Analysis of Gd(n,γ) reaction with ^{155}Gd, ^{157}Gd and ^{Nat}Gd targets at JPARC-ANNRI & Development of Gd(n,γ) decay model for Gd-doped n/ν-detectors

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on behalf of **ANNRI-Gd** *Collaboration*

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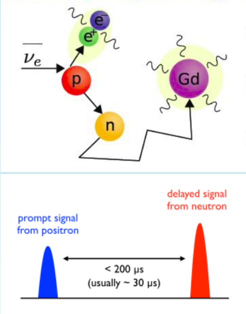
ANNRI-Gd Collaboration

Objective:

- Detection of $\bar{\nu}_e$ via IBD: $\bar{\nu}_e + p \rightarrow e^+ n$ vital to ν-detectors, with reduced background from ν_μQE, ν_eES etc.
- Pair of prompt and delayed coincidence signature offers tremendous bkg. suppression.
- Thermal neutrons captured in the medium: γ-emission.
  by proton $\rightarrow$ 2.2MeV γ in $\sim$200μs;
  by Gd $\rightarrow$ $\sim$8MeV γ in $\sim$30μs.



- Cross section of thermal n-capture on natural Gd $\sim$49000b, while $\sim$0.3b on water(p). Presence of Gd enhances $\bar{\nu}_e$ signal selection drastically.
- For data-analysis, γ rays from n-capture need to be studied, hence simulation of these γ-rays in the detector (specially with partial energy deposition) is essential.

- Appropriate MC model of the gamma spectra: important pre-requisite for n-tagging efficiencies.
- Natural Gd used in detectors: many isotopes of Gd, but mainly two dominate

Isotope	Abundance[%]	n-Cross-section[b][1]
^{152}Gd	0.200	735
^{154}Gd	2.18	85
^{155}**Gd**	**14.80**	**60900**
^{156}Gd	20.47	1.8
^{157}**Gd**	**15.65**	**254000**
^{158}Gd	24.84	2.2
^{160}Gd	21.86	1.4

- So targets for our study/data-checks: Gd_2O_3 enriched with ^{157}Gd (presented earlier), ^{155}Gd, Metal film of ^{Nat}Gd

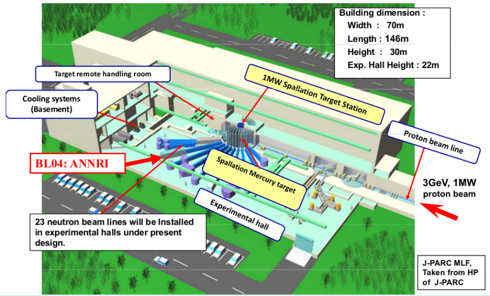
$n +^{155} Gd \rightarrow^{156} Gd^* \rightarrow^{156} Gd + \gamma$ **rays** (8.5MeV total)

$n +^{157} Gd \rightarrow^{158} Gd^* \rightarrow^{158} Gd + \gamma$ **rays** (7.9MeV total)

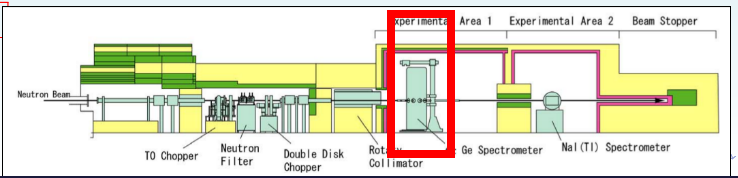
[1] Atlas of Nuclear Resonances, 2006

Experimental Facility:

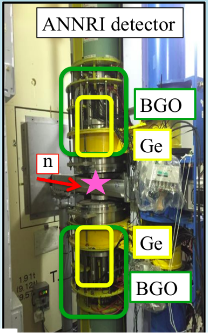
- 3 GeV proton beam of 300kW at JSNS, JPARC-MLF complex.
- Incident on mercury target at 25 Hz (double-bunch mode: 100ns wide, 599 ns apart)$\rightarrow$ spallation neutron beam source
- Be, Fe reflectors confine neutrons from escaping otherwise.
- Moderated by supercritical hydrogen, deliver n-beam of about $1.5 \times 10^7/\text{cm}^2/\text{s}$ (1meV-10eV).



