PAPER • OPEN ACCESS

Neutrino-less double beta decay of ^{48}Ca studied by CaF$_2$(pure) scintillators

To cite this article: S. Umehara *et al* 2020 *J. Phys.: Conf. Ser.* **1342** 012049

View the article online for updates and enhancements.

Neutrino-less double beta decay of ^{48}Ca studied by CaF$_2$(pure) scintillators

S. Umehara^{12}, T. Kishimoto^{23}, M. Nomachi^2, S. Ajimura^2, Y. Takemoto^2, W. M. Chan^2, K. Takihira^2, K. Matsuoka^2, N. Nakatani^2, V. T. T. Trang^2, S. Yoshida^3, W. Wang^3, W. M. Chan^3, T. Maeda^3, T. Ohata^3, K. Tetsuno^3, K. Lee^3, X. Lee^3, M. Shokati^3, B. Temuge^3, K. Akutagawa^3, K. Kanagawa^3, S. Katagiri^3, B. T. Khai^3, M. Tsuzuki^3, N. Yotsunaga^3, M. Moser^3, M. Ishikawa^3, H. Kino^3, E. Kinoshita^3, Y. Sato^3, Y. Tamagawa^4, I. Ogawa^4, K. Nakajima^4, M. Tozawa^4, F. Dokaku^4, T. Hiyama^4, N. Takahashi^4, K. Teranishi^4, H. Hiraoka^4, K. Kawasaki^4, H. Sato^4, K. Shamoto^4, M. Shimada^4, T. Iida^5, K. Fushimi^6, R. Hazama^7, K. Suzuki^8 and H. Ohsumi^9

^{1}Research Center for Neutrino Science, Tohoku University, Japan
^{2}Research Center for Nuclear Physics, Osaka University, Japan
^{3}Graduate School of Science, Osaka University, Japan
^{4}Graduate School of Engineering, University of Fukui, Japan
^{5}Faculty of Pure and Applied Sciences, University of Tsukuba, Japan
^{6}Faculty of Integrated Arts and Science, The University of Tokushima, Japan
^{7}Faculty of Human Environment, Osaka Sangyo University, Japan
^{8}The Wakasa-wan Energy Research Center, Japan
^{9}Faculty of Culture and Education, Saga University, Japan

E-mail: `umehara@awa.tohoku.ac.jp`

Abstract.

We have studied the neutrino-less double beta decay($0\nu\beta\beta$) of ^{48}Ca by using CaF$_2$(pure) scintillators. Analysis for rejection of backgrounds(^{212}Bi→ ^{212}Po events and ^{208}Tl events) was effective to reduce backgrounds in Q$_{\beta\beta}$-value region. No events are observed in the Q$_{\beta\beta}$-value region for the data of 131 days × 86 kg. It gives a lower limit (90% confidence level) of $T_{1/2}^{0\nu\beta\beta}$ > 6.2×10^{22} year (preliminary) for the half-life of $0\nu\beta\beta$ of ^{48}Ca.

1. Double beta decay of ^{48}Ca

The neutrino-less double beta decay ($0\nu\beta\beta$) is acquiring great interest after the confirmation of neutrino oscillation which demonstrated nonzero neutrino mass. Measurement of $0\nu\beta\beta$ provides a test for the Majorana nature of neutrinos and gives an absolute scale of the effective neutrino mass. Many experiments have been carried out so far and many projects have been proposed.

