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The CANDLES experiment for the study of Ca-48 double beta decay

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Abstract

CANDLES studies the double beta decay of ^{48}Ca through CaF_2 scintillation crystals. The CANDLES III detector, located in Kamioka underground laboratory, is currently running. Here we describe recent status of data analysis which includes detector performance, detector stability, and background estimation. Current sensitivity for $0\nu\beta\beta$ half-life is also discussed in this paper.

Keywords: Double beta decay, Neutrino, Calcium 48

1. Ca-48 Double beta decay

The neutrino less double beta decay ($0\nu\beta\beta$) is the only practical way to prove the Majorana nature of the neutrino. CANDLES (CAlcium fluoride for the study of Neutrinos and Dark matters by Low Energy Spectrometer) is a ^{48}Ca double beta decay experiment with CaF_2 scintillator [1]. A distinctive characteristic of ^{48}Ca is the highest Q-value (4.3 MeV) among isotope candidates for $0\nu\beta\beta$. In principle, it enables us to measure signals in very low background (BG) contribution.

2. The CANDLES III detector

The CANDLES III detector (Figure 1) is currently running with 300kg CaF_2 crystals in the Kamioka underground observatory, Japan. The detector consists of 96 pure CaF_2 crystals immersed in liquid scintillator (LS) as 4π active shield. Scintillation lights from CaF_2 and LS are observed by 62 photo-multiplier tubes (13' and 20' PMTs) mounted on 30 m^3 stainless water tank. Decay time constant of CaF_2 scintillation (about 1 μs) is enough longer than that of LS (a few tens ns), so that γ-ray background through LS can be distinguished by pulse shape discrimination.

2.1. Detector performance and stability

The detector performance and stability are checked by about three months data which was taken from June 2013 to Sep. 2013 (60.3 days live time). Energy scale (Escale) for each crystal is calibrated with 0.2% accuracy using ^{88}Y γ-ray source (1.84 MeV). From the ^{88}Y γ-ray data, light yield of CANDLES III is estimated to be 778 [p.e./MeV].

Energy resolution are checked by several energy γ/α BG events (e.g. 1.84 MeV γ of ^{88}Y / 7.7 MeV α of ^{214}Po etc.) and σ = 2.56% is calculated by scaling to the energy at Q-value.

Time and position dependency of Escale are checked by 2.62 MeV ^{208}Tl external γ-ray in the BG data. As

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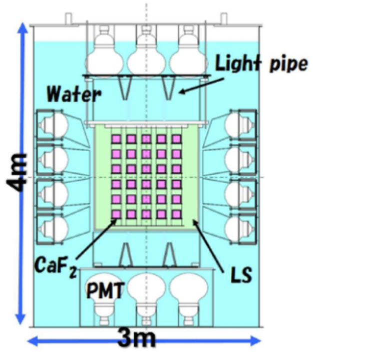

Figure 1: The schematic view of the CANDLES III detector located 1000 m underground in Kamioka, Japan.

Energy resolution	σ = 2.56% @$Q_{\beta\beta}$
Time dep. of Escale	0.3%
Position dep. of Escale	0.5%
Time dep. of Event rate	2.4%

Table 1: Summary of the detector performance and stability for the CANDLES III detector.

seen in Figure 2, very good stability for time and position has been confirmed. Event rate of ^{208}Tl is also checked to prove stable live time and its variation is 2.4%. In consequence, our detector works in stable condition. Detector performance and stability are summarized in Table 1.

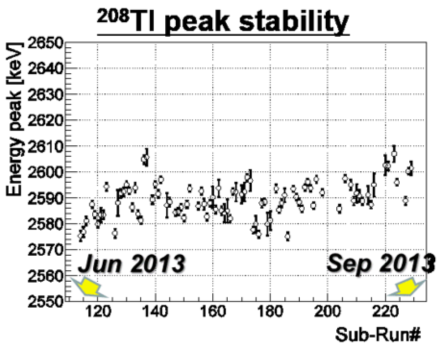

Figure 2: Energy peak of ^{208}Tl 2.62 MeV γ as a function of run number. Energy scale is stable within ±0.3% for three month data taking term.

3. Background of the CANDLES experiment

Although the highest Q-value of ^{48}Ca and 4π active shield of LS strongly suppress remaining BGs, there still exist three possible backgrounds in $0\nu\beta\beta$ region. The CANDLES DAQ system collects each event with 8 μs window using 500 MHz flash-ADC, so that we can use pulse shape discrimination (PSD) method for BG rejection. χ^2_β, χ^2_α and $\chi^2_{\beta+LS}$ are calculated for each event by fitting with β, α and LS refference pulse shapes. χ^2 can strongly reduce LS included BGs. We additionally use Shape indicator method [2] in order to distiguish β and α event. Here we discuss a BG study by PSD with 60 days data and the results are summarized in Table 2.

3.1. ^{212}Bi - ^{212}Po sequential decay

In ^{232}Th chain, ^{212}Bi and ^{212}Po nuclei undergo β and α decays with very short interval of 300 ns half-life. Since this interval is shorter than 4 μs event window of CANDLES, they are identified as one event with high end point of 5.3 MeV visible energy. However after rejecting double pulse event by PSD, this BG is reduced by two orders of magnitude and the number of remaining events can be ignored.

