The PIKACHU experiment for the study of ^{160}Gd double beta decay

2024 Mar. 4th (Mon)

Takashi Iida (U. of Tsukuba)

For the PIKACHU collaboration

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UGAP2024 workshop @Tohoku Univ.

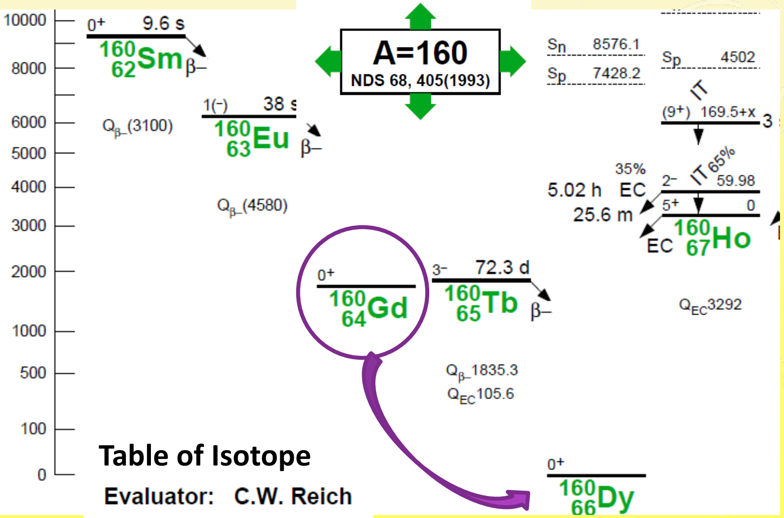
Contents

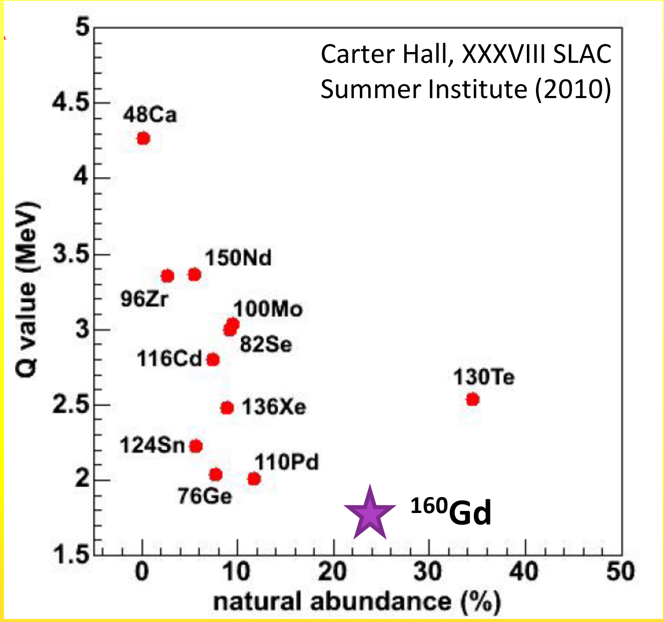
Double beta decay of ^{160}Gd

- Gadolinium (Gd) is a rare earth element lanthanide with atomic number 64 and atomic weight is 157.3.

- The ^{160}Gd isotope is one of the double beta-decay candidate nuclei.
  - ✓ Q-value : 1730 keV
  - ✓ Natural Abundance : 21.8%

Energy state of a nucleus with mass number 160





Both 0νββ, 2νββ are undiscovered

Nuclear matrix element (NME) of ^{160}Gd $2\nu\beta\beta$

- Two theoretical models predict $2\nu\beta\beta$ half-lives whose predictions differ by more than an order of magnitude.

$$T^{2\nu}_{1/2} \sim 6.02 \times 10^{21}\ \mathrm{yr}\quad [1]\ \ \text{(pseudo-SU (3) model)}$$

$$T^{2\nu}_{1/2} \sim 4.7 \times 10^{20}\ \mathrm{yr}^{*}\quad [2]\ \ \text{(QRPA model)}$$

* using same phase-space factor as ref. [1]

Theoretical description of the double beta decay of ^{160}Gd

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[1] J. G. Hirsch et al., Phys.Rev. C 66, 015502 (2002)

Global calculation of two-neutrino double-β decay within the finite amplitude method in nuclear density functional theory

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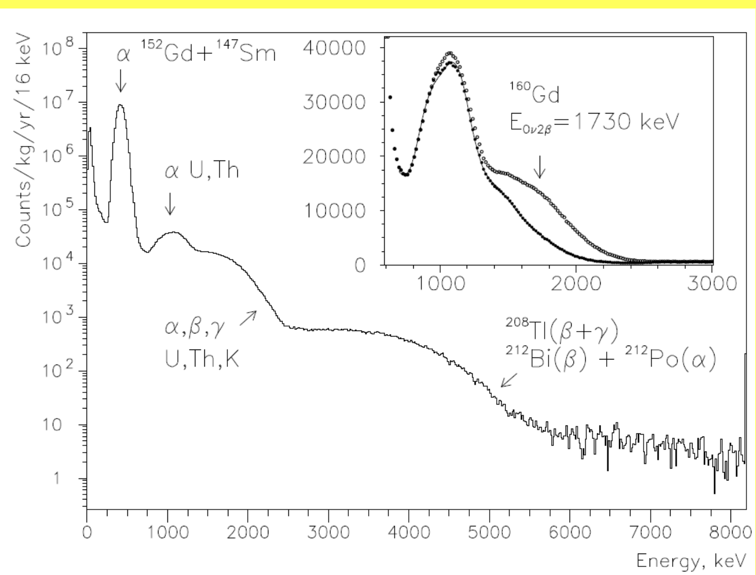
[2] N. Hinohara et al., Phys. Rev. C 105, 044314 (2022)

Previous research in Ukraine

- The world's best ββ search for ^{160}Gd is an experiment in Ukraine using a 2-inch GSO scintillator [3].
- α/β-rays from U/Th series impurities in the crystal was a serious background (BG).
- If the sensitivity increased by more than an order of magnitude, sensitivity approaches to predicted half-life of ^{160}Gd 2νββ.



