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Status and future prospect of 48Ca double beta decay search in CANDLES

T Iida[1], K Nakajima[2], S Ajimura[1], T Batpurev[3], W M Chan[3], K Fushimi[4], R Hazama[5], H Kakubata[3], B T Khai[3], T Kishimoto[3], X Li[3], T Maeda[3], A Masuda[2], K Matsuoka[3], K Morishita[2], N Nakatani[5], M Nomachi[1], S Noshiro[2], I Ogawa[2], T Ohata[3], H Osumi[6], K Suzuki[7], Y Tamagawa[2], K Tesuno[3], V T T Trang[3], T Uehara[3], S Umehara[1], and S Yoshida[3]

[1] Research Center for Nuclear Physics (RCNP), Osaka University, Ibaraki, Osaka 567-0047, Japan
[2] Graduate School of Engineering, University of Fukui, Fukui, 910-8507, Japan
[3] Graduate School of Science, Osaka University, Toyonaka, Osaka 560-0043, Japan
[4] Institute of Socio Arts and Science, The University of Tokushima, Tokushima 770-8502, Japan
[5] Faculty of Human Environment, Osaka Sangyo University, Daito, Osaka 574-8530, Japan
[6] Faculty of Culture and Education, Saga University, Saga 840-8502, Japan
[7] The Wakasa-wan energy research center, Tsuruga, Fukui 914-0192, Japan

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

Abstract. The observation of neutrino-less double beta decay ($0\nu\beta\beta$) would be the most practical way to prove the Majorana nature of the neutrino and lepton number violation. CANDLES studies ^{48}Ca double beta decay using CaF_2 scintillator. The main advantage of ^{48}Ca is that it has the highest Q-value (4.27 MeV) among all the isotope candidates for $0\nu\beta\beta$.

The CANDLES III detector is currently operating with 300kg CaF_2 crystals in the Kamioka underground observatory, Japan. In 2014, a detector cooling system and a magnetic cancellation coil was installed with the aim to increase light emission of CaF2 scintillator and photo-electron collection efficiency of the photo-multipliers. After this upgrade, light yield was increased to 1000 p.e./MeV which is 1.6 times larger than before.

According to data analysis and simulation, main background source in CANDLES is turned out to be high energy external gamma-ray originating neutron capture on the surrounding materials, so called (n,γ). Upgrading the detector by installing neutron and gamma-ray shield can reduce the remaining main backgrounds by two order magnitude. In this report, we discuss the detail of (n,γ) and background reduction by additional shielding.

1. Introduction

One of the most persistent and momentous questions about the neutrino is whether neutrino is Dirac particle or Majorana particle. If neutrino is Majorana particle (i.e. the neutrino is its own anti-particle), left- and right-handed neutrino can have different mass terms respectively. Assuming heavy, GUT scale mass of the right handed neutrino, it is naturally possible to explain extremely small mass of the neutrino (Seesaw mechanism [1]). In addition, Majorana neutrino

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violates the lepton number conservation. The matter-antimatter asymmetry in the present universe can be theoretically explained by considering CP violation and the decay of right-handed heavy neutrinos in the early universe (Leptogenesis [2]).

2. The CANDLES detector

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 [3].A distinctive characteristic of ^{48}Ca is the highest Q-value (4.27 MeV) among isotope candidates for $0\nu\beta\beta$. In principle, it enables us to measure signals in very low background (BG) contribution.

2.1. Detector description

The CANDLES III detector (Figure 1) is 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. In 2014, a detector cooling system and a magnetic cancellation coil were installed with the aim to increase light emission of CaF2 and collection efficiency of the photo-multipliers.

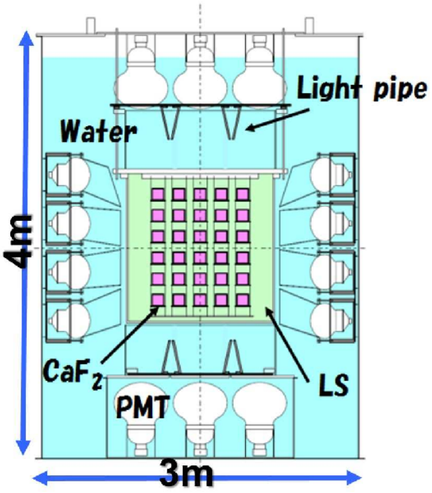

Figure 1. The schematic view of the CANDLES III detector located 1000 m underground in Kamioka, Japan.

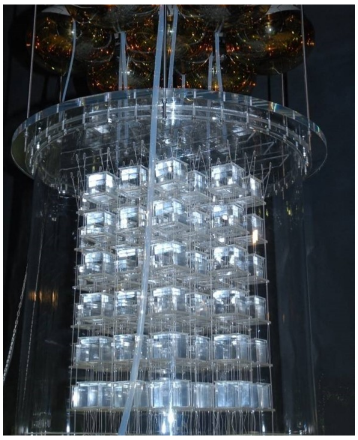

Figure 2. Picture of 96 CaF_2 crystals used in CANDLES.

