PROCEEDINGS OF SCIENCE

Search for neutrino-less double beta decay of ^{48}Ca – CANDLES –

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The neutrino-less double beta decay is acquiring great interest after the confirmation of neutrino oscillation which demonstrated nonzero neutrino mass. In order to search for neutrino-less double beta decay of ^{48}Ca, we proposed the CANDLES project by using CaF_2(pure) scintillators. Now we installed the CANDLES III system at the Kamioka underground laboratory. The CANDLES III system realizes the low background condition by a characteristic structure and data analyses for background rejection. Furthermore we installed new shielding system in order to reduce γ-ray backgrounds from neutron capture reaction. Here we report performances of the CANDLES III system.

The 26th International Nuclear Physics Conference
11-16 September, 2016
Adelaide, Australia

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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 $0\nu\beta\beta$ 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.). Figure 1 a) shows a schematic view of the CANDLES III system. 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. The CaF_2(pure) scintillators, which are main detectors, are immersed in the liquid scintillator. The liquid scintillator acts as a 4 π 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 $Q_{\beta\beta}$ region

As mentioned above, backgrounds can be strongly limited because of the 4 π active shield and the highest $Q_{\beta\beta}$-value of ^{48}Ca. The remaining backgrounds are following processes:
(a) $^{212}\text{Bi} \xrightarrow[\beta]{} {}^{212}\text{Po} \xrightarrow[\alpha]{} {}^{208}\text{Pb}$ (Th-chain)
(b) $^{208}\text{Tl} \xrightarrow[\beta]{} {}^{208}\text{Pb}$(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. Details are described in this session.

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

^{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 μsec). 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

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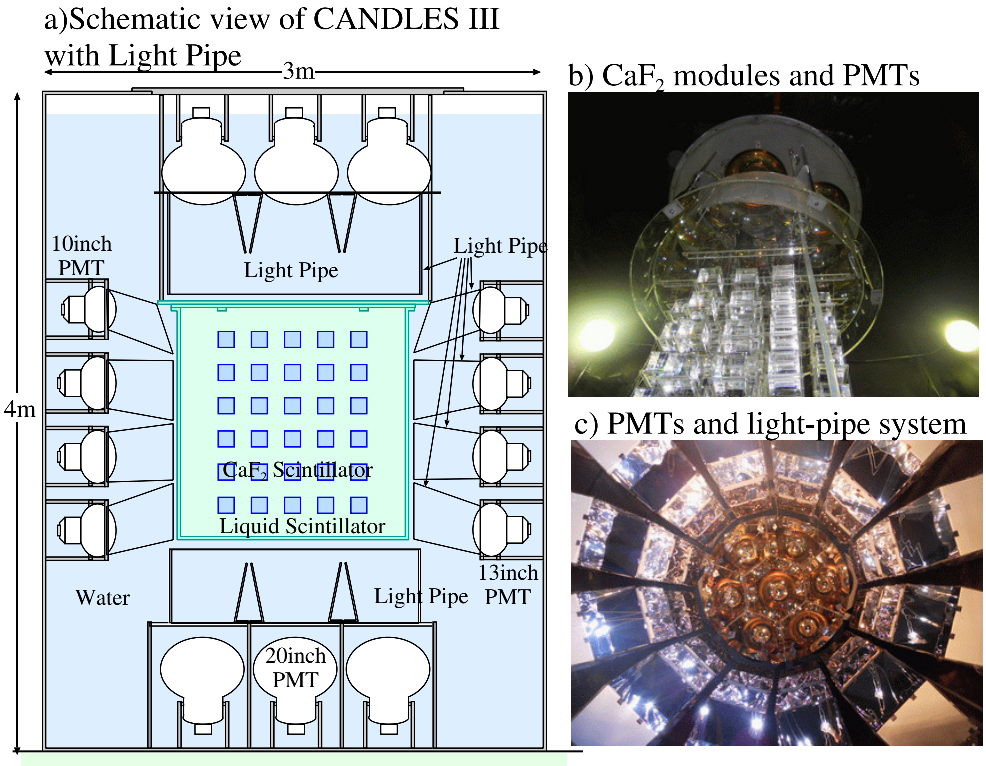