World best ^{160}Gd ββ search	
Detector	GSO scintillator
^{160}Gd mass	100g
Exp. period	~2 yr
Main BGs	Internal α/β of U/Th External γ from PMT
0νββ limit※	$> 2.3 \times 10^{21}$ yr
2νββ limit※	$> 2.1 \times 10^{19}$ yr

※ 90% C.L.

[3] F.A.Danevich et al., Nucl. Phys. A, Vol. 694, Iss. 1–2, 2001, Pages 375-391

The PIKACHU experiment

Pure Inorganic scintillator experiment in KAmioka for CHallenging Underground sciences

- Double beta decay experiment ^{160}Gd using **$Ce{:}Gd_3Ga_2Al_3O_{12}$（GAGG）**

♣ Phase 1（2024～）

Update $0\nu\beta\beta$ search sensitivity of ^{160}Gd using large crystals of similar purity as GSO in previous studies.

♠ Phase 2（2026～?）

Discovery of ^{160}Gd $2\nu\beta\beta$ using ultra-high purity crystals with an order of magnitude higher purity.

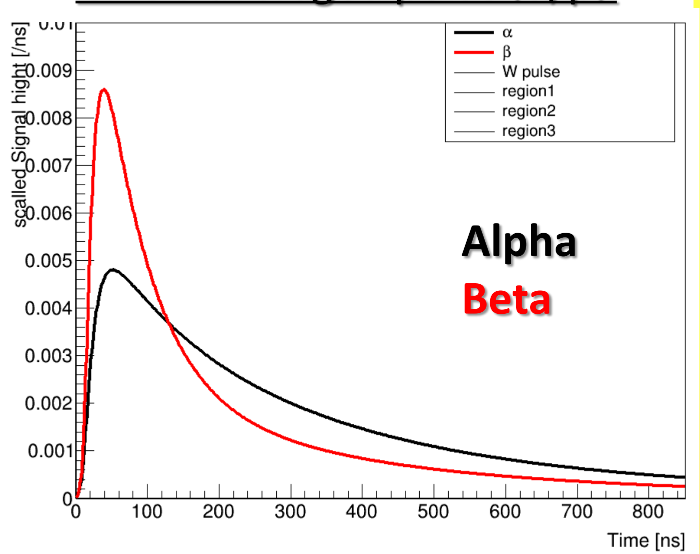
6 Japanese institutes and 12 collaborators!

Our strategy to increase sensitivity

- **Large crystal**: One GAGG crystal includes 3-4 times more ^{160}Gd than GSO.
- **High LY**: Six times higher light yield enable us better energy resolution.
- **PSD**: α and β can be completely separated by PSD。
- **Low BG tech.**: Low radioactivity PMT for DM search etc.

◆ It is then necessary to remove radioactive impurities of the U/Th series inside the crystals.

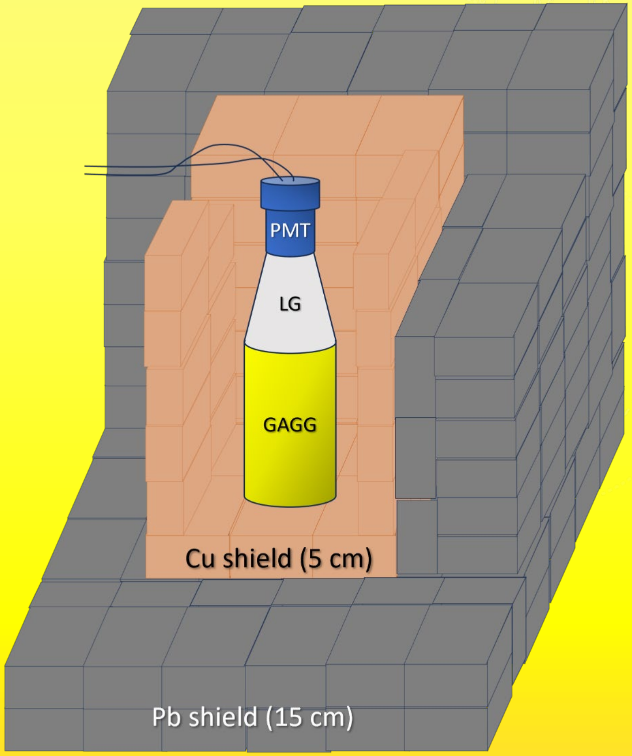
GAGG averaged pulse（α/β）



	Ukraine	PIKACHU
Detector	GSO scintillator	GAGG scintillator
Amount of ^{160}Gd	100 g	700 g（2 crystals）
LY	10,000 ph./MeV	60,000 ph./MeV
Exp. period	2 years	2 years?
BG level	Refer [3]	1/10 by PSD
$T_{1/2}$ limit	$T^{0\nu} > 2.3 \times 10^{21}$ y $T^{2\nu} > 2.1 \times 10^{19}$ y	0νββ search ph.1 2νββ discovery ph.2

BG study in Kamioka @2021

- BG survey using conventional GAGG was carried out in Kamioka in Jul. 2021.
- The detector module was installed in the Pb/Cu shield in the KamLAND area. Thanks to Inoue-san, Koga-san and Ikeda-san for the cooperation!
  - ➢ Shield : Pb 15cm &Cu 5cm thick
  - ➢ GAGG : 6.5 cmϕ × 14.5 cmL (3.2 kg)

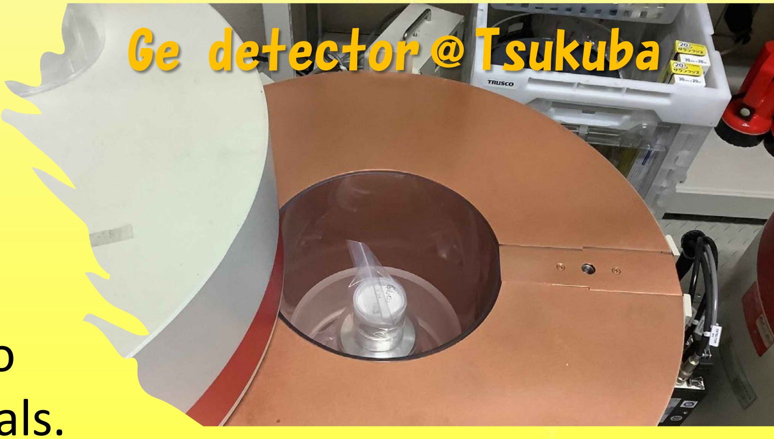


✓ ***As a result, we found that conventional GAGG crystal contains 10 times more U/Th compared to GSO in Ukraine ☹☹☹***

Development of high purity GAGG

The following materials are used for growing large-sized GAGG crystals.

