Measurement of Relative Intensities of the discrete γ-rays from the thermal neutron capture reaction $^{155,157}Gd(n,\gamma)$ using ANNRI detector (J-PARC).

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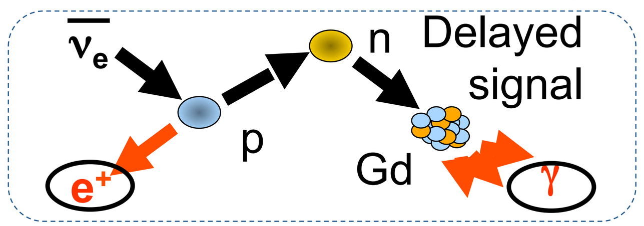
1. Introduction, Gd(n, γ) reaction

- **Among all stable nuclei, Gd has the largest thermal neutron capture cross-section. Gd(n, γ) reaction emits total ~8MeV γ-rays.**
- **Application of Gd(n, γ) reaction**
  - Gd(n, γ) reaction is used for neutron tagging to identify anti-neutrino interactions from other reactions.

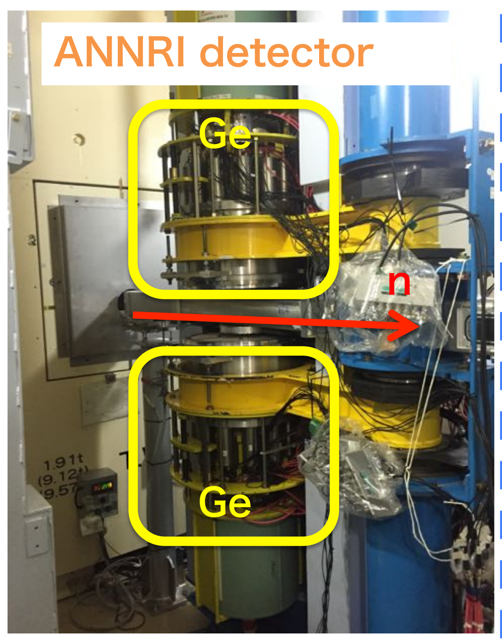


Reliable Gd(n, γ) MC is needed for neutrino detection experiments.

2. Experiment at ANNRI / J-PARC

Experimental Setup:

- Neutron beam line at J-PARC/MLF.
  - High intensity pulse neutron beam.
  - $\Delta E_n/E_n$~1%, p beam power 300 kW.
- ANNRI detector is used for measuring γ-rays.
  - Two clusters of Ge detector + BGO (Bismuth Germanium oxide) anti-Compton veto detector.
  - Solid angle : Ge 22%, BGO VETO 55%



2.1. Experimental Data

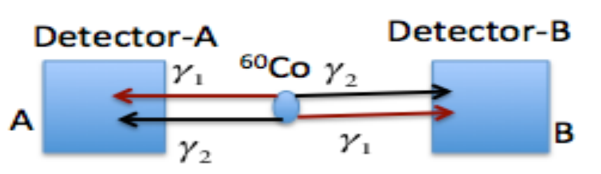
- Experimental data are taken for enriched Gd.

Experimental period : 2014.12.11-16 (2014B0126)
Target : Enriched Gd(A=155(91.65%), 157(88.4%) Gd_2O_3 powder)
Total event : 8×10^9 events
Calibration source : ^{22}Na, ^{60}Co, ^{137}Cs, ^{152}Eu, NaCl

2.2. Measurement of Photo-Peak Efficiency :

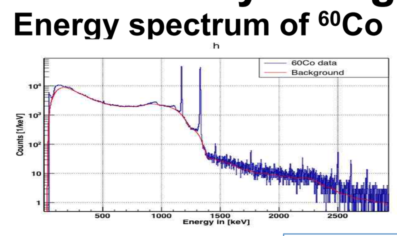
- Absolute Efficiency : ^{60}Co, ^{22}Na
- Relative Efficiency : $^{35}Cl(n,\gamma)^{36}Cl$, ^{152}Eu