- BL04: Accurate Neutron-Nucleus Reaction Measurement Instrument, ANNRI

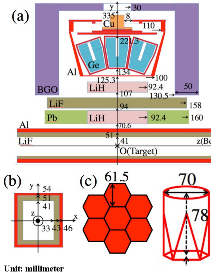


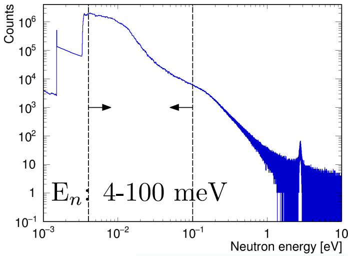
The ANNRI spectrometer:



- Located 21.5m from the neutron beam source
- 14 hexagon-Ge-crystal detectors in 2 clusters 26.8cm apart
- Target placed at centre, 22% solid angle covered.
- 20 Anti-coincidence shields BGO for veto: cover 55% solid angle

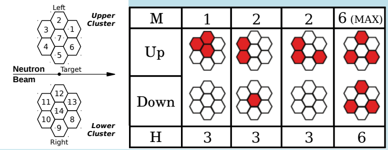
- Analysed Data dated: Dec. 2014, Mar. 2013
- Li-layering to reduce background.





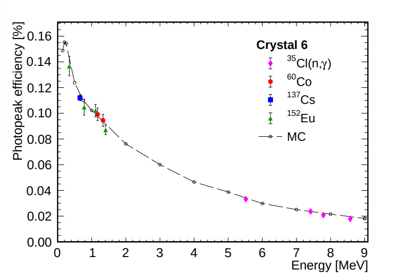
Data analysis:

- To measure: Single energy spectrum, Multiplicity (M), TOF (E_n)
- Hits: #Ge-crystals recording signal/ energy; energy threshold 100keV each.
- Devised algorithm for *clustering of hits* w.r.t. *different mutiplicity* e.g. M1HX (X=1,2,3,...), etc..

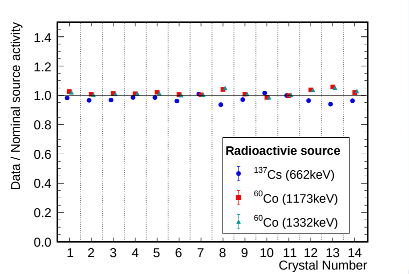


- Calibration sources: ^{60}Co, ^{137}Cs, ^{152}Eu, ^{35}Cl(n,γ)

"Photo-peak efficiencies of Crys.6"

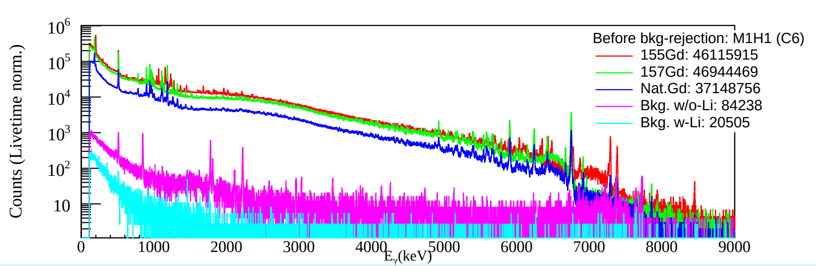


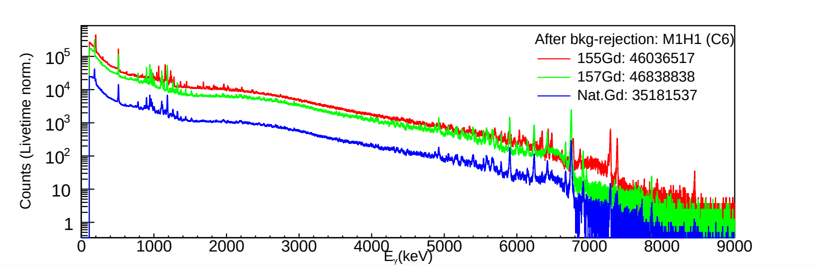
"Uniformity-check of 14 crystals"



Data Spectra with Gadolinium samples:

