PROCEEDINGS OF SCIENCE

Analysis of Gd(n,gamma) reaction with 155, 157 and natural Gd targets taken with JPARC-ANNRI and development of Gd(n,gamma) decay model for Gd-doped neutron/neutrino detectors

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The importance of a good model for the γ-ray energy spectrum from the radiative thermal neutron capture on Gadolinium (Gd) is specially increased in the present era of Gd-enhanced $\bar{\nu}_e$-search detectors. Its an essential prerequisite for MC studies to evaluate the neutron tagging efficiency, in order to enhance signal sensitivity in the Gd-loaded $\bar{\nu}_e$-search detectors. The γ-ray spectra produced from the thermal neutron capture on enriched gadolinium targets (^{155}Gd, ^{157}Gd and Natural Gd) in the energy range 0.11 MeV to 8.0 MeV, were measured using the ANNRI Germanium Spectrometer at MLF, J-PARC. Based on the data acquired and a GEANT4 simulation of the ANNRI detector, we reported the energy spectrum of ^{157}Gd(n, γ) and developed a γ-ray emission model of ^{157}Gd(n, γ) in our previous publication. We now present the analysed data of ^{155}Gd(n, γ) and ^{nat}Gd(n, γ) reactions, the energy spectra of γ-rays and an improved model for ^{155}Gd(n, γ), ^{157}Gd(n, γ) and ^{nat}Gd(n, γ) reactions. The consistency of the results from the devised model is checked among all the 14 germanium crystals, at the level of 15% spectral shape deviation at 0.2 MeV binning.

The 39th International Conference on High Energy Physics (ICHEP2018)
4-11 July, 2018
Seoul, Korea

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PoS(ICHEP2018)120

1. Introduction

Gadolinium (Gd) is being used in a number of neutrino experiments for enhanced detection of electron anti-neutrinos ($\bar{\nu}_e$) through neutron-tagging in the inverse beta decay reaction ($\bar{\nu}_e + p \rightarrow e^+ n$), as in SK-Gd [2, 3], for example. The large cross section of thermal neutron-capture on Gd (i.e. Gd(n,γ)) is due to the contributions of two of its isotopes, ^{155}Gd (254000 b) and ^{157}Gd (49000 b).

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

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

The emitted γ-spectrum and its corresponding Monte Carlo (MC) modelling for ^{157}Gd has already been discussed in [1]. However, the neutrino experiments use natural Gd (^{nat}Gd), which comprise of 14.80% of ^{155}Gd, and 15.65% of ^{157}Gd. We present the spectra from ^{155}Gd, and ^{nat}Gd, modify our "ANNRI-Gd" model with the contributions from ^{155}Gd and present our final MC for ^{nat}Gd(n, γ).

2. Experiment and data analysis

We measured the emitted γ-spectra from Gd(n, γ) with the Accurate Neutron-Nucleus Reaction Measurement Instrument (ANNRI spectrometer) [4, 6, 7, 5, 8] in BL04 of JPARC-MLF facility. ANNRI is located 21.5 m away from the neutron beam source, and comprise of two clusters, each with 7 germanium (Ge) crystals, 8 co-axial detectors and Bimuth Germanium Oxide (BGO) anti-coincidence shields. We report the data, which was taken in March 2013 and Dec. 2014. The two main target samples were Gd_2O_3 enriched with 91.85% ^{155}Gd, and a metal film of ^{nat}Gd with 99.9% purity. We analysed our data for neutron energies 4-100 meV. The data was grouped into samples according to the clustering algorithm described in [1]. We calibrated the detector using the sources ^{60}Co, ^{137}Cs, ^{152}Eu, ^{35}Cl(n,γ). We show the spectra of the most dominant sample (detected multiplicity(M)=1 and number of crystal hit(H)=1) after subtracting the corresponding background in figure 1. The background was measured with the empty target holder in the n-beam. The spectrum for ^{157}Gd is also shown for reference or reminder.

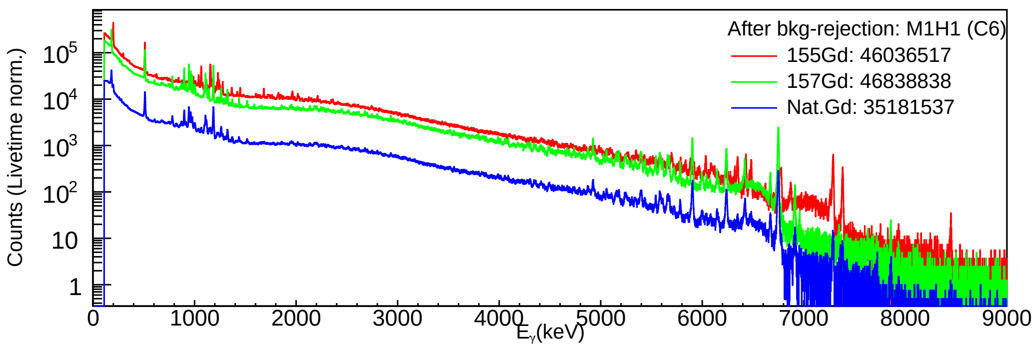

Figure 1: Single energy hit spectrum or M1H1 Spectra with Gadolinium samples, after subtracting the background, from one of the crystals. The numbers are the data statistics.