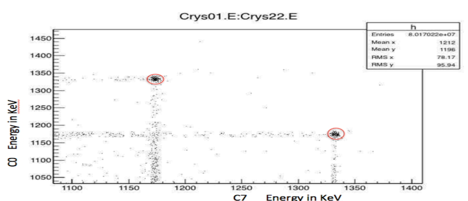
2.2.1. Measurement of Photo-Peak Efficiency Using Coincidence Method: ^{60}Co source



γ_1=1.173MeV, γ_2=1.332MeV

Energy spectrum of ^{60}Co





Number of events of both the detectors

$$N_1^{(A)} = \beta T \eta^A \varepsilon_1^{(A)} (1 - C^A_{\gamma_2} \eta^A \varepsilon_2^A)$$
$$N_2^{(A)} = \beta T \eta^{(A)} \varepsilon_2^{(A)} (1 - C^A_{\gamma_1} \eta^A \varepsilon_1^A)$$
$$N_1^{(B)} = \beta T \eta^{(B)} \varepsilon_1^{(B)} (1 - C^B_{\gamma_2} \eta^B \varepsilon_2^B)$$
$$N_2^{(B)} = \beta T \eta^{(B)} \varepsilon_2^{(B)} (1 - C^B_{\gamma_1} \eta^B \varepsilon_1^B)$$
$$N_3 = \beta T \eta^A \varepsilon_1^{(A)} \eta^{(B)} \varepsilon_2^{(B)} W(z)$$
$$N_4 = \beta T \eta^{(A)} \varepsilon_2^{(A)} \eta^{(B)} \varepsilon_1^{(B)} W(z)$$

Where,
β= activity of the radioactive source (in Bq)
T= Measurement time (in sec)
η= Geometrical acceptance
ε= Photo-peak efficiency
ε_{abs}=ηε=Absolute photo-peak efficiency.

Live time correction, $r_L = \frac{N_d}{N_t}$

N_t = number of random timing pulser events.
N_d= number of pulser events detected
Let, $h = r_L^{(A)}, i = r_L^{(B)}, j = r_L^{(AB)}$
Where , h= live time correction of detector A,
i= live time correction of detector B.
j=live time correction of AB together.
and ,f=W(z) , $W(z) = 1 + 0.1020 P_2(z) + 0.0091 P_4(z)$
$z = \cos\theta$
Where θ be the angle between the two detectors.

Let $a = \beta T, b = \eta^{(A)} \varepsilon_1^{(A)}, c = \eta^{(A)} \varepsilon_2^{(A)}, d = \eta^{(B)} \varepsilon_1^{(B)}, e = \eta^{(B)} \varepsilon_2^{(B)}, f = W(z)$

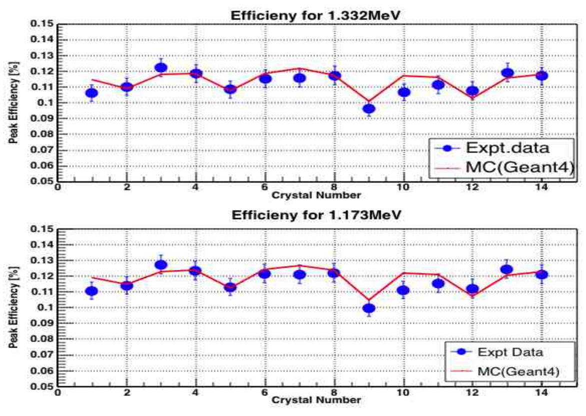
χ^2 method

$$\chi^2 = \left(\frac{observe - expected}{\sigma}\right)^2 \quad \chi^2 = \left(\frac{N_1^{(A)} - hab(1 - C^A_{\gamma_2} c)}{\sigma_1}\right)^2 + \left(\frac{N_2^{(A)} - hac(1 - C^A_{\gamma_1} b)}{\sigma_2}\right)^2 + \left(\frac{N_1^{(B)} - iad(1 - C^B_{\gamma_2} e)}{\sigma_3}\right)^2 + \left(\frac{N_2^{(B)} - iae(1 - C^B_{\gamma_1} d)}{\sigma_4}\right)^2 + \left(\frac{N_3 - abefj}{\sigma_5}\right)^2 + \left(\frac{N_4 - acdfj}{\sigma_6}\right)^2$$