1.	**Gadolinium oxide (Gd_2O_3)**	**3.8 kg**
2.	**Gallium oxide (Ga_2O_3)**	**2.0 kg**
3.	**Aluminum oxide (Al_2O_3)**	**750 g**
4.	**Cerium oxide (CeO_2)**	**15 g**



Ge detector in Tsukuba and Kamioka were used to investigate radio impurities inside the raw materials.

- ✓ Pure Gd_2O_3 was made in cooperation with Nippon Yttrium (NYC), a company that makes $Gd_2(SO_4)_3$ for SK-Gd. Purification by resin was carried out (¥50,000/kg).
- ✓ Al_2O_3 is difficult to purify because it is insoluble in acid. Several samples were measured with a Ge detector and the lowest impurity one is selected for use.
- ✓ Ga_2O_3 and CeO_2 were also measured with a Ge detector, but these raw materials were sufficiently high purity.

Summary of raw material purification

[mBq/kg]

	Gd_2O_3 High-purity	Gd_2O_3 Original	Al_2O_3 High-purity	Al_2O_3 Original
^{238}U	< 16.3	1750 ± 221	< 28.3	476 ± 44
^{235}U	< 10.0	130 ± 40	< 7.82	< 21.1
^{232}Th	1.66 ± 0.41	270 ± 12	5.85 ± 2.80	16.0 ± 6.6
^{40}K	< 2.70	84.8± 28.7	< 36.58	< 96.48

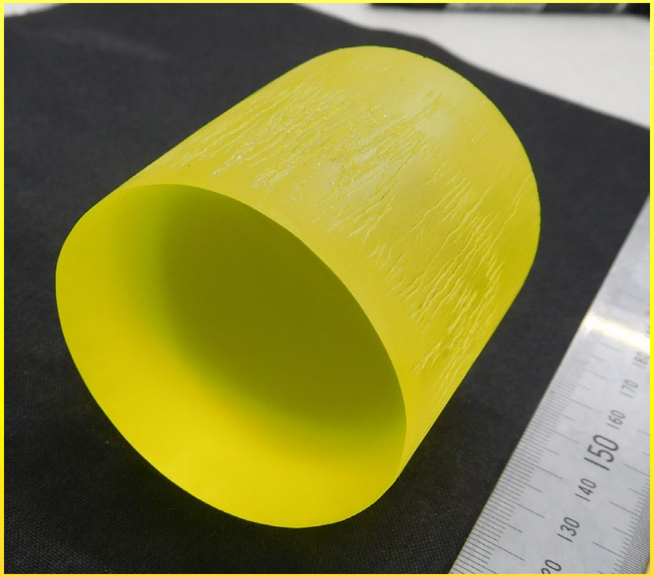
	Ga_2O_3	CeO_2
^{238}U	< 69.2	< 59.0
^{235}U	< 8.54	< 15.5
^{232}Th	< 10.8	4.4 ± 1.9
^{40}K	< 35.8	< 23.5

- ^{238}U, most important BG in PIKACHU, was significantly reduced by purification of Gd_2O_3 and selection of Al_2O_3.
- For Ga_2O_3 and CeO_2, original materials were enough pure.

✓ ***The purification process reduced the ^{238}U impurity by more than two orders of magnitude!!***

High purity GAGG crystal for PIKACHU

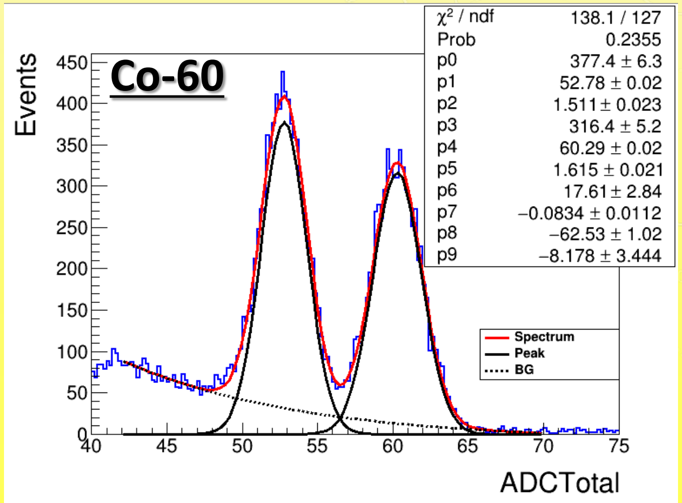
- Using high purity raw materials obtained by purification and selection, GAGG crystals of 2-inch size were grown at Tohoku University.
- The crystals were cut and polished, and the detector was fabricated by winding a reflective sheet and coupling it with a PMT and light guide.