Figure 1: a)Schematic drawing of CANDLES III. CaF_2(pure) scintillators are immersed in liquid scintillator. Scintillation lights from both CaF_2(pure) and liquid scintillator are viewed by large photomultiplier tubes (PMTs). The light-pipe system was set between the PMTs and the liquid scintillator vessel to increase the photo-coverage, although the photomultiplier tubes had small photo-coverage. b) Picture of CaF_2 modules and PMTs in the CANDLES III system. c) Picture of the light-pipe system and PMTs.

as shown in figure 2 a). Energy deposited by the consecutive decays in the CaF_2(pure) scintillator 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. Details of the analyses are described in [2, 3]. As the result of the analyses, 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 through 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_α = 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 [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

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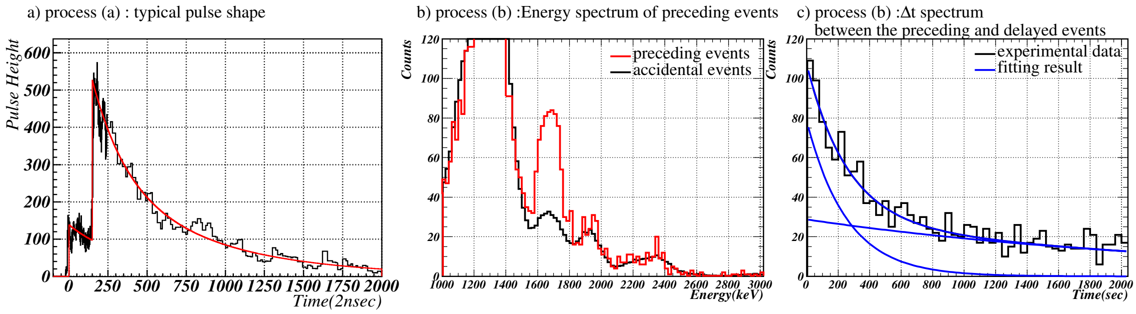

Figure 2: a) Typical pulse shape of process (a) ^{212}Bi→^{212}Po→^{208}Pb. The pulse shape can be clearly rejected as background events. b) The energy spectra of the preceding events of ^{208}Tl. Red/black line corresponds to the preceding/accidental events, respectively. The peak at 1.7 MeV was due to ^{212}Bi decay (E_α = 6.1 MeV). c) Δt distribution between the preceding and delayed events. By fitting with two exponential function, we obtained the half-life of 178 $\pm$ 55 sec.

the candidate events of the preceding α-rays is shown in figure 2-b). The peak at 1.7 MeV was likely due to 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-c). 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 178 $\pm$ 55 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%.

3.3 process (c) γ-ray from neutron capture

Although maximum energy deposit from process (a) and (b) is 5.2 MeV, there are 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, Ni in the rock and stainless steel. The estimated event rate from the γ-rays is 76 $\pm$ 9 (stat.) events/year in the CANDLES system[5].

Thus we need to install new shielding system to reduce the γ-ray background. Design of the shielding system was optimized by the simulation. The schematic view of the shielding system is shown in figure 3 a). The shielding system consists of silicone rubber sheet containing 40 wt% of B_4C of 5 mm in thickness and Pb bricks of 7 - 12 cm. The sheet containing B will reduces caputure reaction of thermal neutron on the stainless steel tank. The Pb bricks will directly reduce γ-ray background emitted from neutron capture reaction. Construction of the shielding system was completed in the beginning of 2016[6].