Where ,
$C_{\gamma_2}^A$ =is the coincidence summing factor of A due to γ_2.
$C_{\gamma_1}^A$ =is the coincidence summing factor of A due to γ_1.
$C_{\gamma_2}^B$ =is the coincidence summing factor of B due to γ_2.
$C_{\gamma_1}^B$ =is the coincidence summing factor of B due to γ_1.

$$C^A_{\gamma_2} = \frac{N_t^A}{N^B_{\gamma_1}} \quad C^A_{\gamma_1} = \frac{N_t^A}{N^B_{\gamma_2}} \quad C^B_{\gamma_2} = \frac{N_t^B}{N^A_{\gamma_1}} \quad C^B_{\gamma_1} = \frac{N_t^B}{N^A_{\gamma_2}}$$

Using MINUT program, we calculated the absolute photo-peak of detector A and B.



Good agreement between data and MC(Geant4) efficiency.

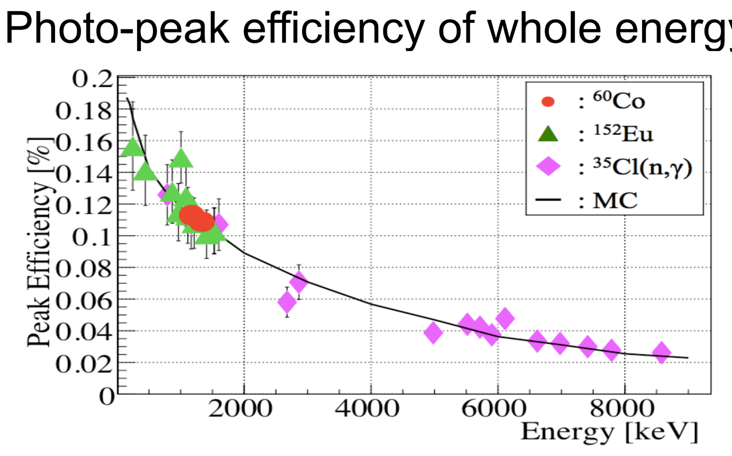
2.2.2 Measurement of Relative Efficiency: $^{35}Cl(n,\gamma)^{36}Cl$

Number of events of any photo peaks
N=βTηε = Intensity. Efficiency
Then efficiency can be written as $\varepsilon = \frac{N}{I}$
Where I is the intensity of any photo peaks (from table value).

Relative efficiency, $\varepsilon_R = \frac{\varepsilon}{\varepsilon_{max}}$

ε_{max} be the maximum efficiency.

Photo-peak efficiency of whole energy of γ in single Ge detector



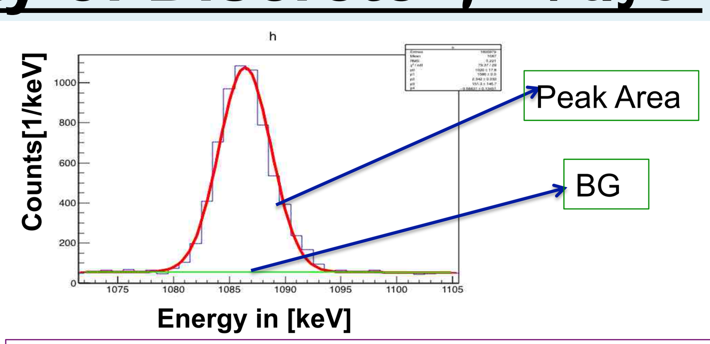
- Absolute photo-peak efficiency (0.11%@1.17MeV for 1 crystal) was measured using ^{60}Co (1.17, 1.33MeV).
- Relative efficiency values were measured using $^{35}Cl(n,\gamma)^{36}Cl$. Thus, the detection efficiency from 0.5 MeV to 9 MeV is well understood with ±7% accuracy.