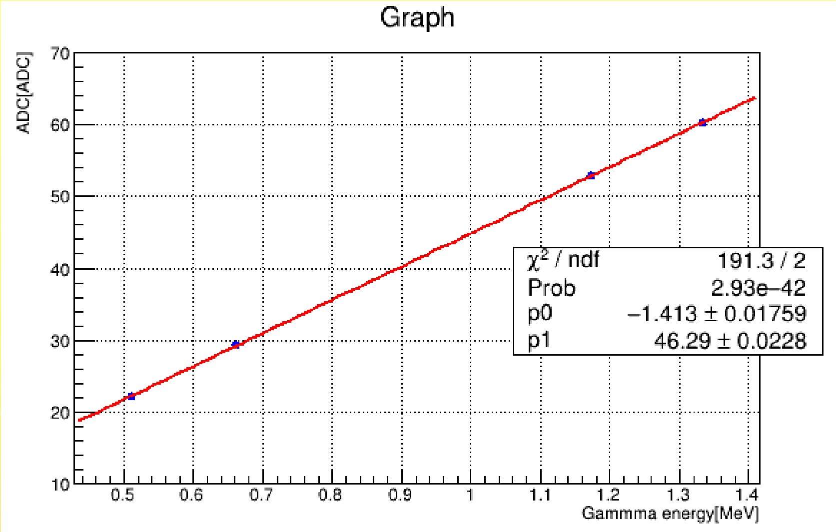


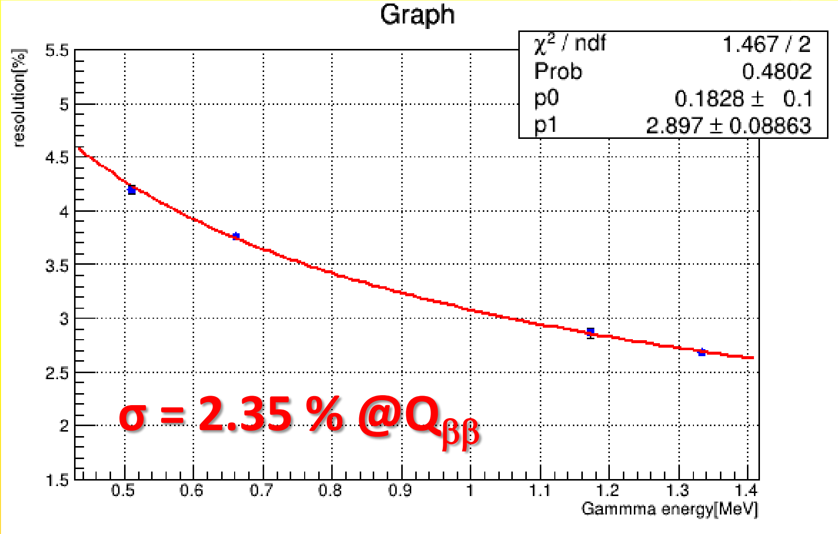
Energy calibration

- Data acquisition with three gamma-ray sources
- Fit γ-ray peak (exp + gaus)

Source	γ Energy
Cs-137	662 keV
Na-22	511 keV
Co-60	1173 keV
	1333 keV





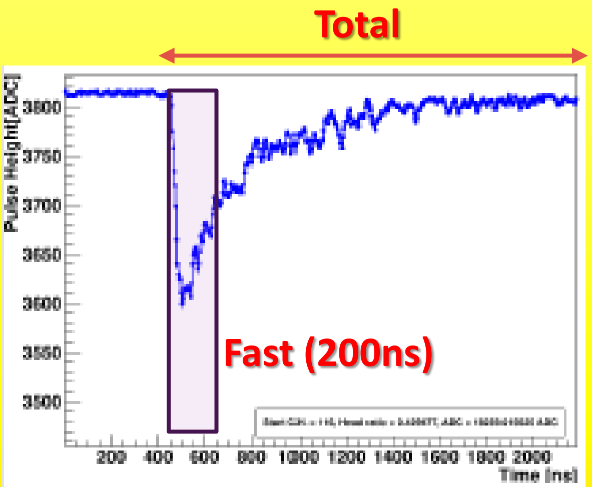


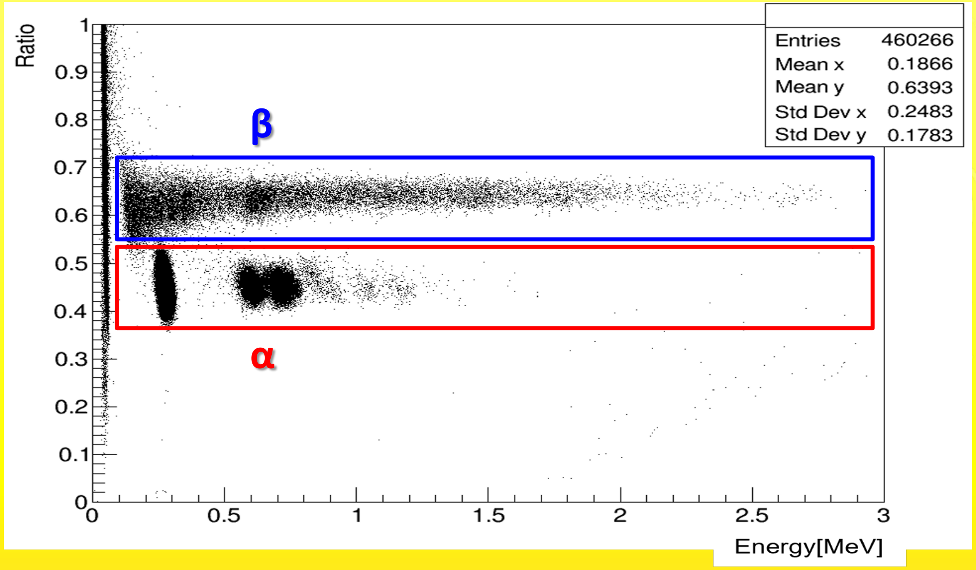
PSD capability of high-purity GAGG

- Pulse shape discrimination method (PSD) is Important for removing BGs.

- BG measurements carried out in Tsukuba and evaluate the PSD performance of high purity GAGG.

Ratio = Fast (200ns) / Total





✓β/α are completely distinguishable above 300 keV !!

