Recent progress in the double beta decay search in ^{160}Gd with the PIKACHU experiment

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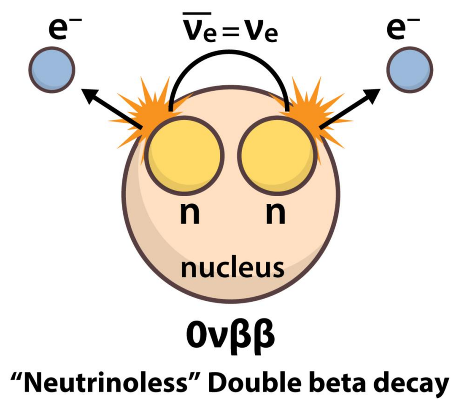
1. Introduction

Double beta (2β) decay



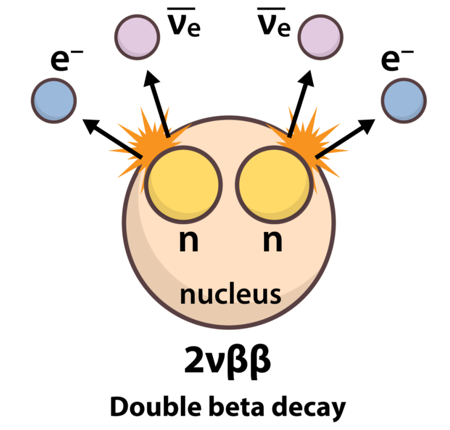
✓ Neutrino−less 2β decay (0ν2β)

- Evidence for Majorana nature of neutrinos
- Not yet observed
- Half-life constrains the effective Majorana neutrino mass $\langle m_{\beta\beta} \rangle$

$$(T_{1/2}^{0\nu})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)\, |M_{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$

Phase space

Nuclear Matrix Element (NME)



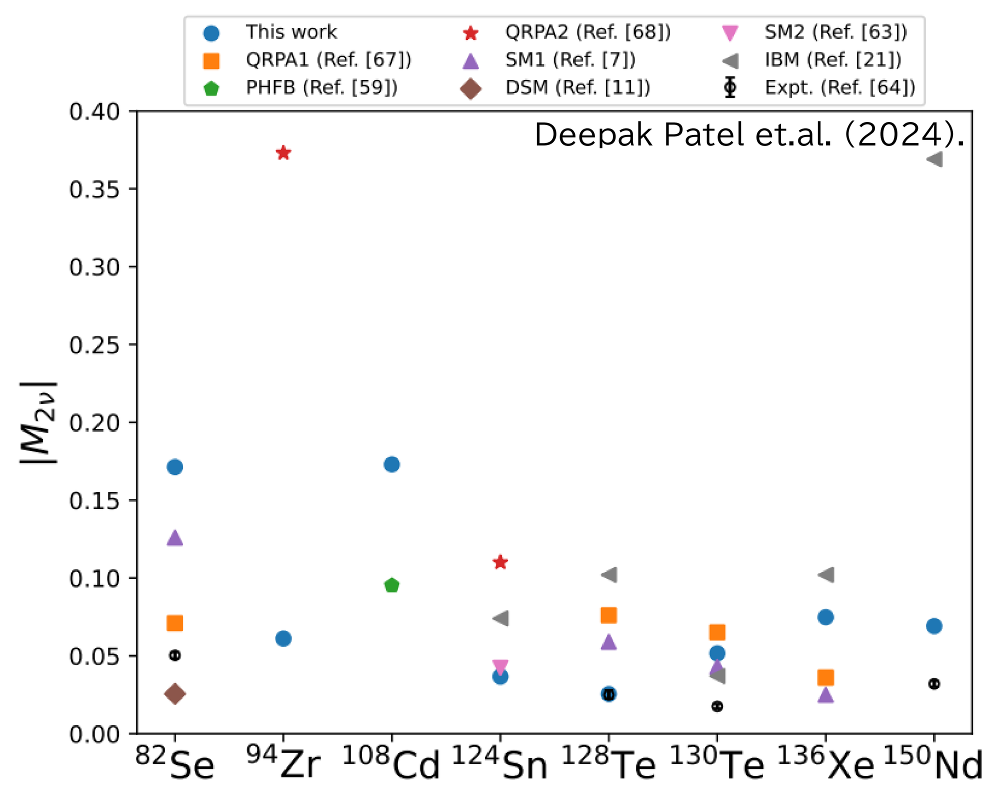
✓ Two-neutrino 2β decay (2ν2β)