3. Measurement Relative Intensity of Discrete γ-rays

Intensity can be written as

$$I = \frac{N_{sig}}{\varepsilon}$$

where N_{sig} is the number of signals and ε is the efficiency.
N_{sig} can be written as $N_{sig} = N_{raw} - BG$
where N_{raw} be the total number of raw events and BG be the background events.
N_{raw} was evaluated by the summation of counts in the channel interval {C_{ch}−3×FWHM, C_{ch}+3×FWHM}, where C_{ch} was the channel of the peak center and FWHM was the full width at the half maximum of the γ-ray photo-peak.

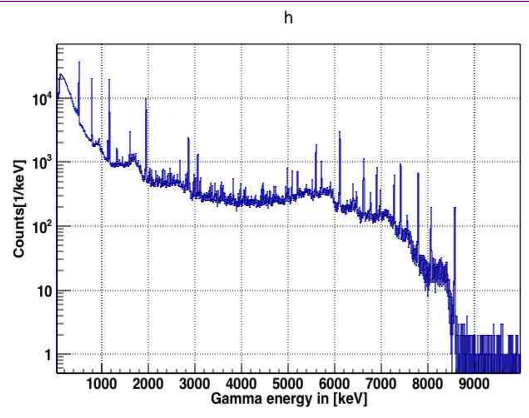


Relative intensity can be written as

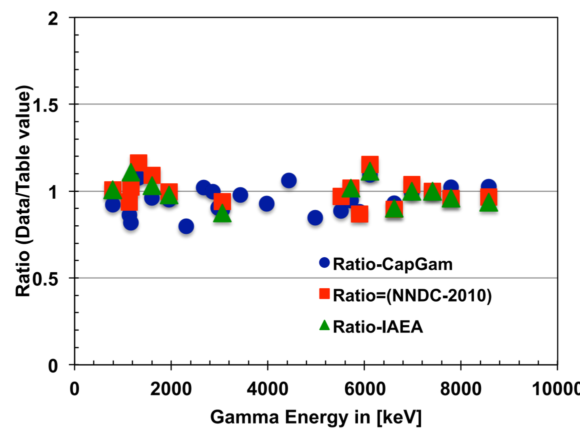
$$I_R = \frac{I}{I_{Norm}} \times 100\%$$

Where I be the intensity of any photo-peak and I_{norm} be the value of intensity by which we make normalized.

γ-ray spectrum of $^{35}Cl(n,\gamma)^{36}Cl$



Ratio (data/Table value) for ^{36}Cl



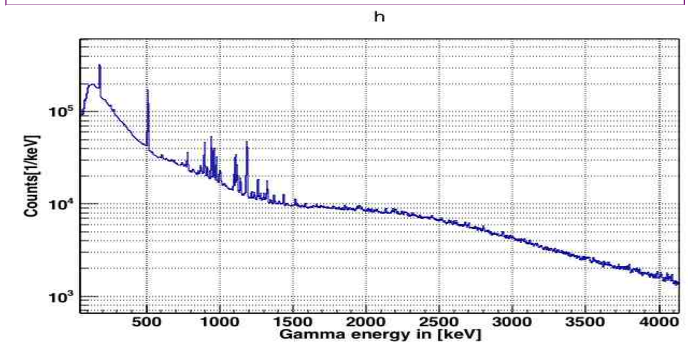
- Our data agree fairly well with table value of NNDC (CapGam).

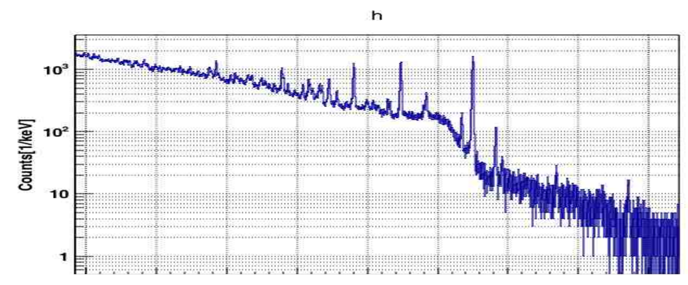
Relative intensities of γ-rays from the $^{35}Cl(n,\gamma)^{36}Cl$ reaction