Among double beta decay nuclei, ^{48}Ca has an advantage of the highest Q$_{\beta\beta}$-value (4.27 MeV). This large Q$_{\beta\beta}$-value gives a large phase-space factor to enhance the $0\nu\beta\beta$ rate and the least contribution from natural background radiations in the energy region of the Q$_{\beta\beta}$-value. Therefore good signal to background ratio is ensured in a $0\nu\beta\beta$ measurement. For the $0\nu\beta\beta$
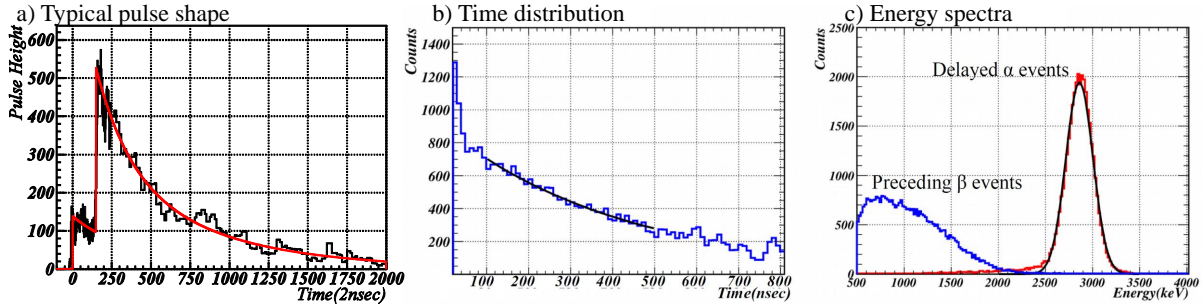
Figure 1. a) Typical pulse shape of process (a) ^{212}Bi$\rightarrow^{212}$Po$\rightarrow^{208}$Pb. The pulse shape can be clearly rejected as background events. From this pulse shape we drive the energy of the preceding β and delayed α events. b) Δt distribution between the preceding β and delayed α events. By fitting with an exponential function, we obtained the half-life of 299 $\pm$ 8 nsec. c) Energy spectra of the preceding β and delayed α events. The spectra is obtained from the events with total energy 3 $\sim$ 7 MeV and 20 $<\Delta t<$ 1900 nsec. In this figure, the peak at 2860 keV is mainly due to ^{212}Po events and is partically including ^{214}Po(half-life 164 μsec) events.

measurement of ^{48}Ca, we proposed CANDLES(CAlcium fluoride for the study of Neutrinos and Dark matters by Low Energy Spectrometer) project[1].

2. CANDLES III at Kamioka observatory

Now we have developed the detector system CANDLES III at the Kamioka underground laboratory (2700 m.w.e.). The CANDLES III system consists of 96 CaF$_2$(pure) scintillators with total mass of 305 kg and liquid scintillator with total volume of 2 m^3[2]. The CaF$_2$(pure) scintillators, which are main detectors, are immersed in the liquid scintillator. The liquid scintillator acts as a $4\,\pi$ active shield to veto external backgrounds. Scintillation lights from the CaF$_2$(pure) and the liquid scintillator are viewed by 62 large photomultiplier tubes (13" $\times$ 36, 20" $\times$ 14 and 10" $\times$ 12). The signal of the CaF$_2$(pure) scintillator has a decay time of 1 μsec although the liquid scintillator has a width of around a few tens nsec. Thus the signals from the CaF$_2$(pure) scintillators can be discriminated against the background signals on the liquid scintillator by observing pulse shapes.

3. Background in the Q$_{\beta\beta}$-value region

As mentioned above, backgrounds can be strongly limited because of the $4\,\pi$ active shield and the highest Q$_{\beta\beta}$-value of ^{48}Ca. The remaining backgrounds are following processes:

(a) ^{212}Bi $\xrightarrow[\beta]{}$ ^{212}Po $\xrightarrow[\alpha]{}$ ^{208}Pb (Th-chain)

(b) ^{208}Tl $\xrightarrow[\beta]{}$ ^{208}Pb(Th-chain)

(c) γ-rays from neutron capture

The process (a) and (b) are due to radioactive contaminations within the CaF$_2$(pure) scintillators. The processes can be rejected by a pulse shape analysis and time correlation analysis, respectively. In order to reduce background events from the process (c), we installed the shielding system in the CANDLES III system.