- Single energy hit spectrum or M1H1 most dominant: $\sim$70%





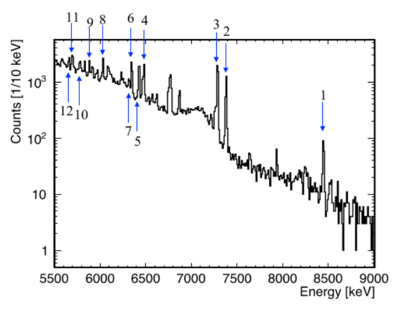
Compare Combined data

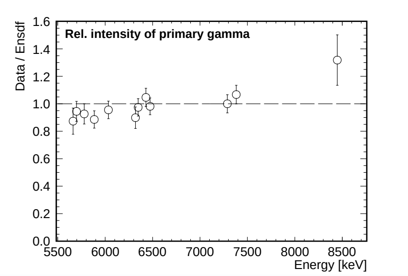
Relative Intensity of ^{155}Gd:

- Continuum parts: 97.36±0.02[%]
- 12 Discrete levels: 2.64±0.02[%]

	1st γ (MeV)	Intensity (%)
1	8.448	0.018±0.002
2	7.382	0.233±0.018
3	7.288	0.453±0.026
4	6.474	0.352±0.007
5	6.430	0.324±0.027
6	6.348	0.303±0.026
7	6.319	0.094±0.005
8	6.034	0.204±0.019
9	5.885	0.174±0.029
10	5.779	0.188±0.008
11	5.698	0.286±0.008
12	5.661	0.154±0.007

- Primary photo peak intensities agree with the Nuclear Structure Database (ENSDF)

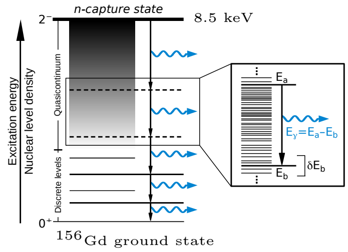




About the "ANNRI-Gd" model:

- ⋆ Our model includes both: the dominant contribution from Continuum γ-emission model and the discrete spectral part.

- Continuum part modelling:
  - The probability(P) of transitioning from level E_a to level E_b emitting γ-ray(E_γ) given by "Transmission coefficient T" and "No. of levels $\rho(E_b)\Delta E_b$"



$$P_a(E_a,E_b)\Delta E_b = \frac{T(E_a,E_b)[\rho(E_b)\Delta E_b]}{\int_0^{E_a} T(E_a,E_b)\rho(E_b)dE_b}$$

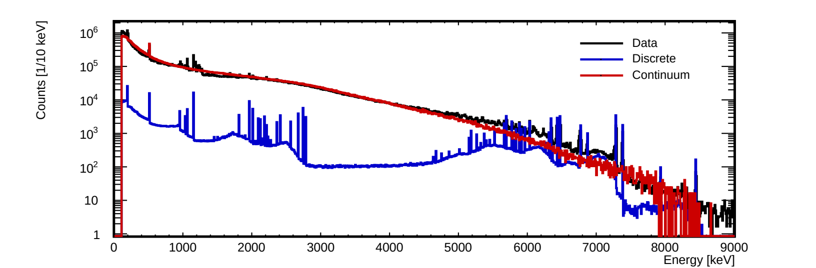
$T(E_a,E_b)$: Photon strength function (PSF) depending on cross sec.(σ_i) and width(Γ_i) of energy level(E_i)

$$T(E_\gamma) = 2\pi E_\gamma^3 \sum_{i=1}^{2} \frac{\sigma_i E_\gamma \Gamma_i^2}{(E_\gamma^2 - E_i^2)^2 + E_\gamma^2\Gamma_i^2}$$

	Energy (E_i) MeV	σ_i (mb)	Width (Γ_i) MeV
^{156}Gd	11.2	180	2.6
	15.2	242	3.6
^{158}Gd	11.7	165	2.6
	14.9	249	3.8