Peak Energy in [keV]	Relative Intensities, I_R(%)			
	MLF (Our Data)	NNDC CapGam	IAEA 1991	NNDC 2010 (Shibata et.al)
786.30+788.42	247.81±0.93	268.71±0.62	246(15)	245.9
1131	16.39±0.48	18.99±0.05		17.5
1162.73+1164.86+1170.94	285.29±0.97	349.42±2.2	257(22)	278.9
1327	13.15±0.53	12.22±0.04		11.3
1601	35.39±0.59	36.87±0.1	34.3(32)	32.4
1951.1+1959.4	301.61±1.10	317.10±0.94	308(18)	302.5
2676	16.50±0.51	16.17±0.19		
2863	55.12±0.66	55.27±0.14		
2975	10.30±0.42	11.41±0.04		
3061	30.59±0.54	34.25±0.09	35(3)	32.6
3428	8.10±0.50	8.29±0.04		
3981	9.36±0.45	10.11±0.08		
4440	12.09±0.57	11.41±0.04		
4979	31.80±0.79	37.47±0.13		
5517	15.11±0.76	17.07±0.08		15.6
5715	52.28±1.04	55.27±0.21	51.4(42)	51.4
5902.7+5913.3	9.98±1.90	11.33±0.04		11.5
6110	219.48±1.51	200.41±0.75	197(16)	190.1
6619.6+6627.8+6642.0	114.85±1.21	123.44±0.6	127.4(76)	128.4
6977	22.29±0.82	22.51±0.12	22.3(2)	21.5
7414	100.00±1.18	100±0.58	100.0(80)	100
7790	82.72±1.01	80.93±0.36	86.1(69)	86.3
8578	27.54±0.60	26.88±0.16	29.4(24)	28.5

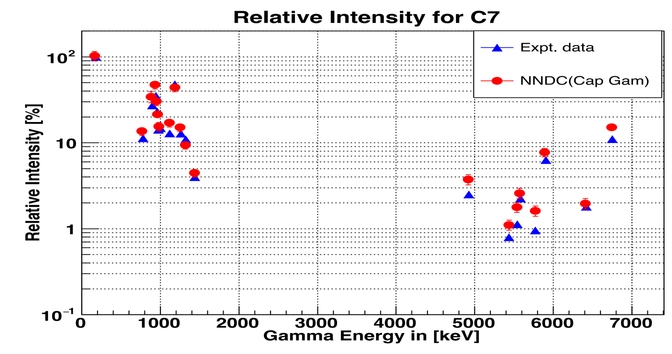
Preliminary

γ-ray spectrum of $^{157}Gd(n,\gamma)^{158}Gd$





Relative Intensity for C7



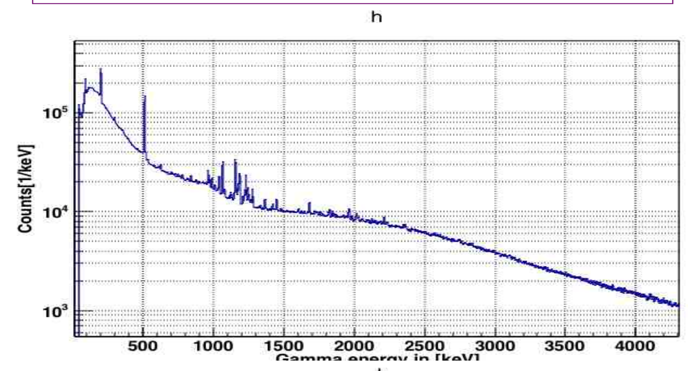
- Fair agreement between our data and NNDC (CapGam) in discrete peaks of ^{158}Gd .

