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Study of ^{48}Ca double beta decay by CANDLES

I Ogawa[1], T Kishimoto[2,3], S Umehara[3], G Ito[2], K Yasuda[2], H Kakubata[2], M Miyashita[2], K Takubo[2], K Matsuoka[2], M Nomachi[2], M Saka[2], K Seki[2], K Fushimi[4], R Hazama[5], H Ohsumi[6], K Okada[7], Y Tamagawa[1], T Jinno[1], N Fujiwara[1] and S Yoshida[2]
for the CANDLES Collaboration

[1] Graduate School of Engineering, University of Fukui, Fukui 910-8507, Japan
[2] Graduate School of Science, Osaka University, Toyonaka, Osaka 560-0043, Japan
[3] Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan
[4] Faculty of Integrated Arts and Science, The University of Tokushima, Tokushima 770-8502, Japan
[5] Graduate School of Engineering, Hiroshima University, Higashi-Hiroshima, Hiroshima 739-8527, Japan
[6] Faculty of Culture and Education, Saga University, Saga 840-8502, Japan
[7] Department of Computer Science and Engineering, Kyoto San-gyo University, Kyoto 603-8555, Japan

E-mail: ogawa@u-fukui.ac.jp

Abstract. CANDLES is the project to search for double beta decay (DBD) of ^{48}Ca by using CaF_2 scintillators. The Q-value of ^{48}Ca, which is the highest (4.27 MeV) among potential DBD nuclei, is far above energies of γ-rays from natural radioactivities (maximum 2.615 MeV from ^{208}Tl decay), therefore we can naturally expect small backgrounds in the energy region we are interested in. We have constructed the prototype detector, CANDLES III in our laboratory (Osaka U.) at sea level and studied the basic performance of the system, including the light collection, position reconstruction and background rejection. After R&D study we moved the detector system to new experimental room at Kamioka underground laboratory. Herein the expected performances and current status of the CANDLES system are described.

1. Introduction

The observations of neutrino oscillations have demonstrated that neutrinos have mass, and the existence of neutrino mass opens the possibility that neutrinos could be Majorana particles. As Majorana particles, their mass term would violate lepton number conservation. A neutrinoless double beta decay is the most feasible way to demonstrate that neutrinos are Majorana particles and they violate lepton number conservation.

We have been studying the double beta decay of ^{48}Ca. ^{48}Ca has the highest $Q_{\beta\beta}$ value (4.27 MeV) among all double beta decay nuclei, ensuring a large phase space factor for the decay rate. In addition, its decay is above the energies from the natural radioactivities of β- (max 3.27 MeV from ^{214}Bi) and γ-rays (max 2.6 MeV from ^{208}Tl). Therefore, the background from natural radioactivity is limited in the $Q_{\beta\beta}$-value region. This advantage should be of particular importance for future studies in which vast quantities of the target nuclei are employed. We gave the best lower limit for the half-life of the neutrinoless double beta decay of ^{48}Ca using a

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CaF_2(Eu) detector system[1, 2]. However to reach the mass region of interest, the system must be further developed.

2. CANDLES III at Osaka University

The CANDLES (CAlcium fluoride for the study of Neutrinos and Dark matters by Low Energy Spectrometer) project searches for the double beta decay of ^{48}Ca using undoped CaF_2 (CaF_2(pure)) scintillators[3]. We have constructed the CANDLES III detector at a sea-level laboratory, OULNS (Osaka University Laboratory for Nuclear Studies). The CANDLES III detector consists of CaF_2 modules, a liquid scintillator, water buffer, and PMTs. The CaF_2 modules are immersed in the liquid scintillator, which acts as an active veto (veto phase) by utilizing the difference in the decay time for CaF_2 ($\sim 1\mu$sec) and the liquid scintillator (~ 10 nsec) signals. Both CaF_2(pure) and the liquid scintillator have long attenuation lengths ($\sim$10 m).

The CaF_2 module consists of a CaF_2(pure) crystal, which is a 10 cm cube (3.18 kg), a 5 mm thick mineral oil layer (conversion phase), and a 3 mm thick acrylic container. We have developed highly pure CaF_2 crystals and confirmed their measured levels of radioactive contaminations (36(ave.), 14 ± 5(best) μBq/kg for uranium and 28(ave.), 6 ± 1(best) μBq/kg for thorium). The conversion phase contains a wavelength shifter (Bis-MSB; 0.1 g/ℓ) to convert the emission light of CaF_2(pure), which has a peak in the UV region, to the visible region where the quantum efficiency of the PMTs is sufficient (maximum at $\sim$ 400 nm) and materials in the optical path have good transparencies[5]. The 60 CaF_2 modules are suspended by wires from the ceiling of the liquid scintillator measuring 1 m in diameter and 1 m high.

