CANDLES : Low background double beta decay experiment using ^{48}Ca

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1. Introduction

Neutrino-less double beta decay

- The search for **neutrino-less double beta decay ($0\nu\beta\beta$)** is one of the preeminently important topics in modern physics [1].
- The discovery of $0\nu\beta\beta$ implies important physics related to the origin of matter: the Majorana nature of neutrinos and the lepton number violation. It can also reveal the absolute value and hierarchy of neutrino masses.
- Since $0\nu\beta\beta$;
  is extremely rare signal → **Low background (BG) condition !!**
  has a peak at Q-value → **Energy calibration !!**

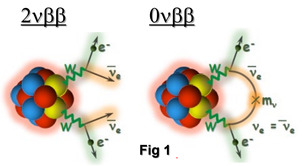


Fig 1

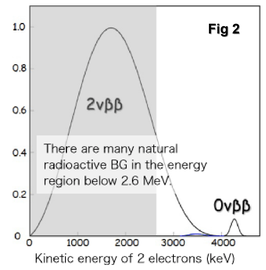


Fig 2

Double beta decay of ^{48}Ca

- **^{48}Ca has the largest Q-value (4.27MeV)** among all the $0\nu\beta\beta$ nuclei and its higher than any natural radioactive BGs.
- Double magic number nucleus, ^{48}Ca, is also the lightest double beta decay nucleus. Therefore, it is suitable for the calculation of nuclear matrix element by shell model, and it is considered to be an interesting target for double beta decay search.

[1] M. Dolinski et al., Annu. Rev. Nucl. Part. Sci. 69, 219 (2019)

2. The CANDLES-III detector

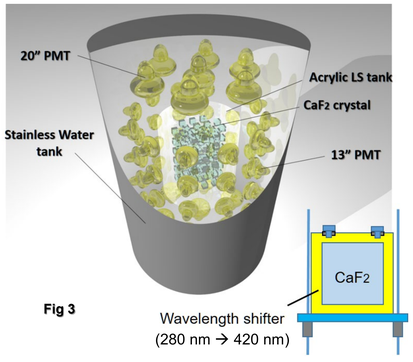


Fig 3

- CANDLES aims to perform the world's most sensitive $0\nu\beta\beta$ search by studying ^{48}Ca.
- **The CANDLES-III (U.G.) detector** is constructed 1,000 m underground in Kamioka observatory, Japan (Fig. 3 and [2]).
  - ✓ **96 pure CaF_2 crystals (305kg)**
    ※So far, natural abundance Ca was used (350g of ^{48}Ca)
  - ✓ **62 photo-multipliers (10", 13" & 20" PMTs)**
  - ✓ **Cooling system (CaF2 cooled down to ~4-5℃)**
  - ✓ **Magnetic cancellation coil (< 40 mG at PMT pos.).**
    → **Light yield = 1,000 [p.e./MeV]**
  - ✓ **4π active shield by liquid scintillator (LS)**
    ※Time const. = 1ms for CaF_2 / ~20ns for LS
  - ✓ **500 MHz Flash-ADC open ~9 μs window to read out waveform of all PMT.**

[2] T. Iida et. al., Journal of Physics: Conference Series 718 (2016) 062026

Taking the advantage of high Q-value of ^{48}Ca, we target background free measurement !!

3. Low background techniques

Pulse shape discrimination analysis

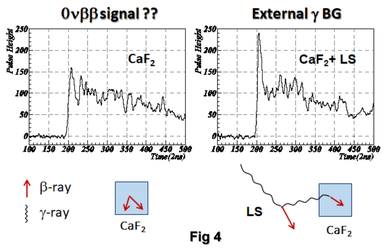


Fig 4

- The time constant of CaF_2 and LS is about 1 μs and 10 ns respectively.
- External γ-rays which deposit energy in surrounding LS can be effectively removed by pulse shape analysis (see Fig. 4).
- α-rays and β-rays in pure CaF_2 crystal are also possible to identify using pulse shape information.
- It is used to eliminate the ^{212}Bi-^{212}Po sequential decay and the β+γ decay of ^{208}Tl, both from Th impurities inside the crystal.
- For more details on the CANDLES waveform discrimination analysis, please refer to the following paper [3].

