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 \(\gamma\)-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 \(\gamma\)-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, \(\gamma\)) and developed a \(\gamma\)-ray emission model of \(^{157}\)Gd(n, \(\gamma\)) in our previous publication. We now present the analysed data of \(^{155}\)Gd(n, \(\gamma\)) and \(^{nat}\)Gd(n, \(\gamma\)) reactions, the energy spectra of \(\gamma\)-rays and an improved model for \(^{155}\)Gd(n, \(\gamma\)), \(^{157}\)Gd(n, \(\gamma\)) and \(^{nat}\)Gd(n, \(\gamma\)) 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.
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,\gamma)) is due to the contributions of two of its isotopes, $^{155}$Gd (254000 b) and $^{157}$Gd (49000 b).

\[
\begin{align*}
  n + ^{155}Gd & \rightarrow ^{156}Gd^* \rightarrow ^{156}Gd + \gamma \text{ rays (8.5MeV total)} \\
  n + ^{157}Gd & \rightarrow ^{158}Gd^* \rightarrow ^{158}Gd + \gamma \text{ rays (7.9MeV total)}
\end{align*}
\]

The emitted $\gamma$-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, $\gamma$).

2. Experiment and data analysis

We measured the emitted $\gamma$-spectra from Gd(n, $\gamma$) 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$_2$O$_3$ 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,$\gamma$). 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.](image-url)
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 $\gamma$ rays for $^{155}$Gd(n, $\gamma$) above 5 MeV as in table 1, and found them in agreement with the values from ENSDF [9]. The discrete peaks contribute only $2.78\pm0.02\%$ of the spectrum. The rest but dominant contribution of $97.22\pm0.02\%$ 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 $\gamma$-ray($E_\gamma$) 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.($\sigma_i$) and width($\Gamma_i$) of energy level($E_i$)

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

with $E_i=(11.2, 15.2)$ MeV, $\sigma_i=(180, 242)$ mb and Width ($\Gamma_i$)= (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, $\gamma$) spectrum in figure 2-bottom. The data spectrum matches well with our MC spectrum.

<table>
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<th>1st $\gamma$ (MeV)</th>
<th>Intensity (%)</th>
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<tr>
<td>1</td>
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<tr>
<td>2</td>
<td>7.382</td>
</tr>
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<td>11</td>
<td>5.698</td>
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<tr>
<td>12</td>
<td>5.661</td>
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Table 1: The relative intensities of the 12 primary discrete peaks of $^{155}$Gd(n, $\gamma$).

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

We finally generate the spectrum for \( {\text{nat}} \text{Gd(n}, \gamma) \), by adding the same generated by our model for \( ^{155} \text{Gd(n}, \gamma) \) and \( ^{157} \text{Gd(n}, \gamma) \) 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, \( \gamma \)). We also show the ratio of data/MC in bins of 200 keV for \( ^{155} \text{Gd(n}, \gamma) \) (red), \( ^{157} \text{Gd(n}, \gamma) \) (green) and \( {\text{nat}} \text{Gd(n}, \gamma) \) (blue), 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 \( {\text{nat}} \text{Gd(n}, \gamma) \). The corresponding spectra from GLG4sim (blue) and GEANT4 (green) are also shown. Right: Data/MC (our model) in bins of 200keV for \( ^{155} \text{Gd(n}, \gamma) \) (red), \( ^{157} \text{Gd(n}, \gamma) \) (green) and \( {\text{nat}} \text{Gd(n}, \gamma) \) (blue).

References