The outside of the liquid scintillator vessel is filled with pure water (water buffer), which also acts as a passive shield against the backgrounds from PMTs and outside the detector. Scintillation lights from both the CaF_2 modules and the liquid scintillator are viewed by 40 large PMTs (32×13" and 8×15" tubes).

2.1. Background rejection

Background events originating outside the CaF_2 module that have a high probability of firing the liquid scintillator are effectively rejected by the 4π active veto system. Figure 1 shows typical pulse shapes of events that fire CaF_2 and/or the liquid scintillator. Pulse shape analysis rejects background events that fire the liquid scintillator (figures 2 and 3). The position cut to reject the events occurring at locations besides the CaF_2 crystals is also applied based on event reconstruction using the charge information of each PMT. Additionally, the event position can be used to reduce the backgrounds from $\beta + \gamma$-decays of ^{208}Tl ($Q_\beta = 5.0$ MeV, $T_{1/2} = 3$ min.) by identifying the preceding α decay of ^{212}Bi in Th-chain.

Because the $Q_{\beta\beta}$ value is higher than the typical energies of natural radiations, the background in the $Q_{\beta\beta}$ value region is due to only the successive decays of radioactive nuclei in the CaF_2(pure) crystal. The candidates other than ^{208}Tl $\beta + \gamma$-decays are pile-up 'Bi-Po' events in U- and Th-chains.

$$^{214}\mathrm{Bi} \xrightarrow{Q_\beta = 3.27\ \mathrm{MeV}} {}^{214}\mathrm{Po}(T_{1/2} = 164.3\ \mu\mathrm{sec}) \xrightarrow{Q_\alpha = 7.83\ \mathrm{MeV}} {}^{210}\mathrm{Pb},$$
$$^{212}\mathrm{Bi} \xrightarrow{Q_\beta = 2.25\ \mathrm{MeV}} {}^{212}\mathrm{Po}(T_{1/2} = 0.299\ \mu\mathrm{sec}) \xrightarrow{Q_\alpha = 8.95\ \mathrm{MeV}} {}^{208}\mathrm{Pb}.$$

The maximum energies deposited are above the $Q_{\beta\beta}$-value of ^{48}Ca where the quenching factor of the CaF_2 scintillator for an α particle is about 0.3.

We measured the pulse shape of events from the CaF_2(pure) scintillator using a 100 MHz flash ADC to demonstrate that the events in sequential decays can be discriminated if the time lag is longer than two channels. Figure 3(a) shows the typical pulse shape of the pile-up events. Additionally, the decays times for the signals between α and β/γ decays differ. Figure 3(b)

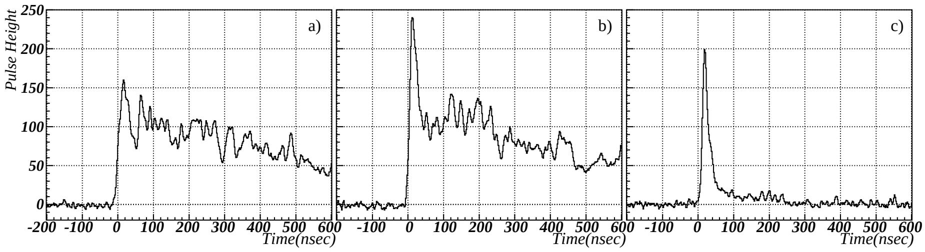

Figure 1. Typical pulse shapes of events. (a) Only the CaF_2 scintillator fires. (b) Both the CaF_2 and the liquid scintillator fires. (c) Only the liquid scintillator fires. The events in (b) and (c) are backgrounds to be rejected.

shows the results of 'shape indicator' analysis[6] using pulse shape information. In the $Q_{\beta\beta}$ region, we can discriminate the pile-up background event, which is mainly from α particles.

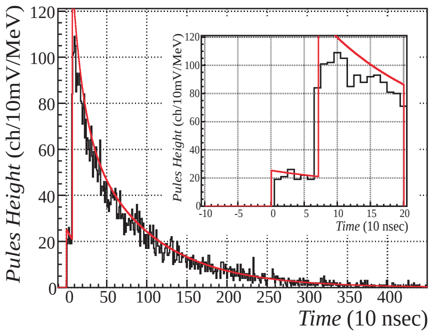

Figure 2. Typical pulse shape of sequential decay events.