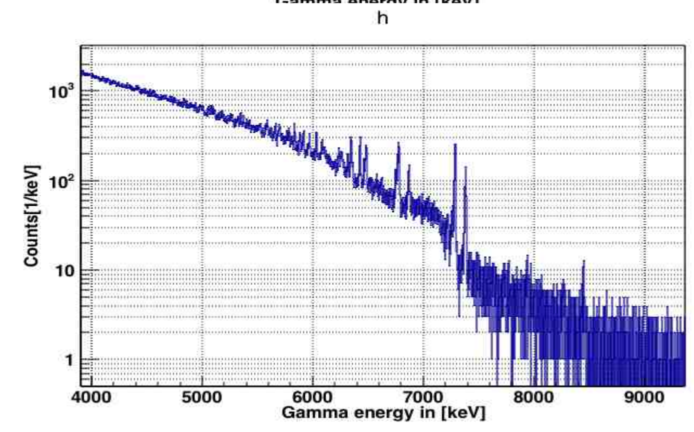
Relative intensities of γ-rays from the $^{157}Gd(n,\gamma)^{158}Gd$ reaction

Peak Energy In [keV]	Relative Intensity, I_R[%]	
	MLF (our data)	NNDC (CapGam)
181	100.0±0.24	100±13.04
780	13.69±0.13	13.64±1.5
897.51+897.62	31.99±0.14	33.82±5.05
944	38.32±0.15	46.64±5.15
962	24.99±0.14	29.73±3.28
978	17.74±0.12	21.06±1.97
998.41+1000.82+1004.04	14.82±0.15	15.5±1.74
1107	25.26±0.11	24.6±2.86
1119	19.61±0.11	17.02±1.88
1184.01+1186	48.02±0.15	43.92±4.82
1259.86+1263.51	12.81±0.13	14.79±1.65
1324	10.95±13	9.27±1.01
1437	3.98±11	4.42±0.49
4925	3.22±0.09	3.71±0.51
5436	0.87±0.06	1.09±0.15
5542	1.57±0.06	1.75±0.23
5582	2.40±0.07	2.56±0.36
5783	2.88±0.08	2.02±0.29
5903	1.16±0.05	1.58±0.22
6420	6.65±0.08	7.69±0.89
6750	1.80±0.06	1.96±0.28

Preliminary

γ-ray spectrum of $^{155}Gd(n,\gamma)^{156}Gd$





- The relative intensities of discrete γ-rays from the n-capture with ^{155}Gd reaction have been calculated for the first time with good accuracy.

Relative intensities of γ-rays from the $^{155}Gd(n,\gamma)^{156}Gd$ reaction

Peak Energy [in keV]	Relative Intensity, I_R [%] MLF[Our data]	Peak Energy [in keV]	Relative Intensity, I_R[%] MLF(our data)
199	100.00±0.23	1449	4.33±0.09
296	6.31±0.17	1604	1.25±0.08
625	2.62±0.10	1681	3.94±0.11
780	2.75±0.12	1962	5.24±0.12
840	3.11±0.10	2211	2.94±0.11
897	1.30±0.11	5348	0.75±0.06
959	6.61±0.10	5660	1.07±0.05
969	5.57±0.09	5836	0.89±0.05
988	4.38±0.10	5918	0.93±0.06
1009	2.33±0.10	6034	1.65±0.05
1039	10.43±0.11	6348	1.55±0.05
1065	20.23±0.11	6429	0.94±0.05
1156	36.56±0.14	6481	0.97±0.04
1186	15.57±0.11	6870	1.13±0.04
1230	9.43±0.09	7288	2.16±0.04
1277	5.71±0.09	7382	4.33±0.03
1366	4.17±0.11		
1420	2.16±0.10		

Preliminary

4. Summary

- In this experiment, we measured the discrete γ-rays from the $^{155,157}Gd(n,\gamma)$ reactions using ANNRI detectors (Ge detectors) with good energy resolution.
- The good agreement between our data and NNDC table value (CapGam) of $^{35}Cl(n,\gamma)^{36}Cl$ and ^{158}Gd in discrete levels.
- The relative intensities of discrete γ- rays of ^{156}Gd was calculated for the first time with so much good accuracy.
- Next we need to estimate the systematic errors due overlap and leakage effect of γ-rays through the detectors to establish the result .