- Rare decay allowed by the Standard model
- Half-life is given by

$$(T_{1/2}^{2\nu})^{-1} = G_{2\nu}(Q_{\beta\beta}, Z)\, |M_{2\nu}|^2$$

NME uncertainties

- The NME has a theoretical uncertainty, which significantly affects constraints on the effective Majorana neutrino mass
- The NME for 2ν2β can be measured experimentally →Provides a benchmark for testing NME calculations

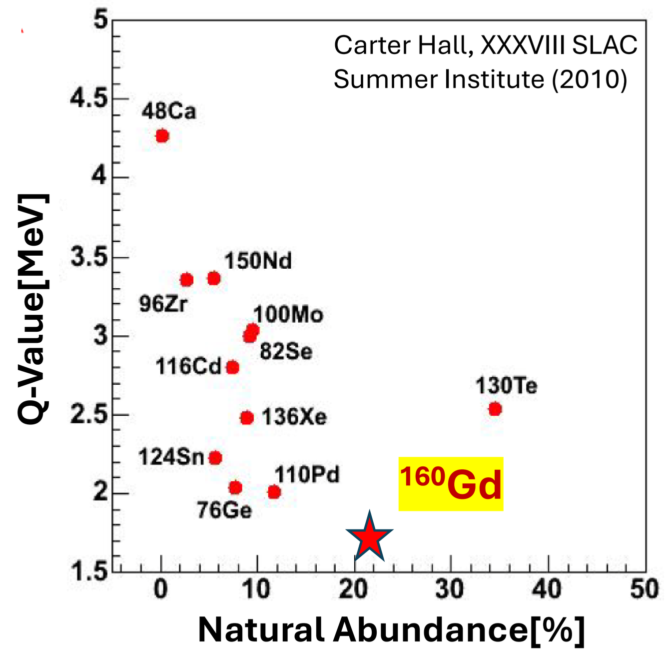


Search for 2β decay in ^{160}Gd

- Target isotope: ^{160}Gd
  - ☻ High natural abundance: 21.8%
  - ☹ Low Q-value: 1.73 MeV
- Even 2ν2β has not yet been observed
- Current lower-limit: $T_{1/2}^{2\nu} > 1.9 \times 10^{19}$ yr (90% C.L.) [1]
  - obtained with a 2-inch GSO (Gd_2SiO_5) crystal
- QRPA prediction: $T_{1/2}^{2\nu} = 4.7 \times 10^{20}$ yr [2]

Another order of magnitude

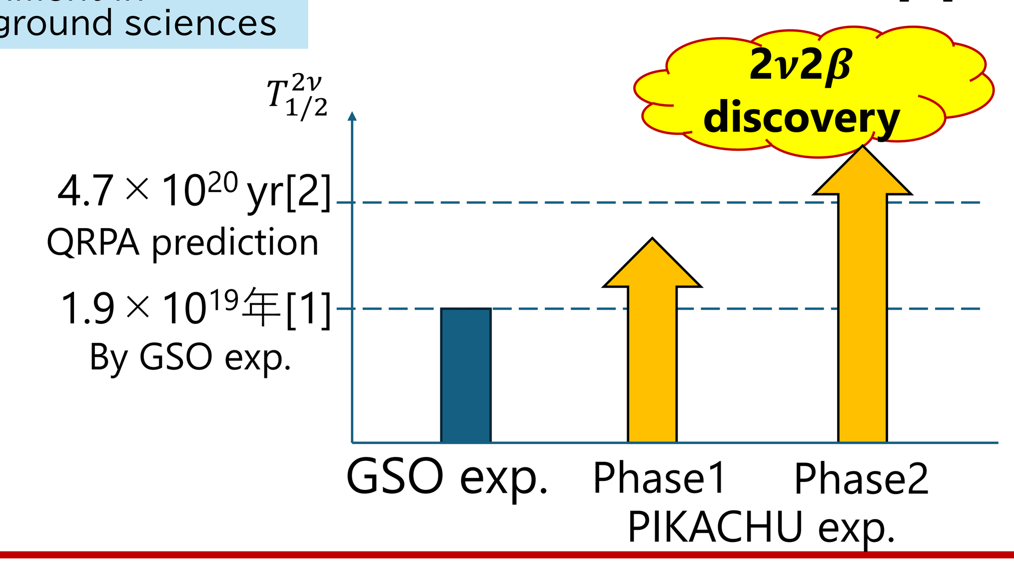
[1] F.A.Danevich et al., Nucl. Phys. A, Vol. 694 (2001) 375-391
[2] N. Hinohara et al., Phys. Rev. C, Vol. 105 (2022) 044314



