CANDLES – Search for Neutrino-less Double Beta Decay of ^{48}Ca –

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CANDLES is the project to search for neutrino-less double beta decay of ^{48}Ca. 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. Here we report performances of the CANDLES III system.

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) system[1].

2 CANDLES III at Kamioka observatory

We installed 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. 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" $\times$ 48 and 20" $\times$ 14). 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) 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 highest $Q_{\beta\beta}$-value of ^{48}Ca. The remaining backgrounds are following processes:
(a) $^{212}\mathrm{Bi} \underset{\beta}{\longrightarrow} {}^{212}\mathrm{Po} \underset{\alpha}{\longrightarrow} {}^{208}\mathrm{Pb}$ (Th-chain)
(b) $^{208}\mathrm{Tl} \underset{\beta}{\longrightarrow} {}^{208}\mathrm{Pb}$(Th-chain)
(c) γ-ray from neutron capture
In this section we mention about study for the rejection of process (a) and (b).

^{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. Energy deposited by the consecutive decays in the CaF_2(pure) scintillator is E_{max} = 5.3 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 3 orders of magnitude.

The other background candidate is process (b) of ^{208}Tl events. ^{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 the candidate events of the preceding α-rays is shown in figure 1-a). 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 1-b). 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 187 $\pm$ 56 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

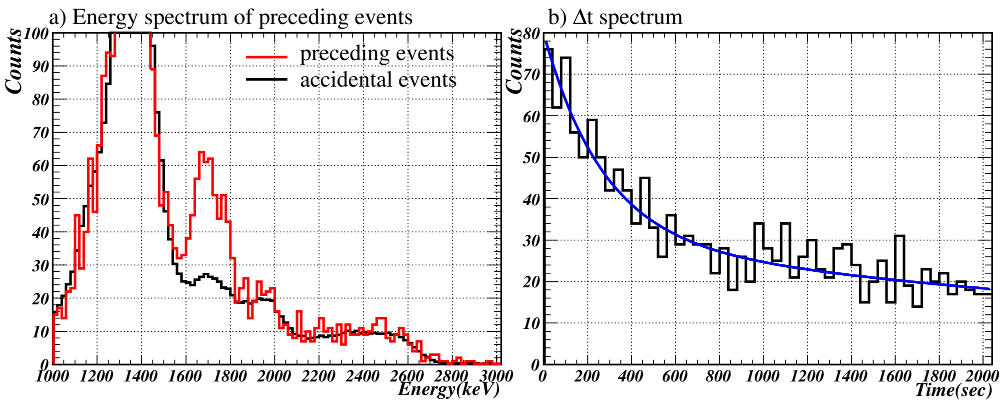

Figure 1: a) The energy spectra of the preceding events of ^{208}Tl. Red (black) line corresponds to the preceding (accidental) events. The peak at 1.7 MeV was due to ^{212}Bi decay (E_α = 6.1 MeV). b) Δt distribution between the preceding and delayed events. By fitting with two exponential function, we obtained the half-life of 187 $\pm$ 56 sec.

^{212}Bi α-rays and we found that ^{208}Tl can be rejected by the time correlation analysis.

As mentioned above, it is important to detect the preceding ^{212}Bi. Thus installation of a fast read-out DAQ system leads the good rejection efficiency for ^{208}Tl, because of least detecting loss in dead time. In early 2013 we installed a new DAQ system, of which read-out speed was improved 2.4 times as high as the previous one[5]. The dead time was decreased from 21% to 2%. As the result the event rate of the selected ^{212}Bi events was improved from 8.9$\pm$0.9 events/day to 12.7$\pm$0.7 events/day. This means that the rejection efficiency of ^{208}Tl was improved by 30%.

4 Analysis

In order to check the background rejection, we performed a pilot run. 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 4987 kg·days of data from Jun. to Sep. 2013. The energy spectrum using the 26 CaF_2(pure) scintillators, which are the high purity scintillators, is shown in figure 2. As the result, we observed 6 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 from process (a) and (b) was estimated by radioactivities of the CaF_2(pure) scintillators. The background rate was $\sim$ 1 event/4987 kg·days. In the CANDLES system, the other background candidate is γ-rays from neutron capture in the surrounding materials of the detector (process (c)). In order to estimate the background rate from neutron capture γ-rays, we performed a

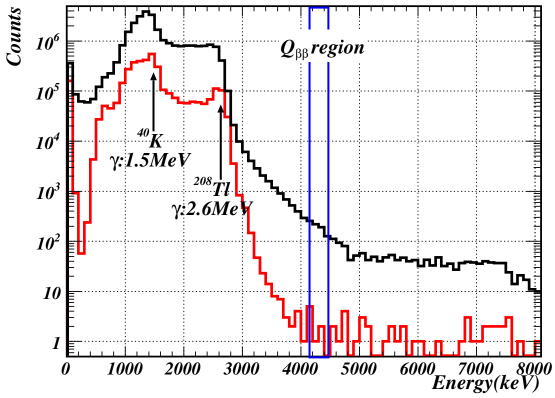

Figure 2: Energy spectra with/without the event selection. Black line represents an experimental data without the event selection. After the event selection, 6 events are seen in the $0\nu\beta\beta$ window.

special run using a ^{252}Cf neutron source. Based on the result of the special run and Monte-Carlo simulation, we estimated that the event rate from the γ-rays is 3.4 event/4987 kg·days. By using the expected background rate, we present an experimental sensitivity. The sensitivity with the 90 % C.L. is 0.8×10^{22} year.

5 Future perspective

In order to reduce the γ-rays from neutron capture, we plan to install a shielding system in the CANDLES III system in early 2015. The shielding system consists of boron/cadmium sheet and Pb blocks. We estimate to reduce the γ-ray rate by $\sim$ 2 orders of magnitude.

Other improvement for the CANDLES III system is a cooling system. The CaF_2(pure) scintillator is known that amount of light output increases with low temperature. The increasing rate of the light yield is 2%/°C. We have already installed the cooling system and will start operation of the system. We estimate to increase the light yield by 30%.

6 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 $\rightarrow$ Po and ^{208}Tl. We performed the pilot run in order to check the background rate. The sensitivity of the $0\nu\beta\beta$ half-life is 0.8×10^{22} year with the pilot run . In near future we will upgrade the CANDLES III system to reduce the background rate. After the upgrade the sensitivity will be $\sim 10^{24}$ year for the $0\nu\beta\beta$ half-life.

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