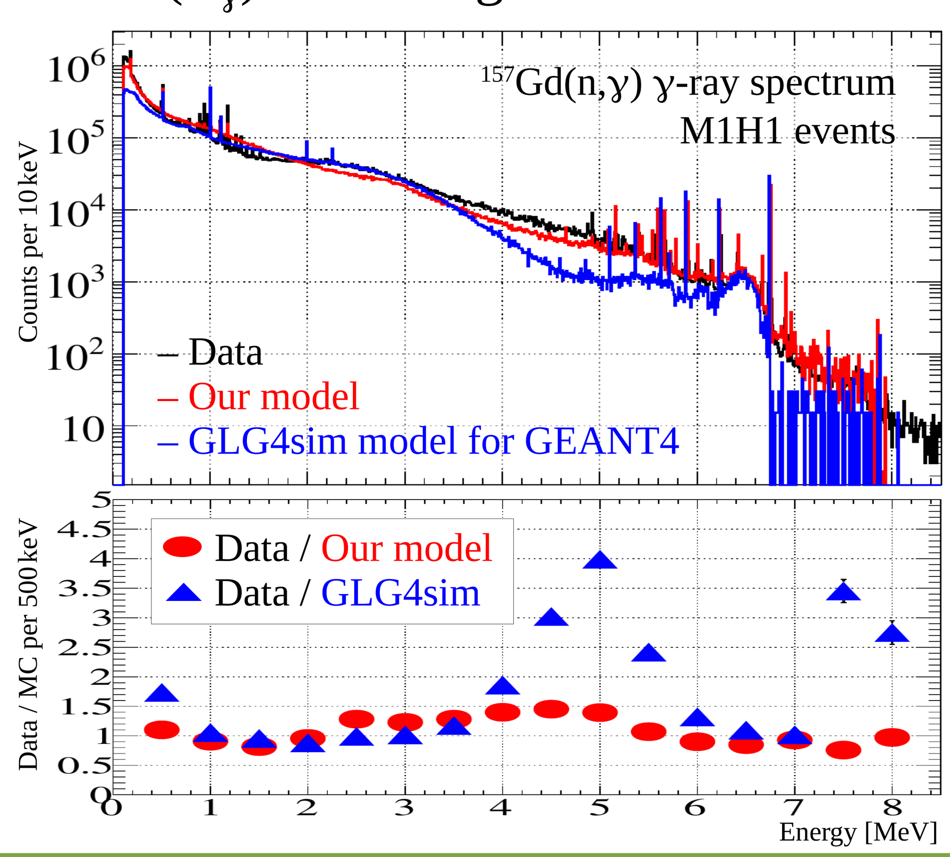
The continuum part of the ^{158}Gd spectrum (transitions within the energy region of high *nuclear level density* (NLD) ρ(E) or down to the domain of discrete nuclear levels) contributes (93.2±0.1)% in our data. For our model, we compute the probability P for the transition from level E_a to E_b under emission of a γ-ray ($E_\gamma = E_a - E_b$) with the *transmission coefficient* $T(E_\gamma)$ according to

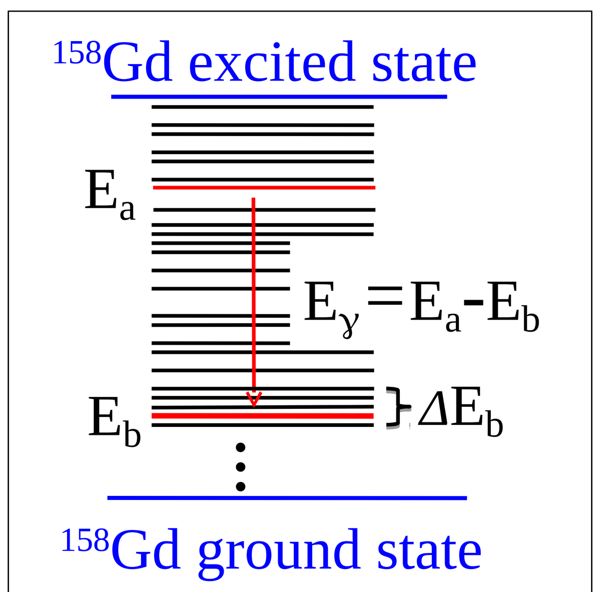
$$\frac{dP}{dE}(E_a,E_b)\,\Delta E_b = \frac{T(E_\gamma)\rho(E_b)\Delta E_b}{\int_0^{E_a} T(E_\gamma)\rho(E_b)\mathrm{d}E_b},\quad T(E_\gamma) = 2\pi E_\gamma^3 f(E_\gamma,T).$$

We use the HFB-model [RIPL-3] for ρ(E) and the EGLO *photon strength function* (PSF) [Nucl. Data Sheets 110]

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

T is the nuclear tempearture. E1 resonance parameter values for energies E_i, strengths σ_i and widths Γ_i are from [PRC 47, 312]. For single-γ-ray events, our model agrees within about ±50% with the data at ΔE = 0.5 MeV.





4. Summary

- Gadolinium is used to enhance the delayed signal in IBD events.
- We measured γ-rays from the ^{157}Gd(n,γ) reaction with the ANNRI detector.
- We identified 15 discrete peaks in the spectrum and added them to our model.
- Our model agrees within about ±50% with our data (ΔE=0.5 MeV).
- For ^{60}Co and ^{157}Gd(n,γ) we see the expected angular correlation of γ-rays.