PIKACHU experiment

Pure Inorganic scintillator experiment in KAmioka for CHallenging Underground sciences

- Detector: GAGG ($Ce:Gd_3Al_2Ga_3O_{12}$) scintillator
  - ○ Large-volume crystal (11% ^{160}Gd by mass)
  - ○ High energy resolution ($\sigma/Q_{\beta\beta}$ = 2.4%)
  - ○ Pulse shape discrimination (PSD)
- Path toward the discovery of 2ν2β
  - Phase 1: World-leading search for ^{160}Gd 2ν2β
  - Phase 2: Discovery of ^{160}Gd 2ν2β



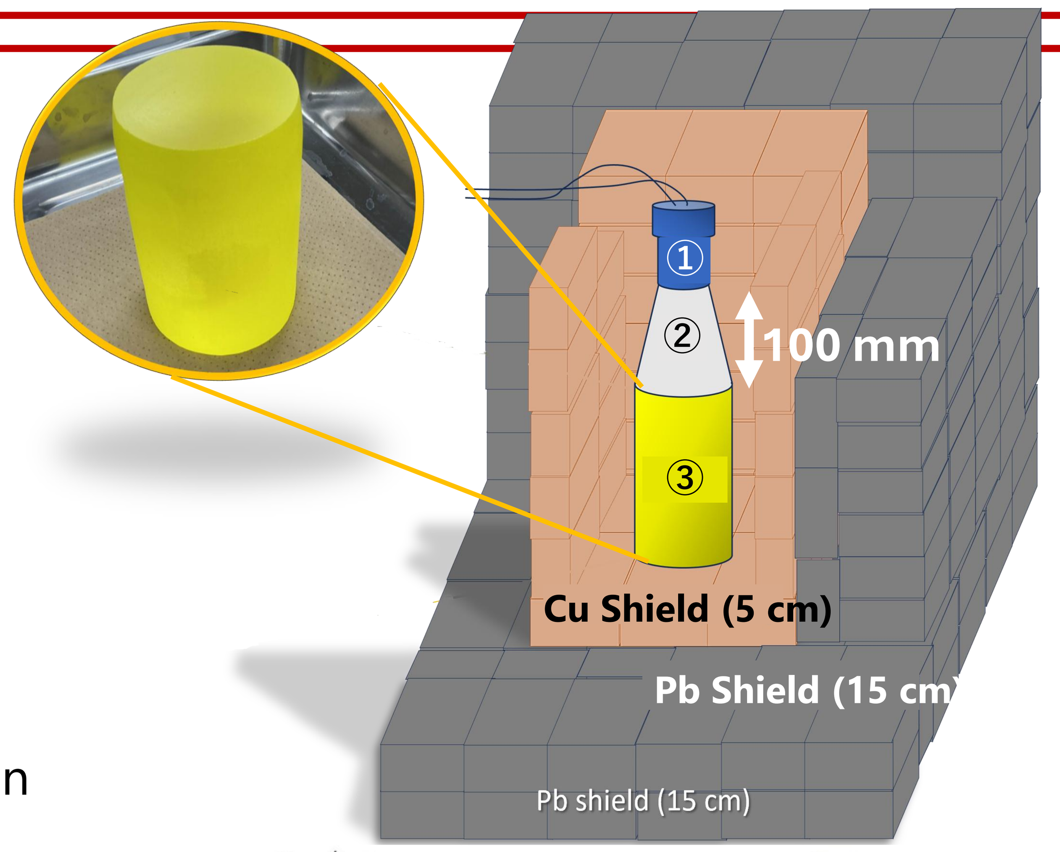
2. Data acquisition

Detector component

[3] T. Omori et al., Prog. Theor. Exp. Phys., Vol. 2024 (2024) 033D01.