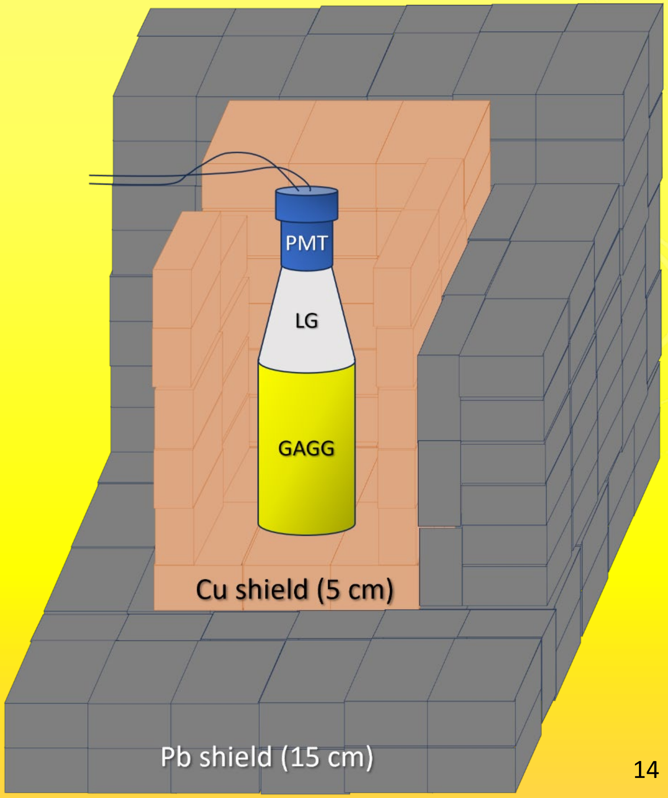
BG study in Kamioka 2023

- A BG survey of high-purity GAGG crystals was carried out in a low-BG environment 1000 m underground in Kamioka.
- BG estimation and sensitivity study for PIKACHU phase 1.

Date：2023 6/12～6/14

✓ Shield : Pb 15cm ＆Cu 5cm thick

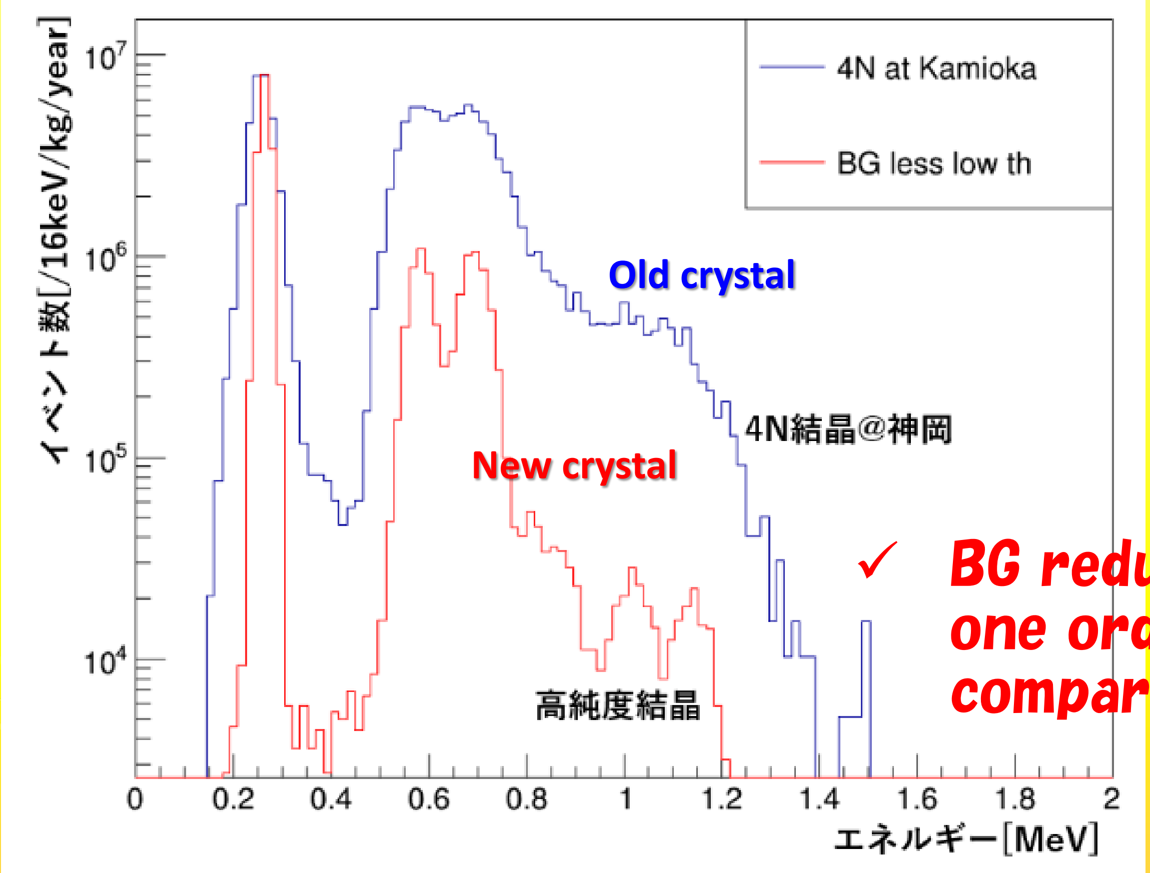
✓ HP-GAGG ：5.4 cmϕ×5.2 cmL (0.8 kg)



BG level compared with old crystal

- The radioactive BG levels inside the crystals were estimated from the α-ray rates.

The α-ray spectra selected by PSD



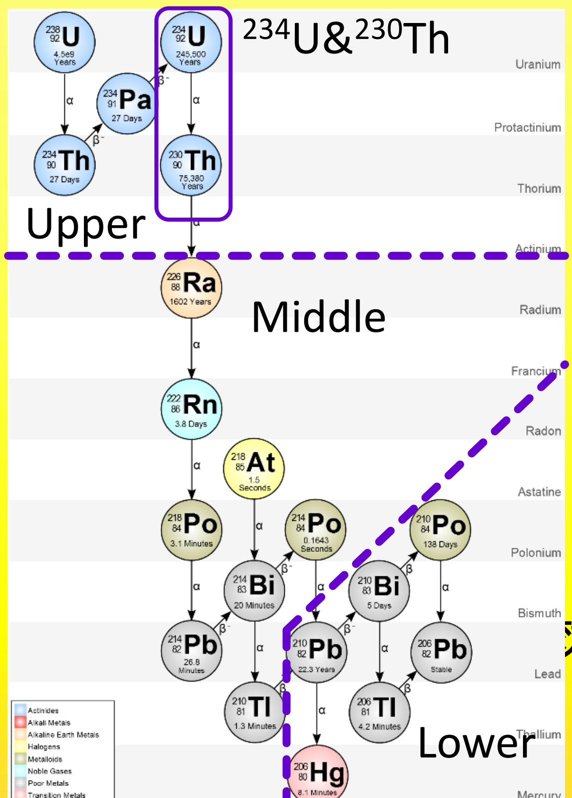
The energy resolution is also improved by changing the crystal composition.