3.2. ^{208}Tl $\beta + \gamma$ decay

Another internal background candidate is ^{208}Tl in ^{232}Th chain which has large $Q_\beta \sim 5.0$ MeV. In order to reject ^{208}Tl, we use time coincidence method between parent ^{212}Bi and daughter ^{208}Tl. Half-life of ^{208}Tl is 3 minutes.

We first select 26 clean crystals and next we find ^{212}Bi α decay candidate by PSD. Then we apply a veto time for 12 minutes after ^{212}Bi. Due to relatively high accidental coincidence, now we cannot apply very strong veto and thus rejection efficiency for ^{208}Tl is only 60%. Detail of ^{208}Tl rejection is disscused in [3].

3.3. Neutron capture gamma-ray

We found that γ-rays from neutron captures on nuclei (e.g. ^{56}Fe, ^{58}Ni) inside the surrounding materials can be dominant BGs in CANDLES. In order to better understand neutron capture γ BGs, we performed a special run with ^{252}Cf neutron source (See Figure 3). The number of this background in Q-value region was estimated as 3.4 event/60days/26crystals by data analysis and Monte-Calro (MC) simulation of neutron capture γ-ray.

4. Sensitivity for $0\nu\beta\beta$

$0\nu\beta\beta$ sensitivity study is done using the data set from Jun. to Sep. 2013 with 60.3 days of live time. The list of applied cut criteria is shown below.

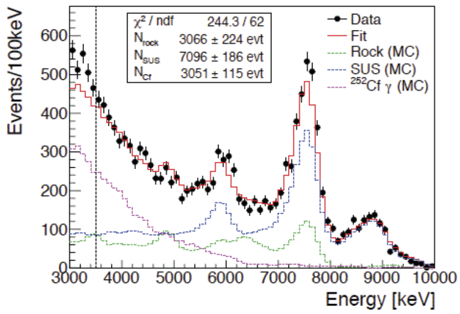

Figure 3: Energy spectrum of neutron source run. Data is fitted by the spectra of neutron capture γ of Rock (green), Stainless steel (blue) and γ originated from ^{252}Cf (pink) obtained from MC simulation. Data and fitted spectrum are almost consistent and well understood above 3.5 MeV.

BG source	Remining BG	rejection eff.
^{212}Bi - ^{212}Po	Ignoreable	> 99%
^{208}Tl $\beta + \gamma$ decay	1 ev/60days	60%
Neutron capture γ	3.4 ev/60days	77%

Table 2: Summary table of the remaining number of backgrounds after all reduction process in the current CANDLES III data.

- χ^2_β <1.5 (remove CaF_2 + LS event)
- -3σ < Shape indicator < 1σ (select β)
- Double pulse cut (remove ^{212}Bi - ^{212}Po)
- 12 min. veto after ^{212}Bi (reject ^{208}Tl)
- 26 crystals selection (^{232}Th < 10 μBq/kg)

After all the cuts applied, the number of events in the energy window of 4.17 - 4.48 MeV is 6 events compared to 4.4 expected number of BGs. Current sensitivity of CANDLES for $0\nu\beta\beta$ half-life (> 0.8×10^{22} year) is obtained by Feldman-Cousins method [4]. Systematic error is not yet included.

This is not the world best limit for ^{48}Ca double beta decay because of the existence of BGs. If we achieve BG free measurement, half-life sensitivity goes up to > 10^{23} year for one year measurement. Therefore we plan some hardware inprovements to reduce BGs, as discussed in the next section.

5. Future plan

5.1. Neutron and γ-ray shield

We are now trying to reduce remaining BGs in Q-value by installing neutron and γ-ray shield in early 2015. Boron or Cadmium sheet will be placed on surface of the stainless water tank to prevent thermal neutrons from being captured by Fe or Ni nuclei inside the tank material.

Also Pb blocks will be arrayed for shielding external neutron capture γ-rays mainly coming from rock of the experimental room. Thickness of Pb shield is 10 cm for side region and 5cm for top and bottom region. Since one order reduction is corresponding to 5 cm Pb, we expect nearly two order BG reduction with this shield.

5.2. Cooling system

CaF_2 scintillator is known that its light output increases about 2% by lowering 1 $°C$ temperature. We plan to cool the detector down to 2 $°C$ to increase the light yield by about 30%. Higher light yield enables us to more easily distinguish the $0\nu\beta\beta$ signal from BGs.

Cooling system has been installed in May 2014, and will start working in Oct. 2014.

6. Conclusion

CANDLES is designed for the study of ^{48}Ca double beta decay. We have started basic studies with the CANDLES III detector installed in Kamioka, Japan. Good performance and stability were confirmed by analyzing 60 days data taken in 2013. Background study was also done with pulse shape discrimination and expected number of backgrounds for ^{208}Tl and neutron capture γ-ray were evaluated from data analysis and simulation.

Sensitivity for $0\nu\beta\beta$ half-life obtained from current data analysis is > 0.8×10^{22} year. By future detector updates, we aim background free measurement whose $0\nu\beta\beta$ half-life sensitivity is corresponding to > 10^{23} year.

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