① 2-inch Bi-alkali PMT
② Acrylic light guide
③ High-purity GAGG scintillator

- Grown from purified raw materials [3]
- 65 mm diameter × 100 mm length
- ^{160}Gd mass : 270 g (2.7× that of the GSO exp.)



Background (BG) reduction

- Kamioka underground to reduce cosmic-muon flux
- Pb/Cu shielding and N_2 purge to suppress external radiation

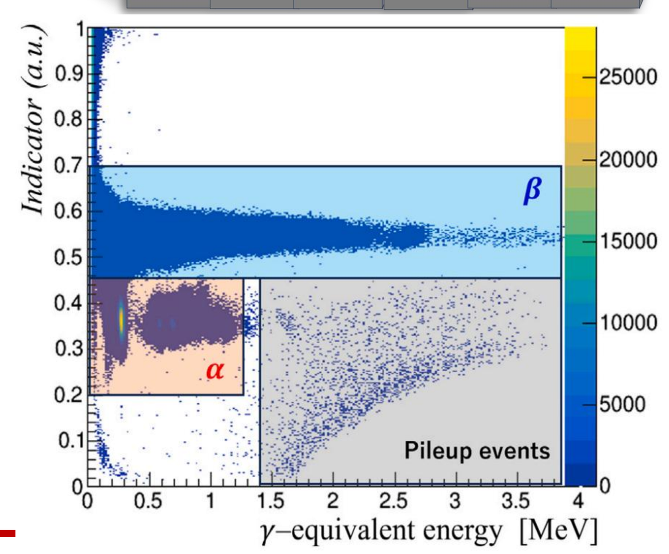
Expected sensitivity

- Data acquisition has been ongoing since December 2024
- Based on 5,226 hours of data, the expected sensitivity is

$$T_{1/2}^{2\nu} = 3.2 \times 10^{19} \text{ yr (90\% C.L.)},$$

estimated from the β-ray BG rate in the ROI (0.72–1.97 MeV).

➤ The present Phase 1 data have the potential to improve upon previous limits by the GSO experiment !



3. Spectral analysis

BG modeling based on GEANT4

- Simulated energy deposition of radiations in GAGG
  - α-ray BG: U/Th chains present in GAGG
  - β(γ)-ray BG:
    - U/Th chain, ^{40}K, and ^{176}Lu present in GAGG
    - U/Th chains and ^{40}K present in PMT (detected as external γ)
- The model incorporates the effects of energy resolution, quenching, and non-proportionality of the detector [4]

[4] T. Omori et al., Nucl. Instrum. Meth. A Vol. 1082 (2026) 171023.

Fitting procedure

- Data: Phase 1 data with a live time of 5,226 hours
- Internal U/Th activities were constrained by α-BG fitting