✓ ***BG reduction of approximately one order of magnitude compared to the old crystals!***

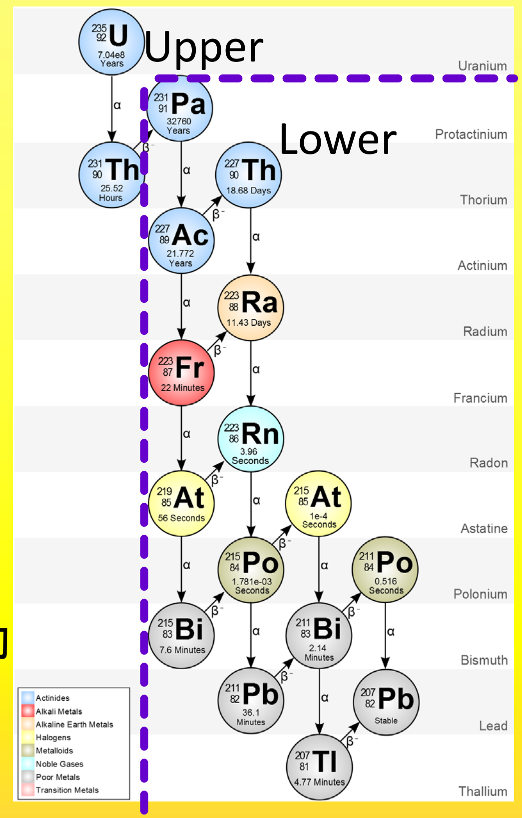
BG modelling with GEANT4

- In order do understand BGs quantitatively, GEANT4 simulation was used.
- Assuming radiative equilibrium below the long–lived ($T_{1/2}$ >10 yr) nucleus, BG energy spectra for ^{238}U, ^{235}U and ^{232}Th were simulated.