3. Modifying the ANNRI-Gd MC Model

The MC model for ^{157}Gd is already described in [1]. We now develop the same for ^{155}Gd. We identified and measured the photo peak intensities of 12 discrete γ rays for^{155}Gd(n, γ) above 5 MeV as in table 1, and found them in agreement with the values from ENSDF [9]. The discrete peaks contribute only 2.78±0.02% of the spectrum . The rest but dominant contribution of 97.22±0.02% comes from the continuum region of the energy levels in ^{156}Gd*.

The modelling of the continuum part uses the Standard Lorentzian PSF model, i.e., it basically employs the Fermi's Golden rule. 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 $\rho(E_b)\Delta E_b$"

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

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

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

with E_i= (11.2, 15.2) MeV, σ_i= (180, 242) mb and Width (Γ_i)= (2.6, 3.6) MeV [10, 11].

Spectral components of the discrete part are added and tuned with that of ^{155}Gd data. The continuum and the discrete component generated by our model shown separately here for ^{155}Gd, along with the data in figure 2-top. They are added in corresponding proportion to generate the final ^{155}Gd(n, γ) spectrum in figure 2-bottom. The data spectrum matches well with our MC spectrum.

	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

Table 1: The relative intensities of the 12 primary discrete peaks of ^{155}Gd(n, γ).

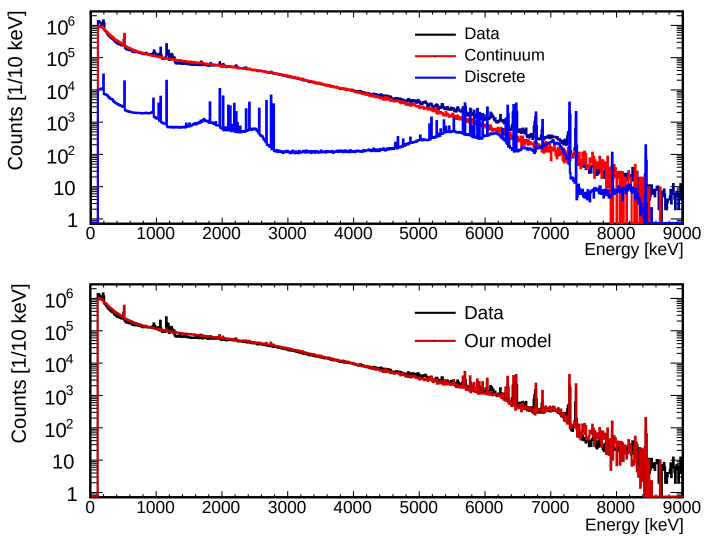

Figure 2: Top: The discrete (blue) and continuum (red) component of our model for ^{155}Gd(n, γ) shown separately, along with the data (black). **Bottom:** Single energy hit spectrum from data (black) and our MC model (red) for ^{155}Gd(n, γ).

4. Results and Summary

We finally generate the spectrum for ^{nat}Gd(n, γ), by adding the same generated by our model for ^{155}Gd(n, γ) and ^{157}Gd(n, γ) in the required ratio of their relative cross-section and abundance, as shown in figure 3-left. The corresponding spectra generated by GLG4sim [12] and the GEANT4-photon evaporation model [13, 14] are also shown. The spectrum generated by our "ANNRI-Gd" MC-model agrees better than most other available MC generators for Gd(n, γ). We also show the ratio of data/MC in bins of 200 keV for ^{155}Gd, ^{157}Gd, and ^{nat}Gd in figure 3-right, as an approximate representation of the goodness of our model.

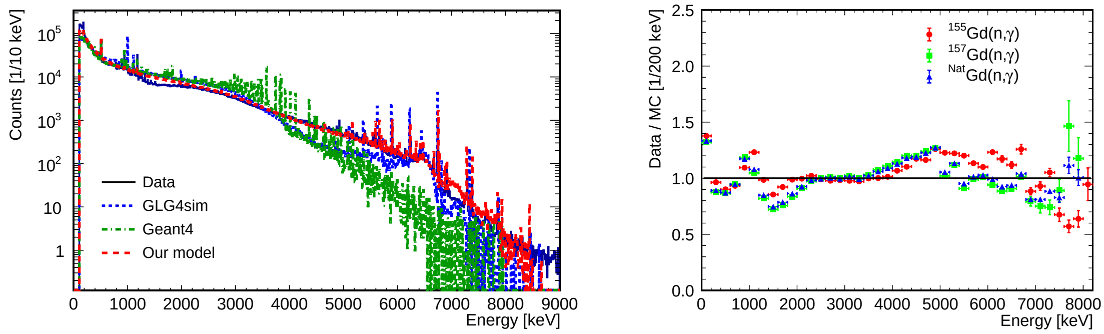

Figure 3: Left: Single energy hit spectra from data (black) and our MC model (red) for ^{nat}Gd(n, γ). The corresponding spectra from GLG4sim (blue) and GEANT4 (green) are also shown. **Right:** Data/MC (our model) in bins of 200keV for ^{155}Gd(n, γ) (red), ^{157}Gd(n, γ) (green) and ^{nat}Gd(n, γ) (blue).

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