A study of gamma-ray production from thermal neutron capture on Gadolinium

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1. Introduction, Gd(n, γ) reaction

- Among all stable nuclei, **Gd-157** has the **largest** thermal neutron capture cross-section. **Gd-155** also has large cross-section.
- Both capture interaction emits total ~8MeV γ-rays.

Reaction	Cross-section (barn)
n+p →d+γ (2.2MeV)	0.3326
n+^{6}Li →α+^{3}He	940
n+^{10}B →α+^{7}Li	3837
n+^{155}Gd→^{156}Gd+γs (8.5 MeV)	60,900
n+^{157}Gd→^{158}Gd+γs (7.9 MeV)	254,000

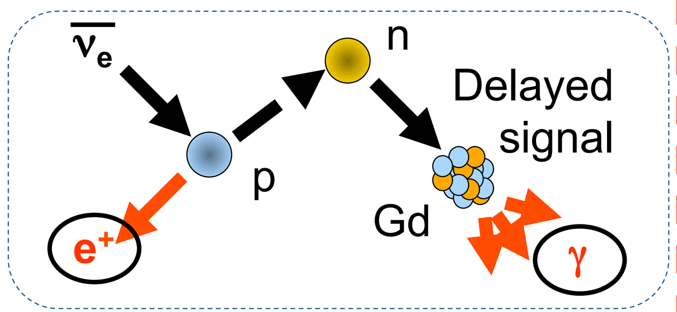
Frequently used neutron absorbers

×15 ~ ×250 Cross-section!

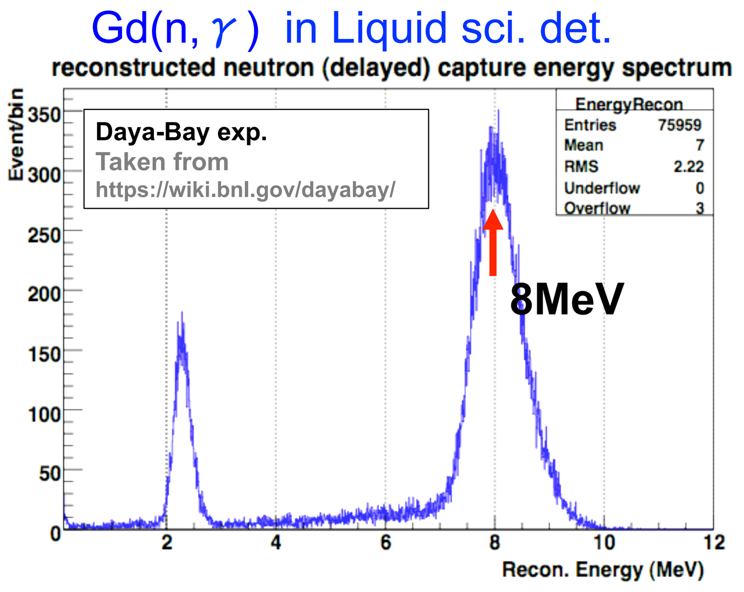
Application of Gd(n, γ) in neutrino experiments

- **Gd(n, γ)** reaction is used for **neutron tagging** to identify anti-neutrino interactions from other reactions.
  → Lowering backgrounds, better analysis.

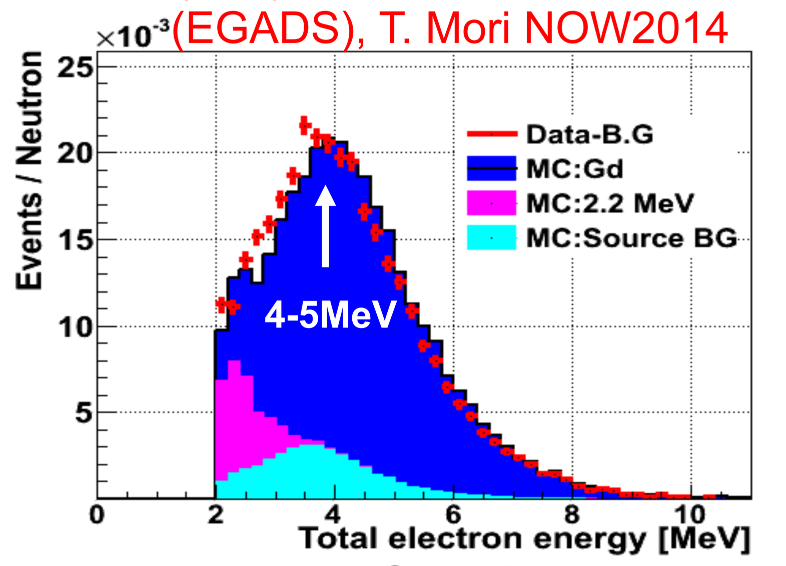
Reliable Gd(n, γ) MC is needed for water Cherenkov detectors, because of their Cherekonv threshold (~1MeV).