[3] S. Umehara et. al., J. Phys.: Cong.Ser., 1643 012028 (2020)

Shield construction for (n,γ) reduction

- When thermal neutrons are captured in rich material surrounding the detector such as rock and stainless steel tank, high energy γ-rays are emitted so called (n,γ), e.g. 7.6 / 9.0 MeV of Fe / Ni [4].

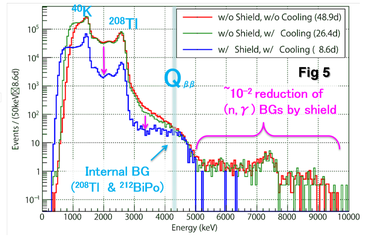


Fig 5

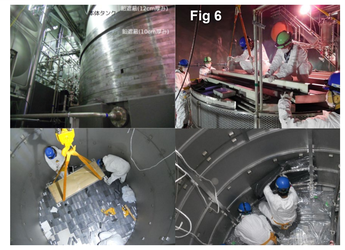


Fig 6

- We constructed a shield against (n,γ) reaction on rock and stainless tank in 2016.
- The shield consists of Pb blocks (7~12 cm thickness) and Si rubber sheet containing 40 wt% of B_4C.

✓ **After installation of the shield, (n,γ) BG level has been reduced by two order of magnitude as shown in Fig. 5.**

[4] K. Nakajima, T. Iida et. al., Astroparticle Physics, Volume 100 (2018), Pages 54-60

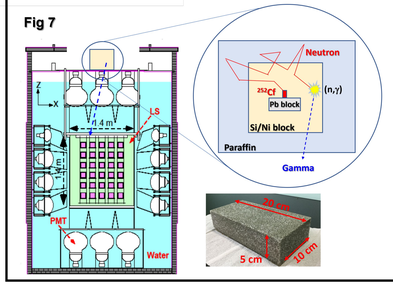
4. Energy calibration at 4.27 MeV

Energy calibration system using (n,γ)

- While high Q-values of ^{48}Ca makes low BG environments, it also make it difficult to calibrate the energy in Q-value region due to the absence of standard γ-ray source.
- γ-ray from neutron capture on nucleus (Fe / Ni / Si etc.) can be a good calibration source around ^{48}Ca Q-value of 4.27 MeV. (see table)
- **We have developed the new calibration system using these γ-rays (Fig.7 and [5]).**

	Neutron cross section	γ-ray energy	Branching ratio
^{28}Si	0.177 barn	3,539 keV	67.2 %
		4,934 keV	63.3 %
^{56}Fe	2.59 barn	7,631 keV	25.2 %
		7,645 keV	21.2 %
^{58}Ni	4.50 barn	8,998 keV	33.1 %

Fig 7



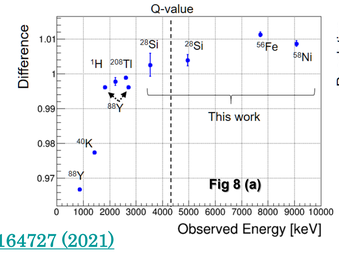


Fig 8 (a)

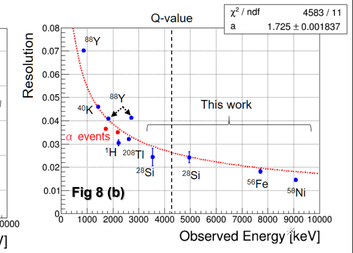


Fig 8 (b)

[5] T. Iida et. al., Nucl. Inst. and Meth. A, Vol. 986 164727 (2021)

Calibration results

- γ-rays from neutron capture on ^{28}Si (3.54 MeV, 4.93 MeV), ^{56}Fe (7.63 MeV, 7.65 MeV) and ^{58}Ni (9.0 MeV) are analyzed using the calibration data.
- Energy dependence of energy scale and resolution are shown in Fig. 8.
- **Good linearity and resolution** are obtained using this new calibration system in CANDLES !!

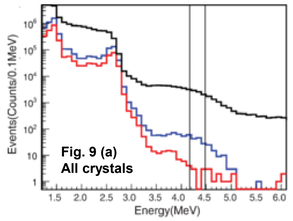
	Results
Energy scale uncertainty	< 0.3% @4.27 MeV
Energy resolution	2.4% @4.27 MeV

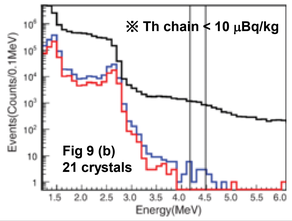
For the detail of energy calibration in CANDLES, please see the paper [5].

5. Analysis, result and future prospect

Background reduction

- **0νββ search** was conducted using 130-days data in region of interest corresponding to –1 sigma +2 sigma from Q-value.
- Applied cut criteria for BG reduction are summarized below. The colors are corresponding to the colors of histogram in Fig. 9.
  1. *No cut*
  2. *External γ-ray cut by LS active shielding*
  3. *^{212}Bi-^{212}Po sequential decay cut using waveform information.*
  4. *β+γ event of ^{208}Tl (Q-value = 5MeV) rejection using delayed coincidence method by tagging parent ^{212}Bi α decay*
  5. *Reconstructed event at the CaF_2 crystal position*





0νββ search result

- **BG level of ~10^{-3} ev/yr/keV/(kg of ^{nat}Ca) was achieved** for the analysis with all crystals. (Fig. 9 (a))
- If we select the crystals whose radio impurity of Th chain less than 10 μBq, **background free measurement** was achieved !! (Fig. 9 (b))
- Observed energy spectrum near the Q-value region was well reproduced by simulated one (Fig. 10).

$T_{1/2} > 5.6 \times 10^{22}$ year was obtained as an upper limit of ^{48}Ca $0\nu\beta\beta$ half-life [6].

[6] S. Ajimura et. al., Phys. Rev. D. 103 092008 (2021)

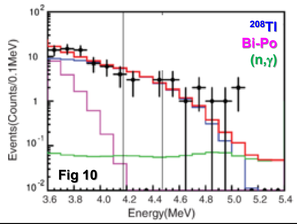


Fig 10

	Anal. with 21 Cr.
Livetime	130.4 days
0νββ eff.	37.5 %
Events in ROI	0
Expected BG	1.0
$T^{1/2}_{0\nu\beta\beta}$ limit	> 5.6×10^{22} [yr]
Sensitivity	2.7×10^{22} [yr]

Future prospect

- We are developing new high-purity CaF_2 crystal production techniques with crystal company.

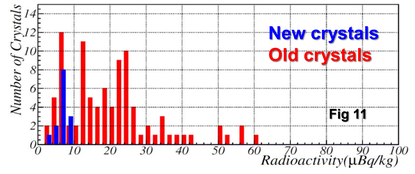


Fig 11

- Radioactivity of newly produced crystals are all less than 10 μBq/kg as shown in Fig. 11.
- We will replace the current crystals whose radioactivity is high with these new clean crystals to enhance the sensitivity of $0\nu\beta\beta$ search.
- **For further future, scintillating bolometer using CaF_2 [7] and ^{48}Ca isotope enrichment technique [8,9] are also under development.**

[7] K. Tetsuno et. al., Journal of Physics: Conference Series 1468 (2020) 012132
[8] T. Kishimoto et. al., PTEP (2015) 3 033D03
[9] K Matsuoka et al 2020 J. Phys.: Conf. Ser. 1468 012199

Stay tuned for future CANDLES results !!!

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