3.1. process (a) $^{212}Bi \longrightarrow^{212}Po \longrightarrow^{208}Pb$

^{212}Po nucleus in process (a) has short half-life 0.299 μsec. On the other hand, the CaF$_2$(pure) scintillator has long decay constant ($\sim 1\,\mu$sec). Thus radiations emitted by consecutive decays of ^{212}Bi and ^{212}Po are measured as one event in ADC gate (4 μsec) for the CaF$_2$(pure) scintillator as shown in figure 1-a). Energy deposited by the consecutive decays in the CaF$_2$(pure) scintillator
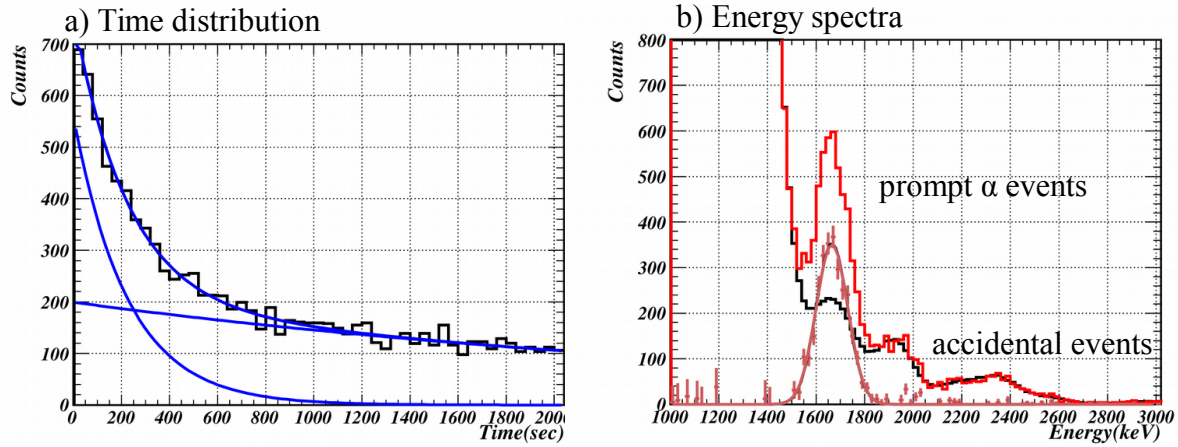
Figure 2. a) Δt distribution between the preceding α and delayed $\beta + \gamma$ events for ^{208}Tl rejection. By fitting with two exponential function, we obtained the half-life of 156 ± 15 sec. b) Energy spectra of the preceding ^{212}Bi α events. Red (black) line corresponds to the preceding (accidental) events. The peak at 1.7 MeV was due to ^{212}Bi decay ($E_\alpha = 6.1$ MeV).

is $E_{max} = 5.2$ MeV, because a quenching factor for α-ray is around 35%. Thus the process is serious backgrounds in a interesting energy window for the $0\nu\beta\beta$ measurement. In order to reject the events, we measured the pulse shape of the consecutive events by using the characteristic 500 MHz flash ADC. Figure 1-b) shows the time distribution between the preceding β and delayed α events. By fitting with an exponential function, we obtained the half-life of 299 ± 8 nsec. This half-life is correnponding to the half-life of delayed ^{212}Po decay. Figure 1-c) shows the energy spectra of the preceding β and delayed α events. The spectra are obtained from the events in total energy region $3 \sim 7$ MeV. The peak at 2860 keV is mainly due to ^{212}Po events. As the result of the analysis, the background from process (a) will be reduced by the 2 orders of magnitude.

3.2. process (b) $^{208}Tl \longrightarrow{}^{208}Pb$

^{208}Tl has large Q_β-value though it emits 2.6 MeV γ-ray. The probability which the high energy γ-rays are contained in a single CaF$_2$(pure) scintillator is small. However the $0\nu\beta\beta$ decay is extremely the rare process. Thus the background has to be seriously considered.