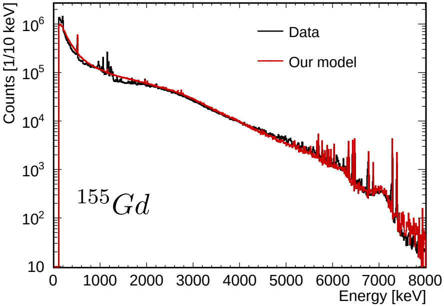
ref.:Kopecky, PRC 47.312

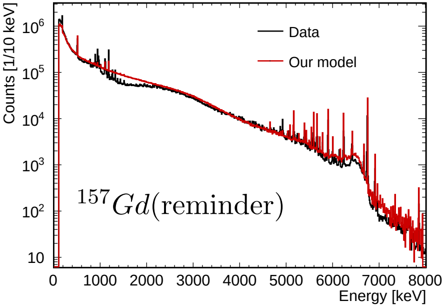
- Discrete part model:
  - Continuum model not enough to match discrete peak intensities
  - Spectral components of discrete part added, tuned with that of ^{155}Gd data (same for ^{157}Gd).
  - The continuum and the discrete component generated by our model shown separately here for ^{155}Gd, along with the data.



Combined Model and Data for ^{155}Gd:

- Continuous+Discrete → Working Model for MC events generation
- Single hit energy spectrum most dominant (∼70%)

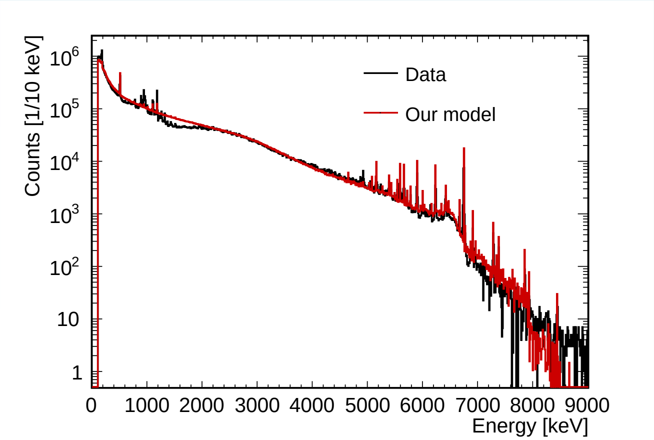




- Max spectral shape agreement of data and ANNRI-Gd model!

Finally: Data and model for ^{Nat}Gd:

- We finally check our model vs. data taken with Natural Gd metal film (99.9% purity).
- MC for ^{Nat}Gd = MC for ^{155}Gd + MC for ^{157}Gd, in ratio of their relative cross-section and abundance.



Comparison of models:

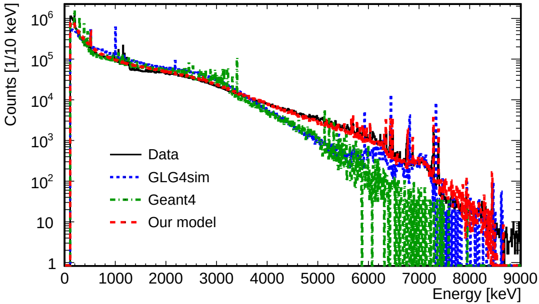
※ We compare spectral agreement between data and MC sample generated by:

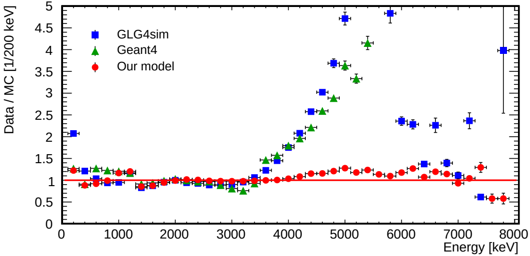
☑ 1. Our model or the ANNRI-Gd model

☑ 2. GLG4sim model

☑ 3. Standard Geant4 using the default photon-evaporation model.

※ ANNRI-Gd model fits the best of three.