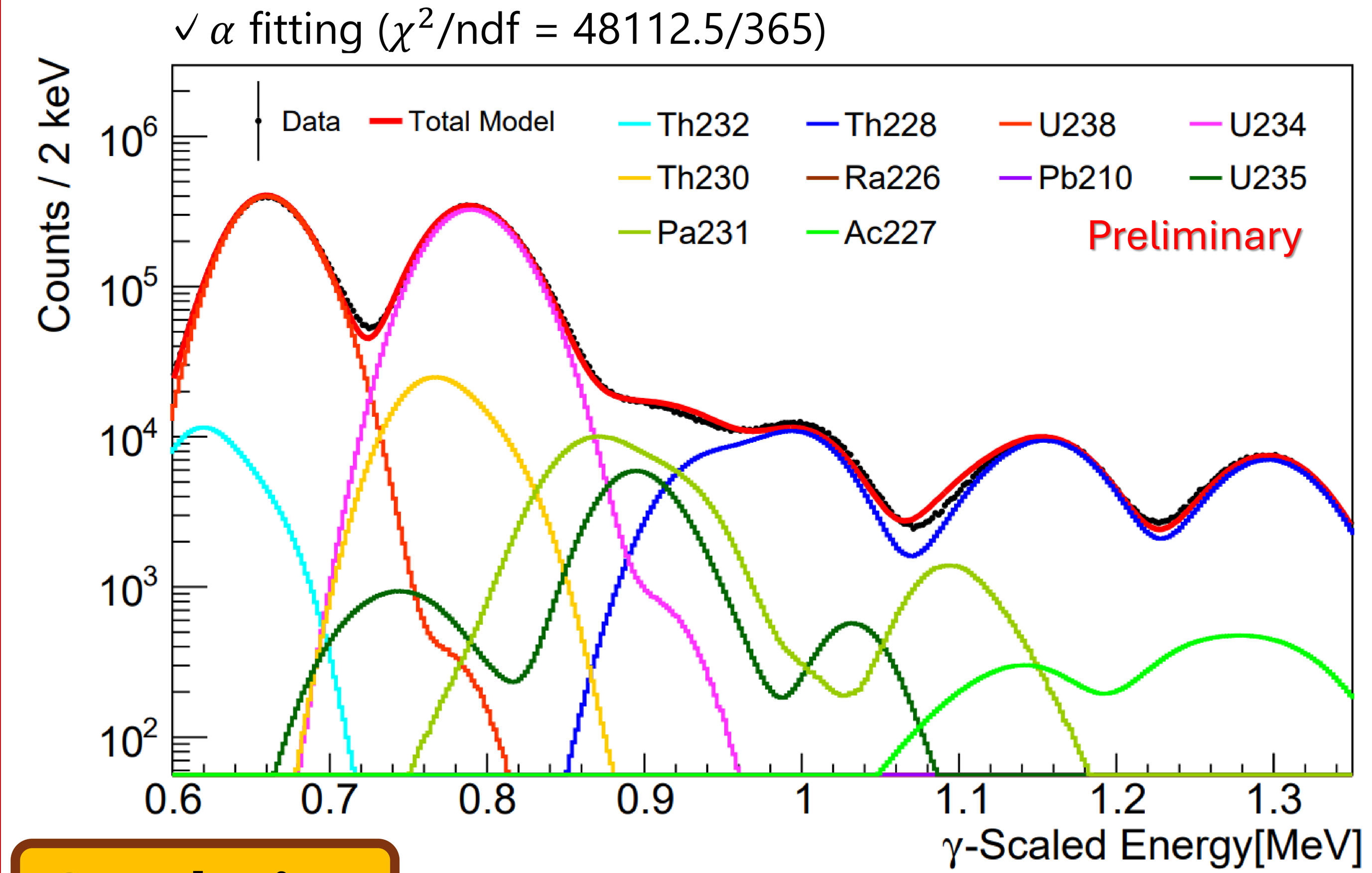
		α component	β component
Fitting range		0.60-1.35 MeV	0.72-1.97 MeV
BG	Internal	^{232}Th, ^{238}U, ^{235}U-Chain	Constrained
		-	^{176}Lu
			$^{40}K_{int.}$
	External (PMT)	-	$^{40}K_{ext.}$
			$^{232}Th_{ext.}$
			$^{228}Th_{ext.}$
			$^{226}Ra_{ext.}$
Signal		-	2ν2β