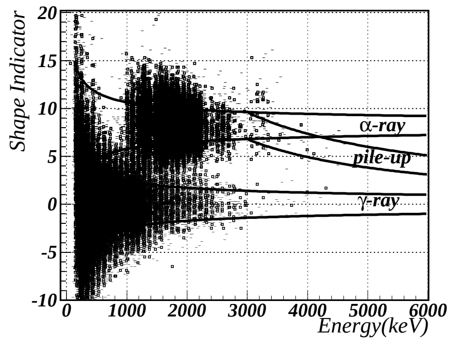

Figure 3. Scattered plot for the pulses corresponding to α-, pile-up and $\beta(\gamma)$-events with 'shape indicator' analysis. Solid lines show the $\pm 1\sigma$ region for each events.

3. CANDLES III(U.G.) at Kamioka

We have moved the detector system to experimental hall-D at the Kamioka Underground Laboratory (2700 m.w.e.), while simultaneously increasing the detector size (CANDLES III(U.G.;<u>U</u>nder<u>G</u>round)). A total 96 CaF_2 modules (six layers where each layer is composed of 16 modules) containing 350 g of ^{48}Ca are immersed in the liquid scintillator (figure 4). Additionally, we increased the sizes of the liquid scintillator vessel and the water tank to 1.4 m (diameter) $\times$ 1.4 m (height) and 3 m (diameter) $\times$ 4 m (height), respectively. Moreover, there are 62 PMTs (48 $\times$ 13" at side wall of the tank and 14 $\times$ 17" tubes at top and bottom of the tank).

Along with the liquid scintillator storage tanks, a water tank and a purification system of the liquid scintillator are installed in hall D. The purification system of the liquid scintillator removes radioactive impurities, especially U and Th, via water-extraction and N_2 gas purge techniques. The liquid scintillator vessel, which contains 96 CaF_2 modules, and the top PMTs are suspended from the top cover of the water tank. We also installed a calibration system for energy and timing using radioactive isotope(s) and pulsed LED for each CaF_2 module.

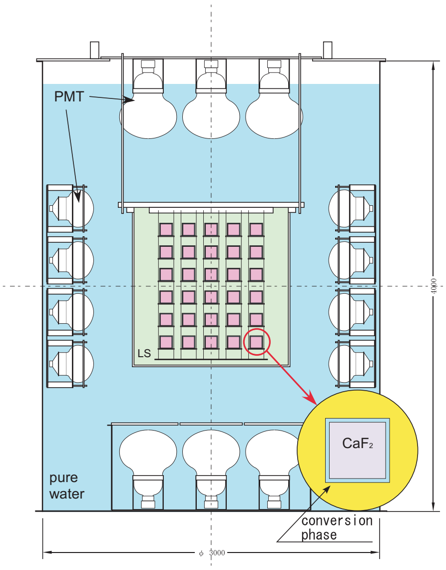

Figure 4. Schematic drawing of CANDLES III.

A DAQ system to record the pulse shapes from 62 PMTs are installed in the DAQ room. The system is based on a fast (500 MHz) flash ADC and an intelligent trigger using FPGA which selects CaF_2 events effectively. Both the DAQ and safety systems can be monitored through the network to safely and continuously operate CANDLES III(U.G.). After finishing the commissioning runs which have started in fall 2011, the CANDLES III(U.G.) will begin collecting data.

4. R&D study for enrichment of ^{48}Ca

To explore the mass region of $\Delta m_\nu^2 \sim 10^{-(2-3)}$, enrichment of ^{48}Ca is crucial. Since there is no gaseous compound of Ca at room temperature, we can not use centrifugal method. Instead of it, chemical methods (chromatography and liquid-liquid extraction) using crown ether and laser isotope separation (LIS) are now under study. The crown ether which consists of a ring containing several ether elements, has been known to strongly bind a cation located at the interior of the ring. In the case of calcium, a light cation (^{40}Ca) is preferentially bound, thus chemical process exhibit isotopic effects. In the tabletop experiments[4], we succeeded to enrich ^{48}Ca.

Based on our experiences in CANDLES III and R&D study of enrichment, we plan to scale up to several tons of calcium to achieve the sensitivity in the mass region of interest.

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