Figure 4 left) shows the result of background reduction by the shielding system. These spectra were obtained from measurements with the ^{252}Cf neutron source. Considering half-life of ^{252}Cf,

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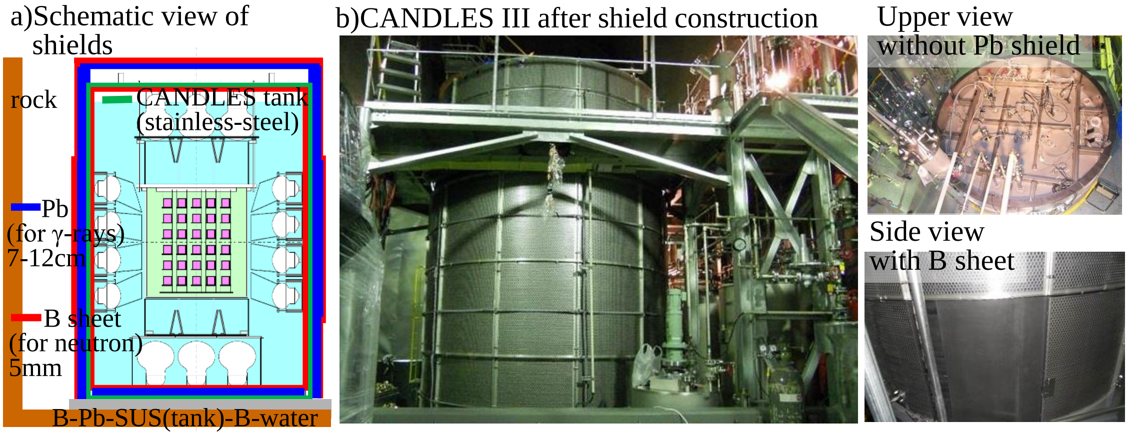

Figure 3: a) Schematic drawing of the shielding system. The system consists of the silicone rubber sheet containing B_4C (B sheet) and the Pb bricks. b) Photograph of the CANDLES main tank after shield construction. Right-upper) Photograph of upper view of the tank. The Pb bricks at an elevation of 1 meter have been installed. Right-lower) Photograph of the installed B sheets on the side of the tank.

reduction factor was obtained to be 1/70. Figure 4 right) shows energy spectra without the ^{252}Cf source before/after construction of the shielding system. We can find that event rate by neutron capture reaction was reduced to $\sim$ 1/100 and event rate of ^{40}K, which is effect to improve the rejection efficiency of ^{208}Tl, was also reduced to 1/3.8.

4. Analysis

In order to check the background rejection, we performed a pilot run of measurement time 21.5 days. The criteria to select candidate events for $0\nu\beta\beta$ are given as follows.
(1) CaF_2(pure) scintillators fire.
(2) No liquid scintillator fires.
(3) The events are not process (a) events.
(4) The events are not candidate of the ^{208}Tl events of process (b).
As mentioned in section 2, criteria (1) and (2) are applied by using the pulse shapes difference between the CaF_2(pure) and liquid scintillators. Criteria (3) and (4) are described in section 3.

A selection of the candidate events was made for 1845 kg·days of data. The energy spectrum using the 27 CaF_2(pure) scintillators, which are high purity scintillators, is shown in figure 5. As the result, 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 in the $Q_{\beta\beta}$-value region. The background rate was estimated to be 0.15 event/1845 kg·days. By using the expected background rate, we present a lower half-life limit and an experimental sensitivity. The current half-life limit and sensitivity with the 90 % C.L. are 6.9×10^{21} year and 5.8×10^{21} year, respectively.