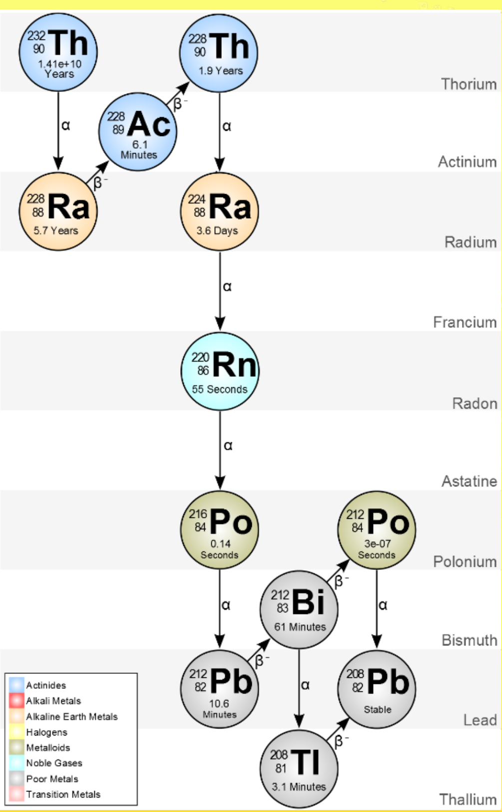
^{238}U-chain



^{235}U-chain

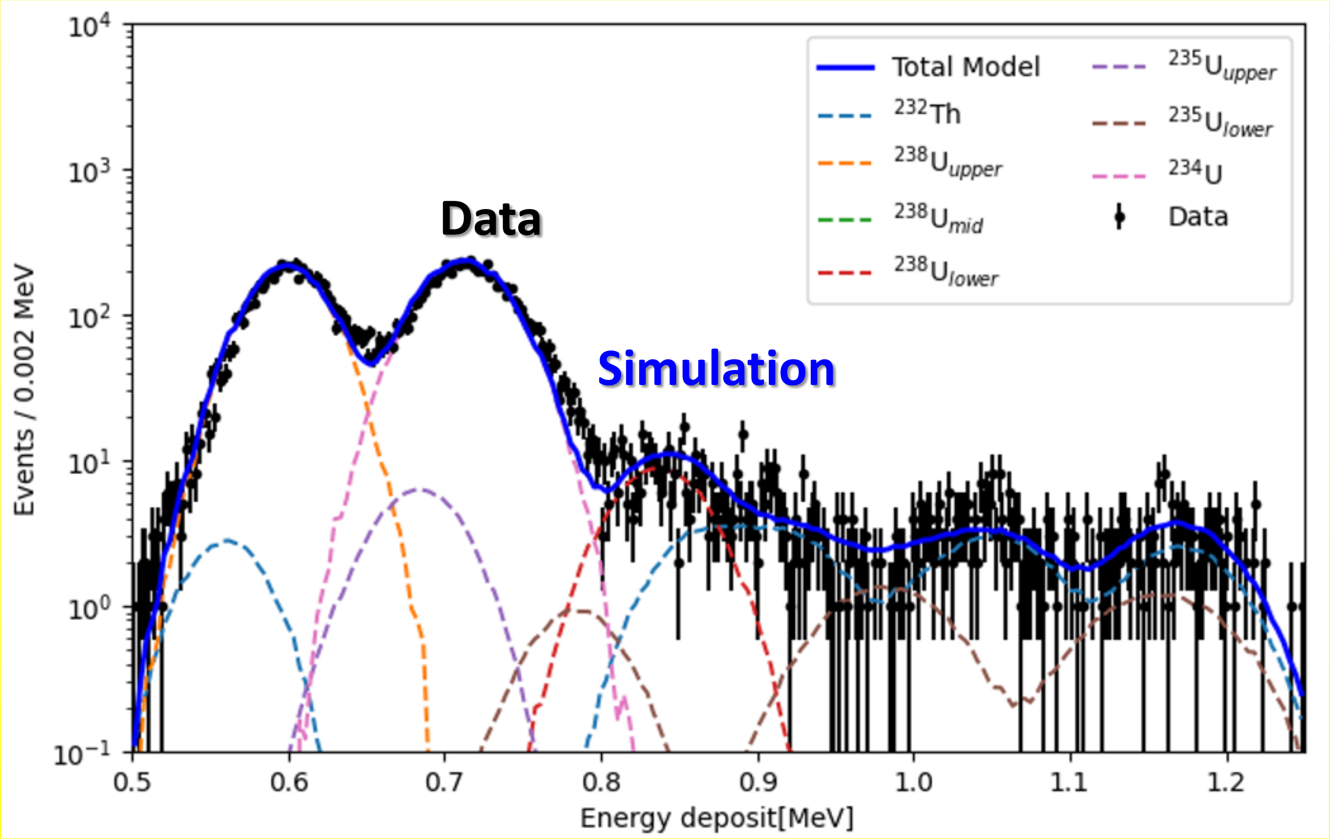


^{232}Th-chain



Understanding α-ray BG by fitting

- Fitting α spectrum (selected by PSD) with the simulated BG spectra.



Unit : mBq/kg

	^{238}U upper	^{238}U middle	^{235}U lower	^{232}Th
Old GAGG	**911±10**	16.5±3.5	73.5±15.3	**64.3±3.0**
HP GAGG	**125±2**	< 0.3	3.2±0.7	**2.2±0.2**

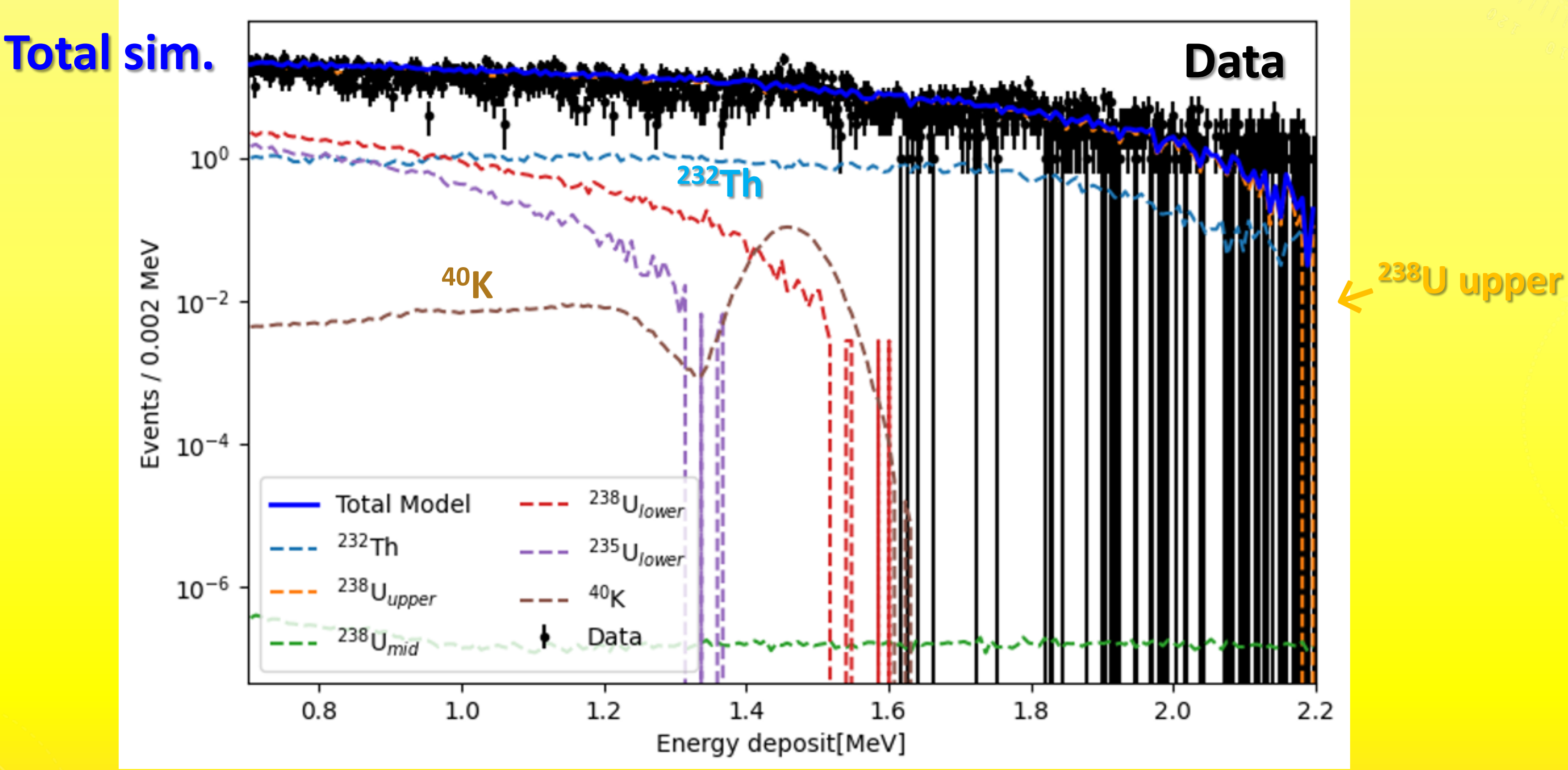
β-ray BG in high-purity GAGG

✓ **Data:** β-ray events were extracted from Kamioka data using PSD.