Gd(n, γ) in Liquid sci. det.



Gd(n, γ) in Water Cherenkov det. (EGADS), T. Mori NOW2014



Present and future neutrino experiments using Gadolinium

Experiment	Detector	Measure
Daya Bay, RENO, Double Chooz	Liquid scintillator	The mixing angle θ_{13}
LENA (plan)	Liquid scintillator	SRN, SN ν, Solar ν, Geo ν, p⁺ decay
EGADS	Water Cherenkov	R&D detector for SK-Gd (GADZOOKS!)*
SK-Gd* (plan)	Water Cherenkov	SRN, SN ν, Solar ν, atm ν, proton decay

* M.Ikeda's presentation at this NNN15.

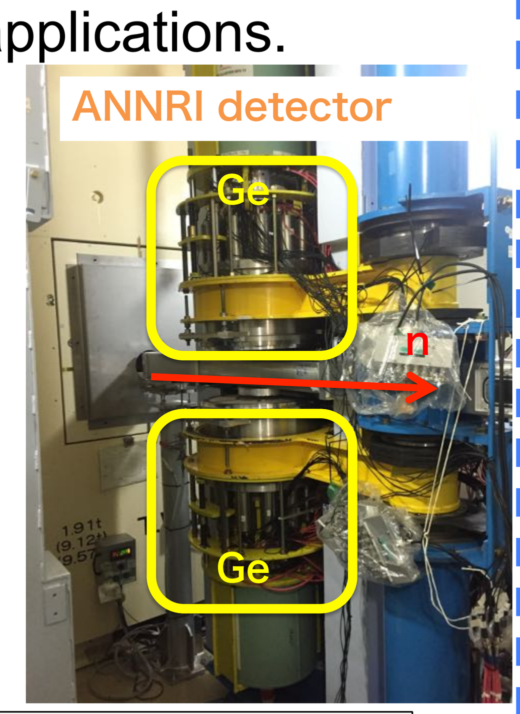