2.2. Performance and stability of the detector

The detector performance and stability are checked by about three months data which was taken from Jul. 2014 to Dec. 2014. 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 about 1000 [p.e./MeV] which is 1.6 times higher than before coil and cooling system installation. Energy resolution are checked by several energy γ/α events (e.g. 1.84 MeV γ of ^{88}Y / 7.7 MeV α of ^{214}Po etc.) and $\sigma = 2.0\%$ 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 seen in Figure 2, very good stability has been confirmed. Event rate of ^{208}Tl is also checked to prove stable live time and its variation is 0.6%. In consequence, our detector works in stable condition. Detector performance and stability are summarized in Table 1.

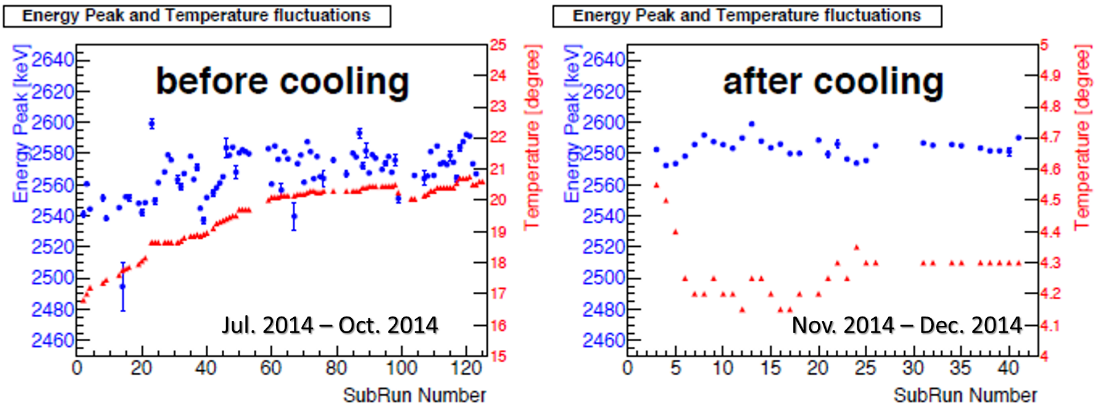

Figure 3. Energy peak of ^{208}Tl 2.62 MeV γ and water temperature as a function of run number. Left figure is before cooling and right figure is after cooling. Energy scale after cooling is stable with ±0.14% for one month data taking term.

Energy resolution	σ = 2.0% @Q$_{\beta\beta}$
Time dep. of Escale	0.14%
Position dep. of Escale	0.2%
Time dep. of Event rate	0.6%

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

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.

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 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$_\beta$ ∼ 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.

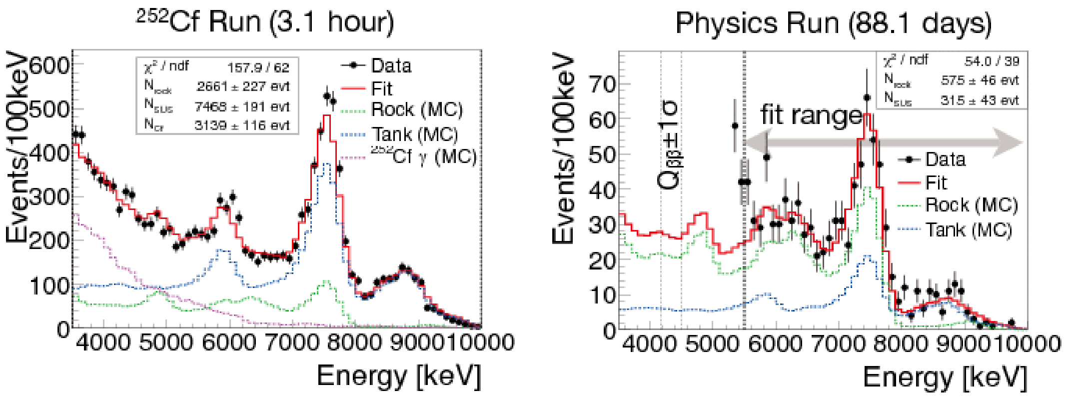

Figure 4. Left: Energy spectrum with ^{252}Cf source. Right: Energy spectrum taken in the normal physics run.

We first find ^{212}Bi α decay candidate by PSD and then 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].