✓ **Simulation:** two β-ray BG models

U/Th decay series in crystal ⇒ Fixed impurity content from α-ray fitting results

^{40}K of PMT origins ⇒ Spectra generated by Geant4 and fitted



✓ **The BG spectrum was successfully reproduced by Geant4!!**

⇒ The dominant BG is upstream of ^{238}U around the Q value (1.73 MeV)

Sensitivity study for PIKACHU Phase 1

We estimate the sensitivity for $0\nu\beta\beta$ search in PIKACHU Phase 1.

$$T^{0\nu}_{1/2} = (\ln 2) N_a \frac{\mathrm{a}}{\mathrm{A}} \epsilon \sqrt{\frac{M \cdot t}{\mathrm{BG} \cdot \Delta \mathrm{E}}}$$

Na: Avogadro number, A: Atomic mass, ε: Efficiency,
a: Natural abundance, M: Mass of target nuclei,
t: Live time, BG･ΔE: Background rate in $Q_{\beta\beta}$ region

✓ Assuming 2 large crystals (6.4kg), HP-GAGG BG rate and 100% eff.

PIKACHU sensitivity = 4.4×10^{21} years

cf. $T^{0\nu} > 1.3 \times 10^{21}$ years in GSO experiment

- ✓ Experiment will start this year with large high-purity GAGG crystals!
- ✓ A further reduction of BG by more than one order of magnitude is needed to search for $2\nu\beta\beta$ of ^{160}Gd in Phase 2.

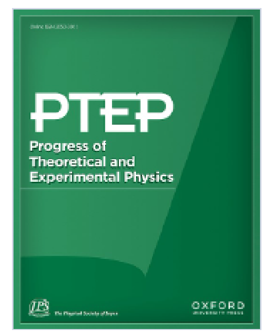
First paper of PIKACHU

JOURNAL ARTICLE ACCEPTED MANUSCRIPT

First Study of the PIKACHU Project: Development and Evaluation of High-Purity $Gd_3Ga_3Al_2O_{12}$:Ce Crystals for ^{160}Gd Double Beta Decay Search

Takumi Omori, Takashi Iida ✉, Azusa Gando, Keishi Hosokawa, Kei Kamada, Keita Mizukoshi, Yasuhiro Shoji, Masao Yoshino, Ken-Ichi Fushimi, Hisanori Suzuki ...
Show more

Progress of Theoretical and Experimental Physics, ptae026, https://doi.org/10.1093/ptep/ptae026
Published: 15 February 2024



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10 out of 85
Physics, Particles & Fields
4 out of 29

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Check it out!!

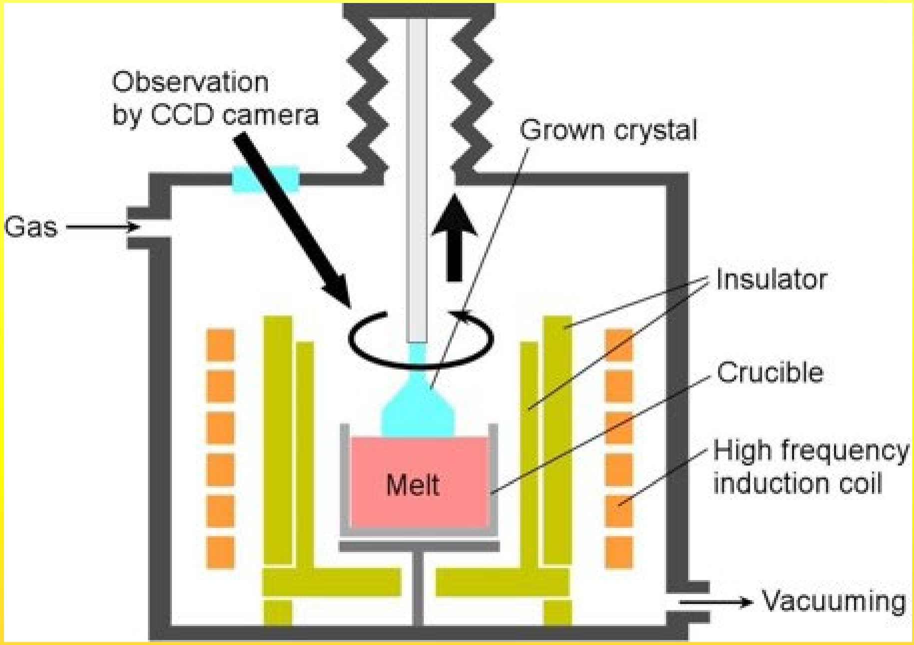
Further purification of GAGG for Phase 2

- The crystal raw materials are of higher purity than the crystals, which suggests that U/Th impurities were contaminated during the crystal growing process.
- The insulator made from ZrO_2 is contaminated by U/Th impurities.
- New crystals are currently being grown, while devising ways to prevent contamination from insulation.

Comparison of U/Th impurities

	^{238}U	^{232}Th
Original GAGG	911±10	289±20
HP-GAGG	**125±2**	10.2±0.4
Gd_2O_3 raw material	**< 16.3**	1.66±0.41

[mBq/kg]



Future prospect

- **PIKACHU experiment Phase 1 will start in 2024.**
- ^{160}Gd $0\nu\beta\beta$ search sensitivity will be updated in two years.
- In parallel with Phase 1 PIKACHU, we develop ultra-high-purity GAGG crystal, whose purity is one more order of magnitude better than current HP-GAGG.
- Start Phase 2 PIKACHU after 2026 with a few tens of UHP-GAGG for the first detection of ^{160}Gd $2\nu\beta\beta$.

We aim to detect ^{160}Gd $2\nu\beta\beta$ in about 5 years!

Summary

- Double beta decay search (PIKACHU) experiment for ^{160}Gd.
- Aiming to increase sensitivity by one order of magnitude over previous studies, to discover $2\nu\beta\beta$.

✓ Development of high-purity GAGG crystals!! BG~1/10 is achieved.

✓ Sensitivity of PIKACHU Phase 1 will be higher than that of the previous study .

New collaborator is always welcome!!

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