In order to reject the ^{208}Tl events, we applied a time correlation analysis. The ^{208}Tl events has a preceding α-decay with a half-life of 3 minutes (^{212}Bi : $E_\alpha = 6.1$ MeV). Thus we can reject the ^{208}Tl events by identifying the preceding α-ray. For identifying the α-ray, we need the good position resolution and the pulse shape discrimination between α- and γ-rays. Details of the analyses are shown in [3, 4]. Based on techniques of the position reconstruction and the pulse shape discrimination, we applied the time correlation analysis for ^{208}Tl. The energy spectrum of the candidate events of the preceding α-rays is shown in figure 2-b). The peak at 1.7 MeV was likely to be the α-rays coming from the preceding ^{212}Bi decays. To confirm origin of the peak, we analyzed the distribution of time lag Δt between the preceding and the delayed events. The time lag Δt distribution of the preceding events with energy of 1.6 - 1.8 MeV is shown in figure 2-a). In order to obtain the half-life, we fitted the time spectrum with two exponential function. The half-life derived from the Δt distribution was 156 ± 15 sec. The half-life nearly agreed with one of ^{208}Tl(183 sec). Thus it was concluded that the peak at 1.7 MeV was due to ^{212}Bi α-rays and we found that ^{208}Tl can be rejected by the time correlation analysis. By this way ^{208}Tl is rejected by $\sim 80\%$.
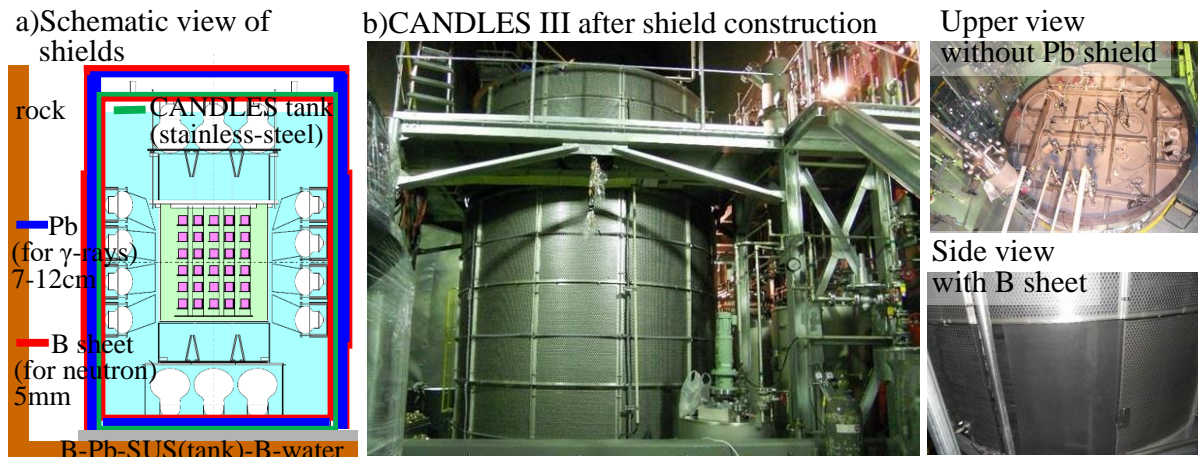
Figure 3. a) Schematic drawing of the shielding system. The system consists of the silicone rubber sheet containing B_4C (B sheet) and the Pb bricks. b) Photograph of the CANDLES main tank after shield construction. Right-upper) Photograph of upper view of the tank. The Pb bricks at an elevation of 1 meter have been installed. Right-lower) Photograph of the installed B sheets on the side of the tank.

3.3. process (c) γ-ray from neutron capture

Although maximum energy deposit from process (a) and (b) is 5.2 MeV, there was background events in an energy region of 5.5 - 9 MeV. The background candidate in the energy region is high energy γ-rays from neutron capture reaction in surrounding materials of the CANDLES system, such as rock and stainless steel. In order to estimate the background rate of γ-rays emitted from neutron capture, we performed a special run using a ^{252}Cf neutron source. Based on the result of the special run and Monte-Carlo simulation, we found that main background in the CANDLES system is γ-rays emitted from neutron capture reaction on Fe and Ni in the rock and stainless steel. The estimated event rate from the γ-rays is 76 ± 9 (stat.) events/year in the CANDLES system[5].

Thus we need to install a shielding system to reduce the γ-ray background. Design of the shielding system was optimized by the simulation. The schematic view of the system is shown in figure 3-a). The shielding system consists of rubber-sheet containing 40 wt% of B_4C of 5 mm in thickness and Pb bricks of 7 - 12 cm. The sheet containing B reduces capture reaction of thermal neutron on the stainless steel tank. The Pb bricks directly reduce γ-ray background emitted from neutron capture reaction. Construction of the shielding system was completed in 2016[2]. Performance of the shielding system was checked with/without a ^{252}Cf neutron source[4]. We found that background rate by neutron capture reaction was reduced to $\sim 1/100$.

4. Analysis

We performed a $0\nu\beta\beta$ measurement for 131 days. The criteria to select candidate events for $0\nu\beta\beta$ are given as follows.

(1) CaF_2(pure) scintillators fire.

(2) The events are not process (a) events.

(3) No liquid scintillator fires.

(4) The events are not candidate of the ^{208}Tl events of process (b).

(5) Position of the events are not in the liquid scintillator region.