4. Neutron capture gamma-ray as a background in CANDLES

Even with the strong active veto using LS, unexpected events were observed in the energy region above Q value (4.27 MeV). Specific peaks are observed around ∼7.5 MeV and ∼9 MeV, which are identified as γ ray events from (n,γ) reaction in the material surrounding detector. When thermal neutrons are captured in rich material surrounding the detector such as rock and stainless steel tank, high energy γ rays are emitted, and deposit its energy in CaF_2 crystals. There is a database of individual γ ray intensity from (n,γ) reaction for each element, and total γ ray spectra can be calculated for each material. Observed peaks around ∼7.5 MeV and ∼9 MeV are from Fe and Cr/Ni contained in stainless steel and rock.

To obtain enough (n,γ) events, ^{252}Cf source was set out of the detector tank. Figure 4 shows energy spectra with ^{252}Cf source and that taken in the normal physics run. Statistics of (n,γ) events of ^{252}Cf source run for 1.5 hour data taking is almost equivalent with 1 year data taking of normal physics run. The spectrum taken with ^{252}Cf source demonstrates that events in the high energy region (5-10 MeV) is caused by (n,γ) reaction. As shown in Figure 4, both observed spectra are fitted well with MC spectra of (n,γ) reaction on rock and on stainless steel tank. The background amount of (n,γ) reaction in $Q_{\beta\beta}$ is estimated to be 76 ± 9(stat.) events/year/96 crystals from MC simulation.

5. Shield for (n,γ) background

Since (n,γ) is the most serious background in CANDLES, it is necessary to install additional passive shield. The goal of (n,γ) background rate is about 1 events/year/96crystals, which is 1/80 level of the current rate. Shield design was optimized using Geant4 simulation. A schematic view of the determined design is shown in the left of Figure 5. We installed Pb shield against (n,γ) reaction on rock and Si rubber sheet containing 40 wt% of B_4C (B sheet) inside and outside of detector to reduce thermal neutron captures on stainless steel tank. Since some non-thermal neutrons are thermalized in water and are captured inside of stainless steel tank, B sheet should also be set inside of the tank. The typical Pb thickness is about 10 cm, because γ rays with several MeV are reduced by 1/100. Considering the weight limit on the top of the detector, Pb thickness in the top is suppressed to 7 cm, and for more effective reduction, Pb thickness is 12 cm in the center of detector side, where thickness of passive water shield is thinnest. In bottom, Pb shield

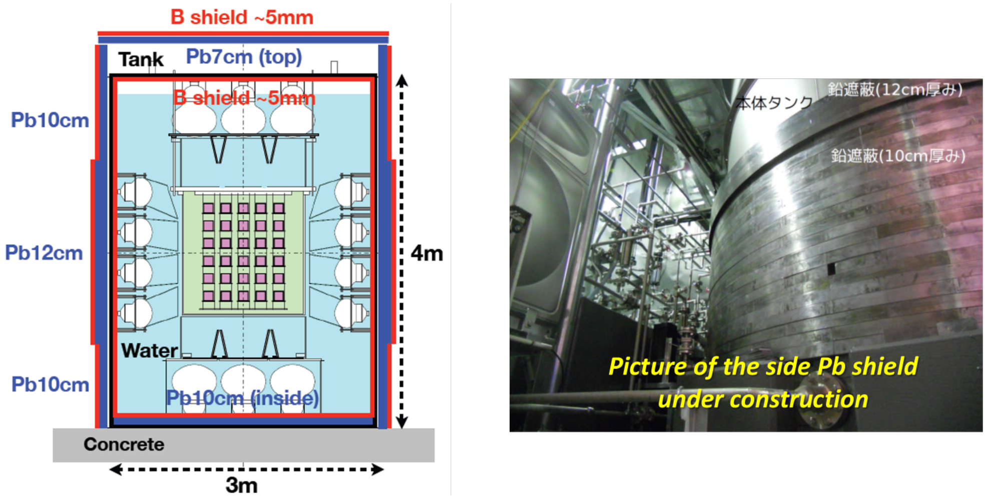

Figure 5. Left: Schematic view of shield design for (n,γ) background reduction. Right: A photograph of Pb shield construction on Mar. 2015.

is set inside of detector. Thickness of B sheet ($\sim$4 mm) is enough to reduce thermal neutrons. By constructing this shield system, total (n,γ) background rate is expected to be $\sim 0.7(\pm 50\%)$ events/year/96crystals estimated by MC simulation. Breakout of (n,γ) background from rock and tank is 0.34±0.14 events/year/96crystals, 0.4±0.2 events/year/96crystals, respectively. Shield construction was completed in the beginning of 2016.

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 commissioning data taken in 2014. Background study was also done and we identified the main background in CANDLES as external gamma-rays from neutron capture on nuclei in the surrounding materials by performing a special data taking with 252 Cf neutron source. In order to reduce this background, shield was designed by Geant4 simulation and constructed over 2015. After the shielding, expected number of (n,γ) BG decrease by two order of magnitude, and it is corresponding to sensitivity for $0\nu\beta\beta$ half-life larger than 10^{23} year after one year measurement.

7. Acknowredgement

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