5. Conclusion

Now the CANDLES III system was installed at the Kamioka underground laboratory. By

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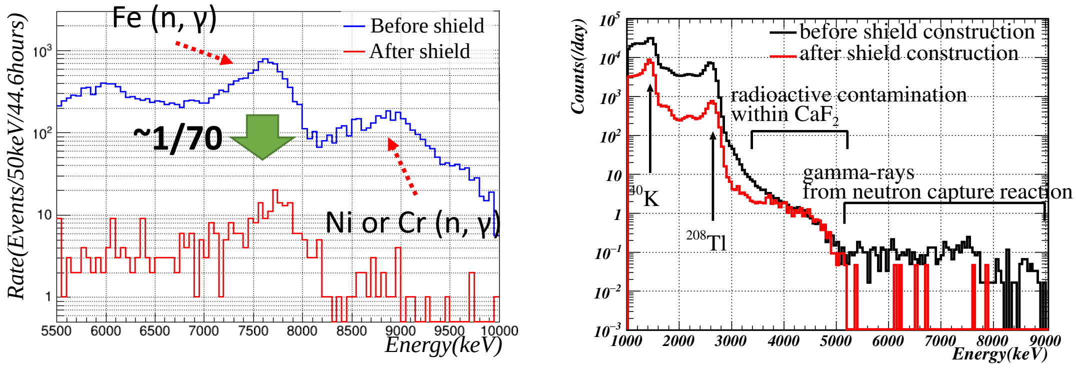

Figure 4: Left) Energy spectra by using ^{252}Cf source. Blue/red lines correspond to energy spectra before/after the shiled construction, respectively. Observed background rate by γ-rays from neutron capture reaction was reduced to 1/70. Right) Energy spectra without ^{252}Cf source. Black/red lines correspond to energy spectra before/after the shiled construction, respectively. By the shielding system, we can find that event rate by γ-rays was reduced to $\sim$ 1/100 and event rate of ^{40}K, which is effect to rejection efficiency of ^{208}Tl, was also reduced to 1/3.8.

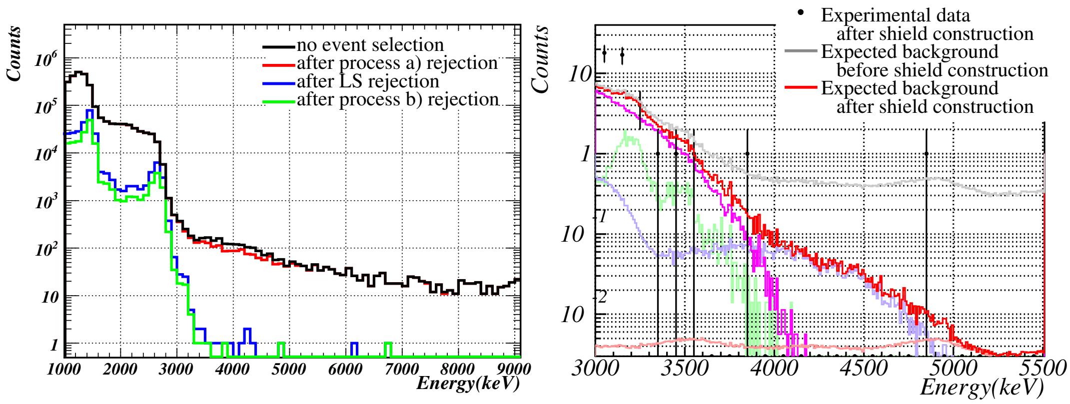

Figure 5: Left) Obtained energy spectra with each event selection by using 27 high purity CaF_2(pure) scintillators. Measurement time is 21.5 days. After rejection of the process (b), there is no event in the $Q_{\beta\beta}$-value region. Right) Simulated background spectra and experimental data. Gray/red lines show total background spectra without/with the shielding system. In an energy region higher than 4 MeV, the background rate is effectively reduced by the shielding system.

improvement of the detector system and the pulse shape analyses, we can reduce the background events from Bi $\rightarrow$ Po, ^{208}Tl and γ-rays neutron capture reaction. We performed the pilot run in order to check the background rate. The current half-life of the $0\nu\beta\beta$ half-life is 6.9×10^{21} year with the pilot run. Currently we continued the low background measurement and aim to improve the rejection efficiency of ^{208}Tl by new pulse shape analysis. Thus the limit will be improved.

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