4. Spectral fitting result

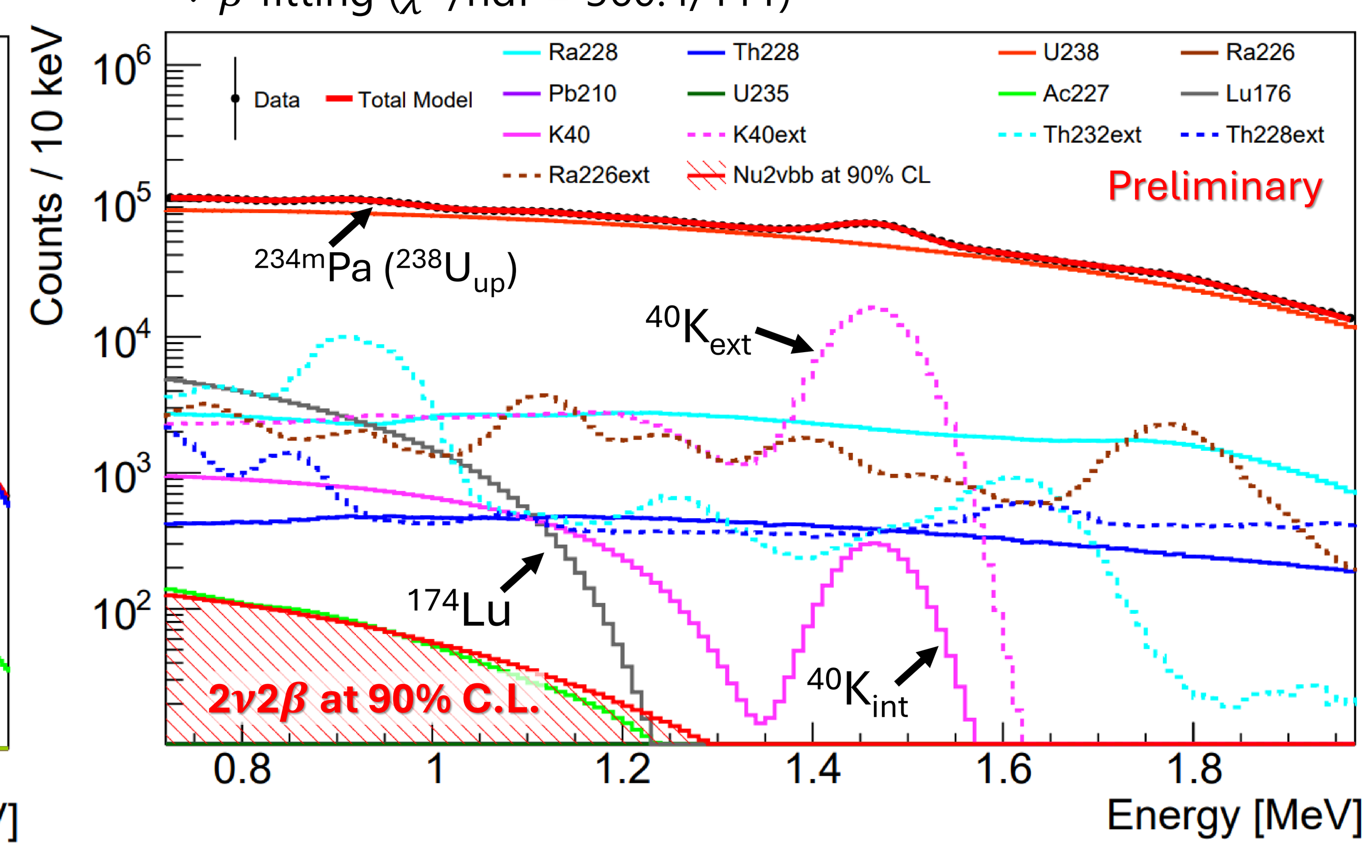
- The best-fit signal rate was (1.7 ± 2.8) × 10^{-3} counts s^{-1} kg^{-1}
  → Assuming the BG-only hypothesis, the profiled likelihood yields

$$T_{1/2}^{2\nu} \geq 3.7 \times 10^{19} \text{ yr at 90\% C.L. (Preliminary)}$$

✓ α fitting (χ^2/ndf = 48112.5/365)



✓ β fitting (χ^2/ndf = 360.4/111)



Conclusion

- PIKACHU experiment were launched toward the first observation of ^{160}Gd 2ν2β using GAGG scintillators
- Phase 1 is ongoing, and the current data indicate the world's best expected sensitivity for ^{160}Gd 2ν2β.
- The expected sensitivity is still more than one order of magnitude away from the predicted half-life
  ⇒ a preliminary lower limit of 3.7 × 10^{19} yr has been obtained under the background-only hypothesis.

Future Prospects

Current Status of GAGG Purification for Phase 2

- Current GAGG: ^{234m}Pa (272 mBq/kg) is the dominant BG
- Current raw materials: < 16.3 mBq/kg

⇒ Contamination is introduced during crystal growth !!

- Suspected source: thermal insulation around the growth crucible.

⇒ Low-radioactivity insulation has been developed and installed.
Now Ultra High-Purity GAGG crystal growth is in progress !!