2. Experiment at ANNRI / J-PARC

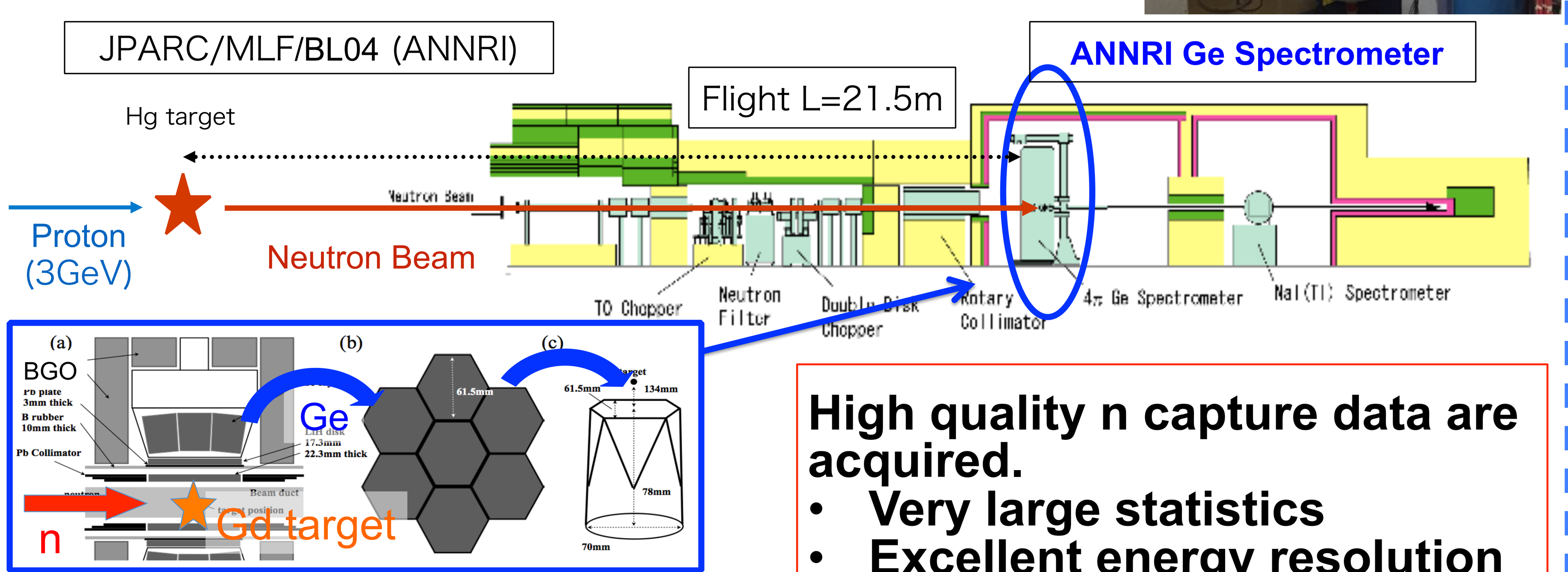
Purpose

- □To study the fundamental information of Gd(n, γ) reaction. (Measurement of the precise energies of continuum and discrete γ-rays.)
- □To provide more precise information and MC simulation for the neutrino experiments using Gd(n, γ) and other applications.

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 Gd.
  - □Two cluster of Ge detectors + BGO anti-Compton veto detector.
  - □ΔE_γ=9keV at 1.3 MeV