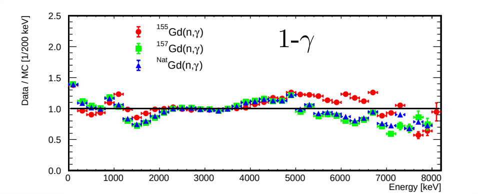




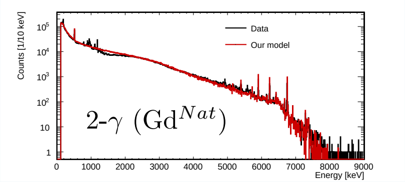
Model Comparisons for ^{157}Gd and ^{Nat}Gd here

Summary:

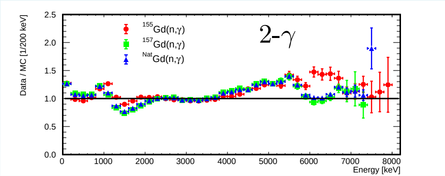
- Improved Monte Carlo models are necessary for better understanding and efficient analysis of data from the n/ν-detectors using Gd.

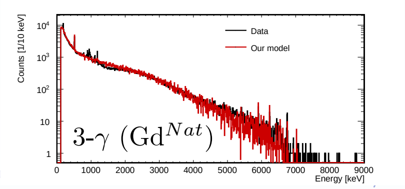


- The **ANNRI-Gd** model very well agrees with the data taken with ^{157}Gd, ^{155}Gd, $^{\mathrm{Natural}}$Gd, for single and multi-gamma cases.



- 1-γ classification: energy spectrum deviation of $\sim$ 15% at 200keV binning (2-γ: $\sim$19%, 3-γ: $\sim$27%).

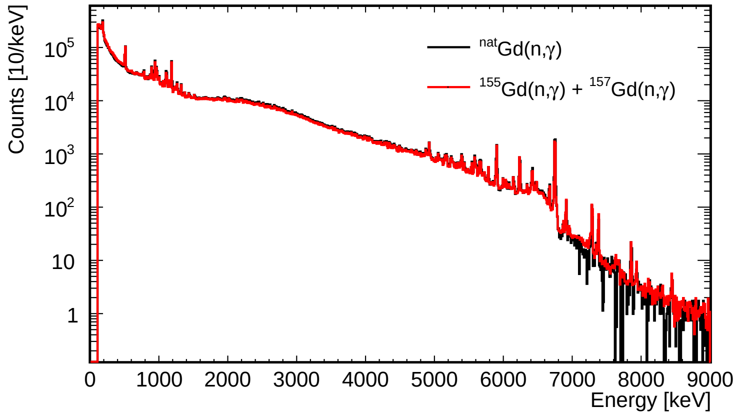




- Upcoming: Angular Correlations with 2γs.

Thank you !

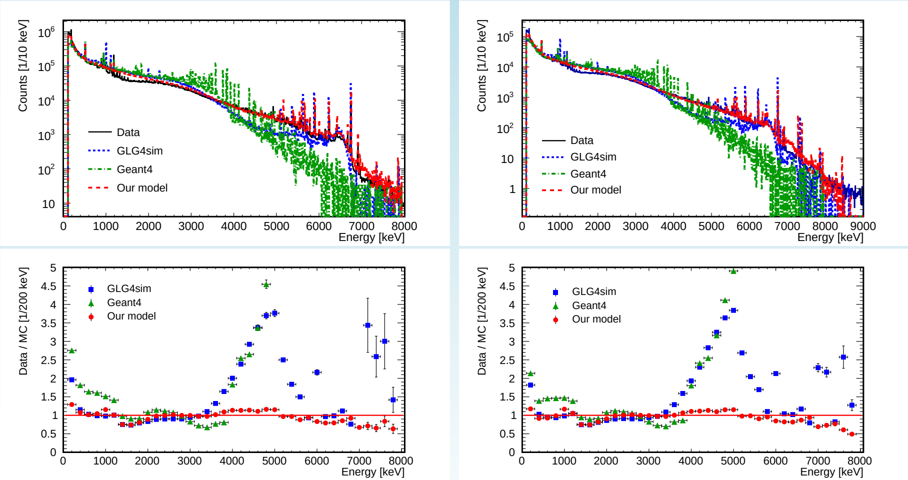
Back ups:


Counts [10/keV]
10^5
10^4
10^3
10^2
10
1
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
Energy [keV]
^{nat}Gd(n,γ)
^{155}Gd(n,γ) + ^{157}Gd(n,γ)

Back

Comparison of models:

^{157}Gd and ^{Nat}Gd



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Deviation of Data/MC from unity: