Status of ^{48}Ca double beta decay search in CANDLES

Yuto Minami[1], Kenichi Fushimi[2], Takaaki Harada[3], Akihiro Hashimoto[4], Ryuta Hazama[5], Tasuku Hiraiwa[4], Tomoki Iga[3], Takashi Iida[6], Yusuke Kawashima[4], Yumiko Kishida[7], Tadafumi Kishimoto[1], Kenji Matsuoka[1], Go Miyoshi[3], Yoshiki Muramatsu[4], Kyohei Nakajima[4], Izumi Ogawa[4], Anawat Rittirong[5], Toshiki Sakai[3], Akitoshi Sakaue[8], Kohtaku Suzuki[9], Yukichi Takihira[1], Yoichi Tamagawa[4], Masashi Tozawa[4], Saori Umehara[1], Asahi Yamamoto[3], Sei Yoshida[3], Tomomi Yoshida[3], and Atsushi Yoshioka[3],

[1]Research Center for Nuclear Physics (RCNP), Osaka University, Ibaraki, Osaka 567-0047, Japan
[2]Graduate School of Technology, Industrial and Social Sciences, Tokushima University, 2-1, Minami Josanajima-cho, Tokushima city, Tokushima, 770-8506, Japan
[3]Graduate School of Science, Osaka University, Toyonaka, Osaka 560-0043, Japan
[4]Graduate School of Engineering, University of Fukui, Fukui, 910-8507, Japan
[5]Department of Environmental Science and Technology, Osaka Sangyo University, Daito, Osaka 574-8530, Japan
[6]Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Ibaraki 305-8571, Japan
[7]Graduate School of Advanced Technology and Science, Tokushima University, 2-1, Minami Josanajima-cho, Tokushima city, Tokushima , 770-8506, Japan
[8]Faculty of Science and Technology, Tokushima University, 2-1, Minami Josanajima-cho, Tokushima city, Tokushima , 770-8506, Japan
[9]The Wakasa-wan Energy Research Center, Tsuruga, Fukui 914-0192, Japan

E-mail: `yminami@rcnp.osaka-u.ac.jp`

Abstract. We study a strategy to reduce veto-time in the search for neutrino-less double-beta decay ($0\nu\beta\beta$) with CANDLES-III system. We develop a new likelihood analysis and apply it to our new Run010 data. We show that we can increase the un-vetoed live-time by 11.8%. Thanks to this improvements, We expect to increase a limit on the life-time of $0\nu\beta\beta$ by a factor of three by analyzing both Run009 and Run010 data.

1. Introduction

The origin of neutrino masses is one of the unsolved puzzles in particle physics. One possibility is that neutrinos have Majorana masses [1]. We can test the Majorana nature of neutrinos by searching for neutrino-less double-beta decay ($0\nu\beta\beta$) events [2]. CANDLES (CAlcium fluoride for the study of Neutrinos and Dark matters by Low Energy Spectrometer) is a project which targets $0\nu\beta\beta$ events from ^{48}Ca using its high $Q_{\beta\beta} = 4.27\,\mathrm{MeV}$ [3]. We developed a CANDLES-III system with 96 CaF_2 scintillation crystals with natural Ca isotope, which corresponds to 350 g of ^{48}Ca [4]. The key to search for $0\nu\beta\beta$ with the CANDLES-III is to identify and remove the β decay background events from impurities in CaF_2 crystals.

Journal of Physics: Conference Series **2156** (2022) 012145 doi:10.1088/1742-6596/2156/1/012145

Ref. [4] shows a results using data with 130.4 days of live-time, which we call Run009. There, β decay events from ^{208}Tl with Q_β-value of 5.0 MeV are dominant background events.

In this proceeding, we introduce a new likelihood analysis to efficiently veto β decay backgrounds from ^{208}Tl. After the Run009, we took data with 652.0 days of live-time in total, which we call Run010. We apply the new likelihood analysis to the Run010 data.

The rest of the proceeding is organized as follows. In Sect. 2, we explain our CANDLES-III system. In Sect. 3, we review the results of Run009 analysis. In Sect. 4, we describe the methodology of the likelihood analysis. We report our results in Sect. 5 and conclude in Sect. 6.

2. CANDLES-III system

CANDLES-III system is equipped with undoped CaF_2 scintillation crystals[1]. CANDLES-III is installed at the Kamioka Underground Laboratory in the Institute of Cosmic Ray Research of the University of Tokyo. The system consists of the following five main components:

- CaF_2 scintillator with 3.2 kg $\times$ 96 CaF_2 crystals which contains 350 g of ^{48}Ca.
- Liquid scintillator as a 4π active shields.
- 62 photo multiplier tubes (PMTs) to observe scintillation lights from CaF_2 and LS.
- Surrounding shields of leads with thickness of $10 - 12$ cm for the reduction of γ-ray backgrounds.
- Surrounding shields of B_4C sheets with thickness of 0.5 cm for the reduction of thermal neutron backgrounds.

3. Review of Run009

We review the Run009 with CANDLES-III system [4]. There are following five main background candidates which we veto and estimate:

- α-ray backgrounds: we use pulse shape discrimination (PSD) technique [4], which use the information of pulse shape, to distinguish β-ray events from α-ray backgrounds.
- External γ backgrounds: we also use PSD technique to remove environmental γ-ray events which deposit energy in the surrounding LS.
- (n, γ) process backgrounds: we reduced the background events by Pb and B_4C shields and estimated the number of events by Monte Carlo (MC) simulations [6].
- ^{212}Bi $\rightarrow$ ^{212}Po sequential decay: since the life time of ^{212}Po's α decay, 0.299 µs, is short we observe the sum of the energy of the both ^{212}Bi 's β decay and ^{212}Po's α decay. we can identify this background events using a rising pulse shape of both events [4].
- ^{208}Tl backgrounds: ^{208}Tl's decay produces β- and γ-rays. We can only measure sum of energies of the two rays, which has cut-off energy of 5.001 MeV. We can veto this background using delayed coincidence method by tagging parent ^{212}Bi's α decay, whose quenched energy is 1.63 MeV.

After the appropriate veto and estimation of background events, Ref. [4] set a half-life limit of $0\nu\beta\beta$ as 5.6×10^{22} yrs using pure 21 crystals among 96 crystals. Since the dominant backgrounds are ^{208}Tl β decay events [4], in this proceeding, we concentrate on the reduction of the background events using a likelihood analysis.

[1] See Ref. [5], for the conceptual design of the CANDLES detector.

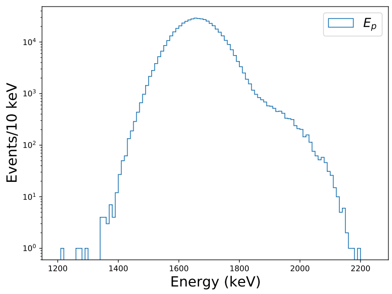

Figure 1. Energy distribution of signal E_p.

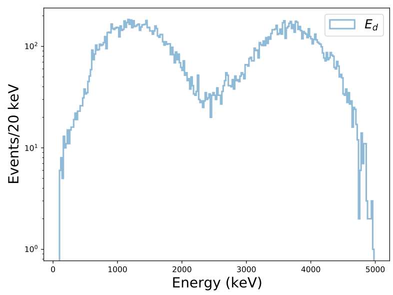

Figure 2. Energy distribution of signal E_d.

4. Likelihood analysis

From here, the signal refers to ^{212}Bi $\to$ ^{208}Tl events and the backgrounds refers to all the other events including accidental coincidence of ^{212}Bi decay and ^{208}Tl decay. With probability distribution function (PDF) of a variables $\vec{x}$ of signal, $P^{\mathrm{S}}(x)$, and of backgrounds, $P^{\mathrm{B}}(x)$, we construct a likelihood function as

$$L(\vec{x}) = \frac{P^{\mathrm{S}}(\vec{x})}{P^{\mathrm{S}}(\vec{x}) + P^{\mathrm{B}}(\vec{x})}. \tag{1}$$

Our strategy is to set a likelihood threshold, ℓ, and identify all the events with $L(\vec{x}) \geq \ell$ as signal events. In this proceeding, we use following three variables as elements of $\vec{x}$:

- E_p: energy of prompt events which are candidates of ^{212}Bi's α-decay.
- E_d: energy of delayed events which are candidates of ^{208}Tl's β-decay.
- ΔT: time difference between the prompt and the delayed events.

4.1. Construction of signal PDF

Since E_p, E_d, and ΔT are independent of each other, we construct a signal PDF of all variables from products of each variable PDF as

$$P^{\mathrm{S}}(E_p, E_d, \Delta T) = P^{\mathrm{S}}(E_p) \cdot P^{\mathrm{S}}(E_d) \cdot P^{\mathrm{S}}(\Delta T). \tag{2}$$

We use public code `Geant3` [7] to estimate $P^{\mathrm{S}}(E_p)$ and $P^{\mathrm{S}}(E_d)$. We estimate $P^{\mathrm{S}}(\Delta T)$ analytically assuming the exponential decay with life-time of 3.08 min.

We show the histograms of E_p and E_d in Fig. 1 and Fig. 2 respectively. We normalize these histograms to unity and use them as PDFs.

4.2. Construction of backgrounds PDF

Similar to signal, since E_p, E_d, and ΔT are independent of each other, we construct a background PDF of all variables from products of each variable PDF as

$$P^{\mathrm{B}}(E_p, E_d, \Delta T) = P^{\mathrm{B}}(E_p) \cdot P^{\mathrm{B}}(E_d) \cdot P^{\mathrm{B}}(\Delta T). \tag{3}$$

We take all the β-tagged events in Run010 data with the PSD technique as $P^{\mathrm{B}}(E_d)$. We take all the events in Run010 data without any tag as $P^{\mathrm{B}}(E_p)$. Since backgrounds events do not depend on time, we use flat distribution for ΔT. We show a histogram of E_p of crystal-01 in Fig. 3 as a example. We normalize these histograms to unity and use them as PDFs.

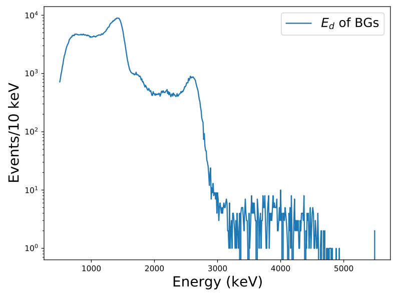

Figure 3. Energy distribution of background E_p.

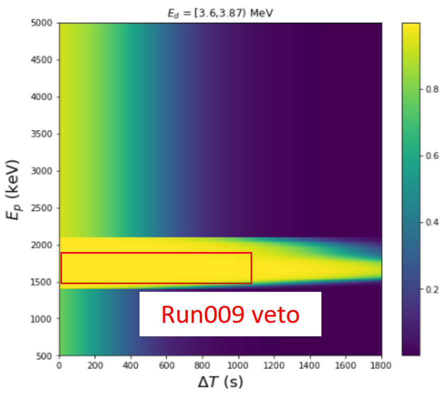

Figure 4. Likelihood distribution in E_p vs ΔT plane with $E_d \in [3.6, 3.87]$ MeV.

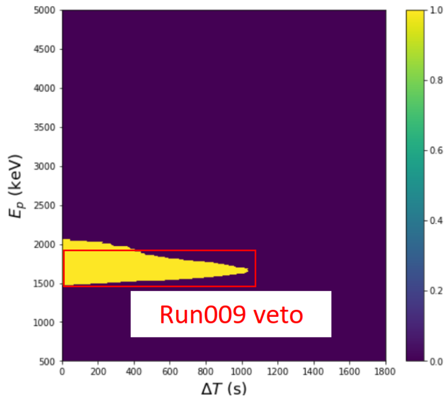

Figure 5. Likelihood which excess the threshold, ℓ, in E_p vs ΔT plane with $E_d \in [3.6, 3.87]$ MeV.

4.3. Construction of likelihood function

To remove statistical uncertainty, we set bin width of the histograms for background PDFs to make the number of events in each bin larger than 100. We then construct a likelihood with Eq. (1) (Fig. 4).

We set the likelihood threshold, ℓ, to make ^{208}Tl efficiency, $\varepsilon^{\mathrm{Run010}}$ to be the same as that of Run009, $\varepsilon^{\mathrm{Run009}}$. The efficiencies are calculated as

$$\varepsilon^{\mathrm{Run009}} = \varepsilon^{\alpha-\mathrm{tag}} \cdot \int_{3.5\,\mathrm{MeV}}^{\infty\,\mathrm{MeV}} dE_d \int_{1.45\,\mathrm{MeV}}^{1.85\,\mathrm{MeV}} dE_p \int_{0\,\mathrm{s}}^{1080\,\mathrm{s}} d\Delta T\, P^S(E_d) \cdot P^S(E_p) \cdot P^S(\Delta T), \tag{4}$$

$$\begin{aligned}\varepsilon^{\mathrm{Run010}} = \varepsilon^{\alpha-\mathrm{tag}} \cdot \int_{3.5\,\mathrm{MeV}}^{\infty\,\mathrm{MeV}} dE_d \int_{0.5\,\mathrm{MeV}}^{\infty\,\mathrm{MeV}} dE_p \int_{0\,\mathrm{s}}^{1080\,\mathrm{s}} d\Delta T\, P^S(E_d) \cdot P^S(E_p) \cdot P^S(\Delta T) \\ \cdot P(L(E_p, E_d, \Delta T) \geq \ell),\end{aligned} \tag{5}$$

where $\varepsilon^{\alpha-\mathrm{tag}}$ is the tag efficiency of α-ray events by PSD technique used in Run009. We show the region where likelihood excess the likelihood threshold in Fig. 5.

5. Results

We apply our likelihood analysis based veto (Run010 veto) to the Run010 data. Since the likelihood-based cut depends on E_d, we use maximum ΔT with $L \geq \ell$ among the all $E_d \geq 3.5\,\mathrm{MeV}$. As a comparison, we also apply veto similar to Run009 (Run009 veto) to the Run010 data.

We define the un-vetoed live-time over live-time as a live-time efficiency. We show the resulted live-time efficiencies of the two vetoes in Table 1.

Table 1. Live-time efficiency with 93 crystals.

	live-time efficiency
Run009 veto	70.9%
Run010 veto	78.9%

We find that we can increase the un-vetoed live-time by 11.3% using the likelihood analysis.

6. Conclusions and discussions

In this proceeding, we study a likelihood method to reduce the veto-time in the search for $0\nu\beta\beta$ with CANDLS-III system. Applying the likelihood method to Run010 data, we find that we can increase the un-vetoed live-time by 11.3%.

A limit on a half-life of $0\nu\beta\beta$ decay, $T^{1/2}$, is proportional to observation time, T^{obs}, over square root of a number of backgrounds of $0\nu\beta\beta$ search, $\sqrt{N_{\mathrm{BG}}}$, as,

$$T^{1/2} \propto \frac{T^{\mathrm{obs}}}{\sqrt{N_{\mathrm{BG}}}}. \tag{6}$$

We can increase the T^{obs} by 11.3%; We can increase the N_{BG} by a factor of six when we use Run010 data in addition to Run009 data. Thus, we expect to give a limit on $T^{1/2}$ as 1.5×10^{23} yr. This is a improvement of a factor of three from Run009 result [4].

Since we find that we can increase the number of events by introducing the likelihood analysis, we can tighten the event selection to achieve more pure measurements with the same live-time efficiency. For example, we plan to veto events what ^{212}Bi-α and ^{208}Tl-β deposit energy in different crystals. This could increase the number of pure crystals with which we give a limit on $T^{1/2}$.

Acknowledgments

This work was supported by Japan Society for the Promotion of Science (JSPS) KAKENHI, Grants No. 19H05804, 19H05809, 26104003, 16H00870, 24224007, and 26105513. This work was supported by the research project of Research Center for Nuclear Physics (RCNP), Osaka University. This work was also supported by the joint research program of the Institute of Cosmic Ray Research (ICRR), the University of Tokyo. The Kamioka Mining and Smelting Company has provided service for activities in the mine.

References

[1] Majorana E 1937 *Nuovo Cim.* **14** 171–184
[2] Furry W H 1939 *Phys. Rev.* **56** 1184–1193
[3] Kwiatkowski A A *et al.* 2014 *Phys. Rev.* **C89** 045502
[4] Ajimura S *et al.* (CANDLES) 2021 *Phys. Rev. D* **103** 092008 (*Preprint* 2008.09288)
[5] Yoshida S *et al.* 2009 *Nucl. Instr. and Meth* **A601** 282–293
[6] Nakajima K *et al.* 2018 *Astropart. Phys.* **100** 54–60
[7] Brun R, Bruyant F, Maire M, McPherson A C and Zanarini P 1987