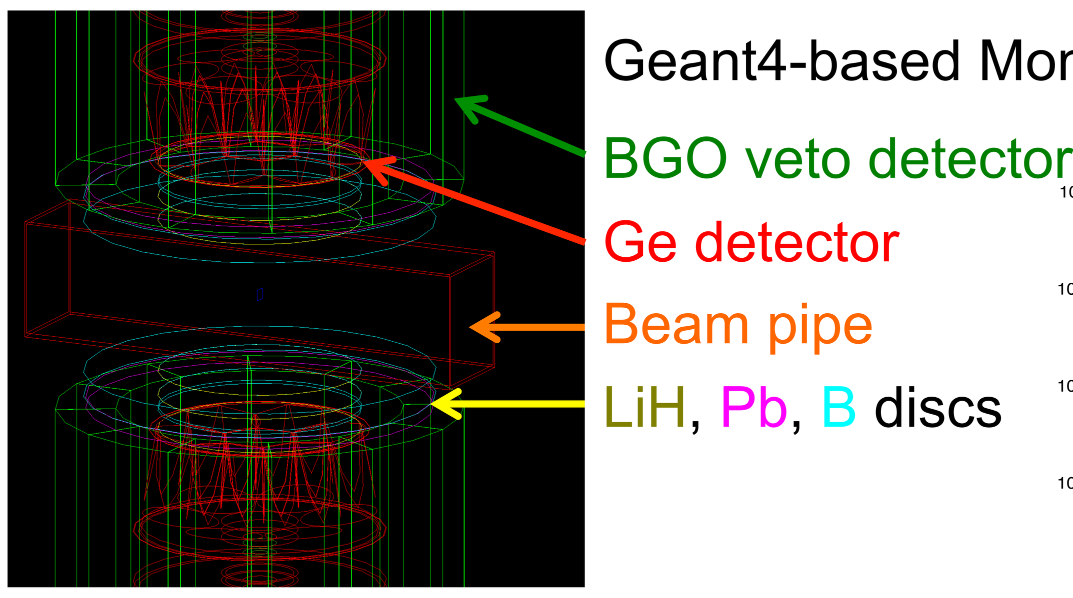
Solid angle : Ge 22%, BGO VETO 55%

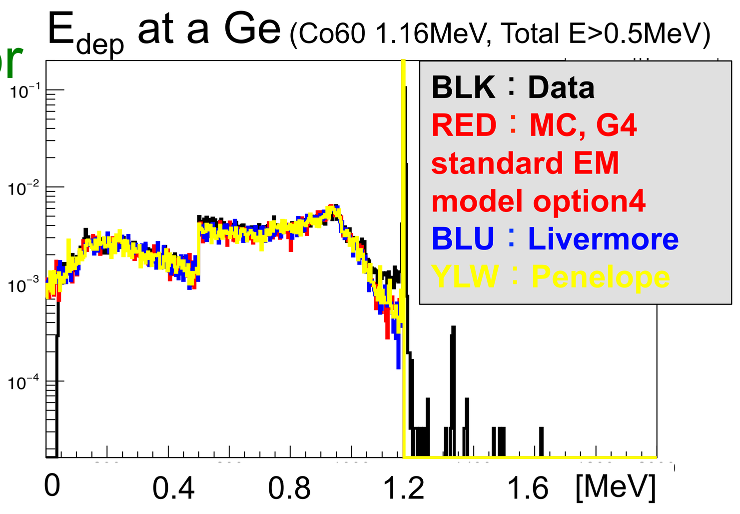
High quality n capture data are acquired.
- **Very large statistics**
- **Excellent energy resolution**

3. Data Analysis and Simulation

3-1. ANNRI Detector Simlation

- A reliable MC is constructed based on Geant4.9.6p02.





3-2. Gadolinium gamma-emission model

- A Gd(n,γ) calculation code is newly written for Geant4.
  - The calculation is based on Kopecky. PRC 47.312.
  - Probability of gamma-emission with the energy e_γ for excited nuclei with E_{ex} is calculated with following function:

$$P(e_\gamma, E_{ex}) = \frac{\sum_{XL} T_{XL}(e_\gamma)\rho(E_{ex}-e_\gamma)}{\int_0^{E_{ex}} \sum_{XL} T_{XL}(e_\gamma)\rho(E_{ex}-e_\gamma)de_\gamma}$$

ρ: Level density
T_{XL} = gamma transition coefficient.
XL=E1, M1, E2…

  - Here Enhanced Generalized Lorentzian (EGLO) is used for Photoabsorption Strength Function (PSF).

$$T_{XL}(e_\gamma) = 2\pi e_\gamma^{2L+1} f_{XL}(e_\gamma)$$

$$f(e_\gamma, T) = A \times \left[\frac{e_\gamma \Gamma(e_\gamma, T)}{(e_\gamma^2 - E^2)^2 + e_\gamma^2 \Gamma(e_\gamma, T)^2} + 0.7\frac{\Gamma(e_\gamma = 0, T)}{E^3}\right]\sigma_0\Gamma$$

  - Required parameters for PSF and these for calculating nuclear temperature T are taken from RIPL-2.
    - Fermi-gas model is applied for calculating the temperature.
  - Level density ρ is taken from RIPL-3 database.
- Discrete gamma-emission is implemented to reproduce our data.