As mentioned in section 2, criteria (1) and (3) are applied by using the pulse shapes difference between the CaF_2(pure) and liquid scintillators. Criteria (2) and (4) are described in section 3. Criteria (5) is effective for rejection of the background events which hit multiple CaF_2(pure)
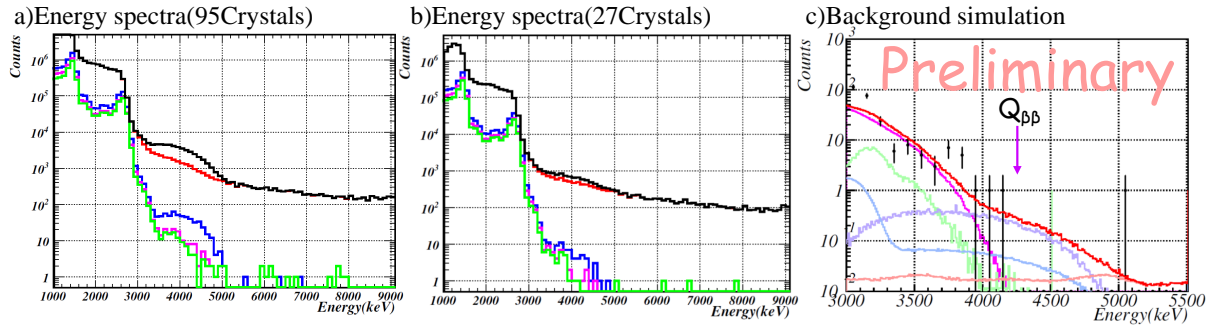
Figure 4. a) and b) Obtained energy spectra with each event selection by using 95/27 CaF_2(pure) scintillators. Details of the event selection are shown as criteria (1) ∼ (5) in text. 27 CaF_2(pure) scintillators are selected as high purity scintillators. Measurement time is 131 days. After the event selections, there are no events in the $Q_{\beta\beta}$-value region. c) Simulated background spectra and experimental data. Red line shows total background spectrum with the shielding system. The background events in the $Q_{\beta\beta}$-value region are mainly due to the radioactive contaminations in the CaF_2(pure) scintillators.

scintillators.

A selection of the candidate events was made for 11247 kg·days of data. Figure 4-a) and b) show the energy spectra obtained from 95/27 CaF_2(pure) scintillators, respectively. 27 CaF_2(pure)s are selected as high purity scintillators. In this figure, the lowest spectrum shows the result of the event selection by criteria (1) ∼ (5). As the result of the high purity 27 CaF_2(pure)s, we observed 0 events in the $0\nu\beta\beta$ window of 4.17 - 4.48 MeV.

Here we estimated background rate in the $Q_{\beta\beta}$-value region. As mentioned above, the 3 processes are expected as the backgrounds. The background rate from process (a) and (b) was estimated by radioactivities of the CaF_2(pure) scintillators. The background rate was estimated to be ∼ 1.2 events. By using the background rate and experimental event rate, we present a lower half-life limit (preliminary) is 6.2×10^{22} year (90 % C.L.). The limit is compatible to the result for more than 2 years by our previous detector ELEGANT VI[6]. We also present an experimental sensitivity since the number of observed events is fewer than that of the expected backgrounds. The sensitivity is 3.6×10^{22} year (90 % C.L.).

5. Conclusion

Now the CANDLES III system was installed at the Kamioka underground laboratory. By improvement of the detector system and the pulse shape analyses, we can reduce the background events from Bi → Po, ^{208}Tl and γ-rays neutron capture reaction. We performed the $0\nu\beta\beta$ measurement in order to check the background rate. The current half-life of the $0\nu\beta\beta$ half-life is 6.2×10^{22} year. Currently we continued the low background measurement and aim to improve the rejection efficiency of ^{208}Tl by new pulse shape analysis. On the other hand we are developing high purity CaF_2(pure) in order to replace the CaF_2(pure) in the CANDLES III system. As the result, we will improve the sensitivity of the $0\nu\beta\beta$ measurement.

References
[1] Kishimoto T *et al.* 2003 *Proc. of 4th Workshop on Neutrino Oscillations and their Origin* p 338
[2] Iida T *et al.* 2016 *Journal of Physics : Conference Series* **718** 062026
[3] Umehara S *et al.* 2014 *EPJ Web of Conferences* **66** 08008
[4] Umehara S *et al.* 2016 *Proceedings of Science (INPC2016)* 246
[5] Nakajima K *et al.* 2015 *AIP Conference Proceedings* **1672** 110004
[6] Umehara S *et al.* 2008 *Phys. Rev. C* **78** 058501