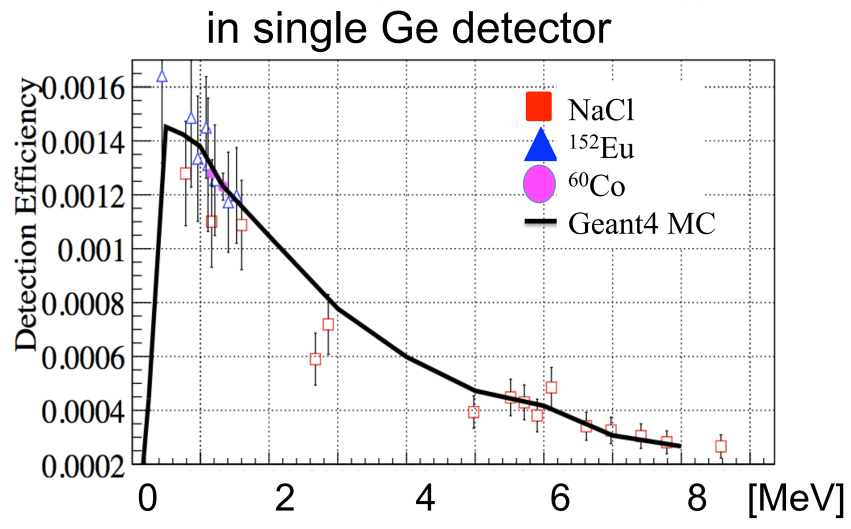
3-3. Comparison with Data and MC

- Experimental data are taken for natural and enriched Gd.

Experimental period	: 2013.3.14-17 (2012B0025)
Target	: Natural Gd (99.99% sheet, 5mm×5mm×10, 20μm)
Total event	: 3×10⁹events
Calibration source	: ^{60}Co, ^{137}Cs

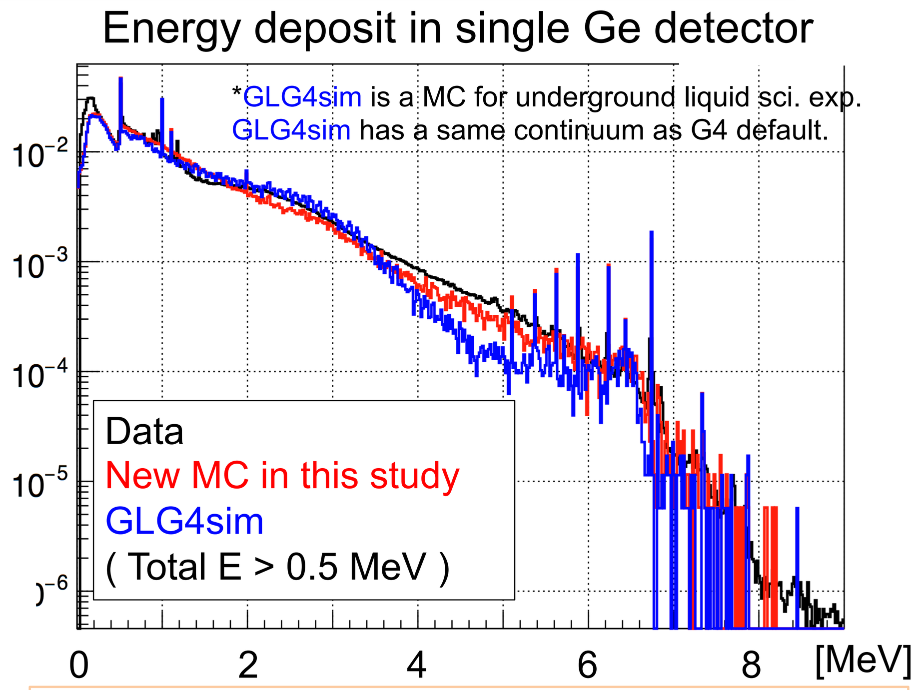
Experimental period	: 2014.12.11-16 (2014B0126)
Target	: Enriched Gd(A=155(91.65%), 157(88.4%) Gd_2O_3 powder)
Total event	: 8×10⁹events
Calibration source	: ^{22}Na, ^{60}Co, ^{137}Cs, ^{152}Eu, NaCl

Detection efficiency of whole energy of γ in single Ge detector



Detector response is well understood for 0.5-9MeV. (±20%)

Energy deposit in single Ge detector



Good agreement between data and MC.

Reliable detector MC and a new tunable Gd(n, γ) model are made. Further tuning will be done based on Data-MC comparison.

4. Summary

- **Gadolinium** is applied for several neutrino experiments for tagging anti-neutrino charged-current reaction.
- A reliable Gd(n, γ) MC is needed for water Cherenkov detectors.
- Experiments to measure Gd(n, γ) is performed with Ge detector array, ANNRI at MLF/J-PARC.
- **Reliable detector MC based on Geant 4.9.6.p02** and a **tunable Gd(n,γ)** model is newly made.
- **Further model tuning will be done.**

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