Activity at Kamioka Double-Beta Decay Facility

S. Umehara for the CANDLES Collaboration
Research Center for Nuclear Physics (RCNP), Osaka University, Ibaraki, Osaka 567-0047, Japan

RCNP has the double beta decay facility at the Kamioka underground laboratory, ICRR, The University of Tokyo, for underground science. At this facility, we have operated two systems for low background measurement. The one is the CANDELS III system for double beta decay measurement and the other is the low background system for measurement of radioactive contaminations.

Study for Double Beta Decay of ^{48}Ca with CANDLES

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. The observation of $0\nu\beta\beta$ provides a test for the Majorana nature of neutrinos and gives an absolute scale of the effective Majorana neutrino mass. In addition, the observation of $0\nu\beta\beta$ proves the lepton number non-conservation. The lepton number non-conservation means "antimatter" and "matter" can convert to each other. This is one of the key points to solve the mystery why the universe mostly consists of "matter".

For the measurement of $0\nu\beta\beta$ of ^{48}Ca, RCNP has operated the CANDLES III system[1] at the Kamioka underground laboratory, ICRR, The University of Tokyo. 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[2]. 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.

Recently we improved the CANDLES system for further background reduction. In the CANDLES system, backgrounds can be strongly limited by the 4 π active shield and the highest $Q_{\beta\beta}$-value of ^{48}Ca. The remaining backgrounds are only following processes: (a) $^{212}\mathrm{Bi} \xrightarrow[\beta]{} {}^{212}\mathrm{Po} \xrightarrow[\alpha]{} {}^{208}\mathrm{Pb}$ (Th-chain), (b) $^{208}\mathrm{Tl} \xrightarrow[\beta]{} {}^{208}\mathrm{Pb}$(Th-chain) and (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. Details are shown in ref.[3, 4].

As the result, the background candidate in the energy region is the events from the process (c), which is the 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

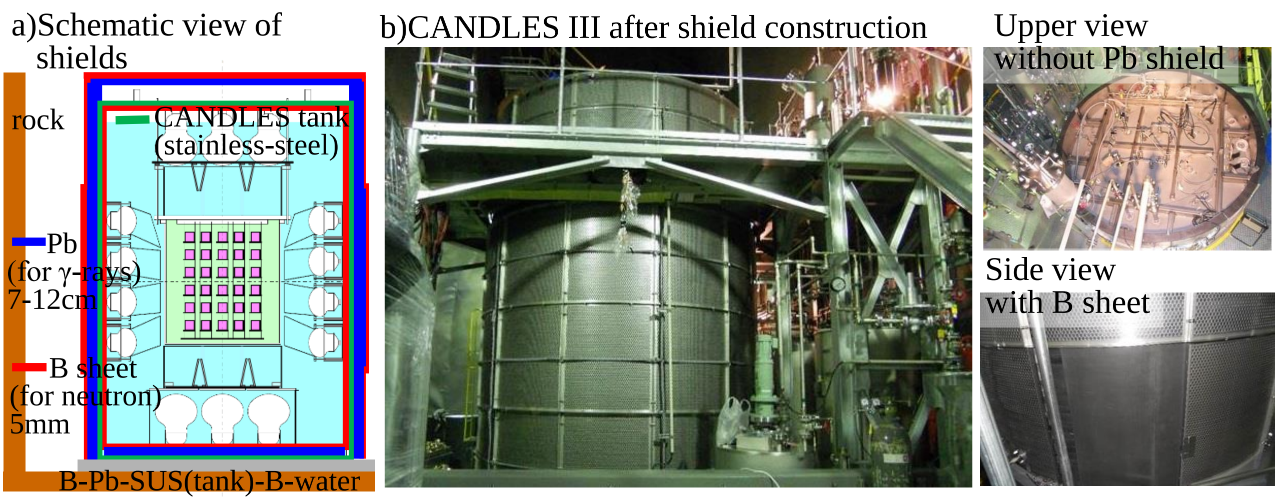

Figure 1: a) Schematic drawing of the shielding system. The system consists of the silicone rubber sheet containing B_4C (B sheet) and the Pb bricks. b) Photograph of the CANDLES main tank after shield construction. Right-upper) Photograph of upper view of the tank. The Pb bricks at an elevation of 1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

reaction on Fe and Ni in the rock and stainless steel. The estimated event rate from the γ-rays is 76 ± 9 (stat.) events/year in the CANDLES system[5].

Thus we need to install a shielding system to reduce the γ-ray background. Design of the shielding system was optimized by the simulation. The schematic view of the system is shown in figure 1-a). The shielding system consists of rubber-sheet containing 40 wt% of B_4C of 5 mm in thickness and Pb bricks of 7 - 12 cm. The sheet containing ^{10}B reduces capture reaction of thermal neutron on the stainless steel tank. The Pb bricks directly reduce γ-ray background emitted from neutron capture reaction. Construction of the shielding system was completed in 2016[2]. Performance of the shielding system was checked with/without a ^{252}Cf neutron source[4]. We found that background rate by neutron capture reaction was reduced to $\sim 1/100$.

After installation of the shielding system, we performed a $0\nu\beta\beta$ measurement for 131 days with low background condition. The criteria to select candidate events for $0\nu\beta\beta$ are given as follows.
(1) CaF_2(pure) scintillator hit.
(2) The events are not process (a) events.
(3) No liquid scintillator hit.
(4) The events are not candidate of the ^{208}Tl events of process (b).
(5) Position of the events are not in the liquid scintillator region.
Criteria (1) and (3) are applied by using the pulse shapes difference between the CaF_2(pure) and liquid scintillators. Criteria (2) and (4) are described in [3, 4]. Criterion (5) is effective for rejection of the background events which hit multiple CaF_2(pure) scintillators.

A selection of the candidate events was made for 11247 kg·days of data. Figure 2-a) and b) show the energy spectra obtained from 95/27 CaF_2(pure) scintillators, respectively. Twenty seven CaF_2(pure) crystals are selected as high purity scintillators. In figure 2, the lowest spectrum shows the result of the event selection by criteria (1) $\sim$ (5). As the result of the high purity 27 CaF_2(pure) crystals, we observed 0 event 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. The background rate from process (a) and (b) was estimated by radioactivities of the CaF_2(pure) scintillators. The background rate was estimated to be $\sim$ 1.2 events. By using the background rate and experimental event rate, we present a lower half-life limit (preliminary) of 6.2×10^{22} year (90 % C.L.). The limit is compatible to the result with more than 2 years of statistics by our previous detector ELEGANT VI[6]. We also present an experimental sensitivity since the number of observed events is fewer than that of the expected backgrounds. The sensitivity is 3.6×10^{22} year (90 % C.L.).

Currently we continued the low background measurement to update the half-life limit and aim to improve the rejection efficiency of ^{208}Tl by new pulse shape analysis. On the other hand we are developing high purity CaF_2(pure) in order to replace the CaF_2(pure) in the CANDLES III system. As the result, we will improve the sensitivity of the $0\nu\beta\beta$ measurement.

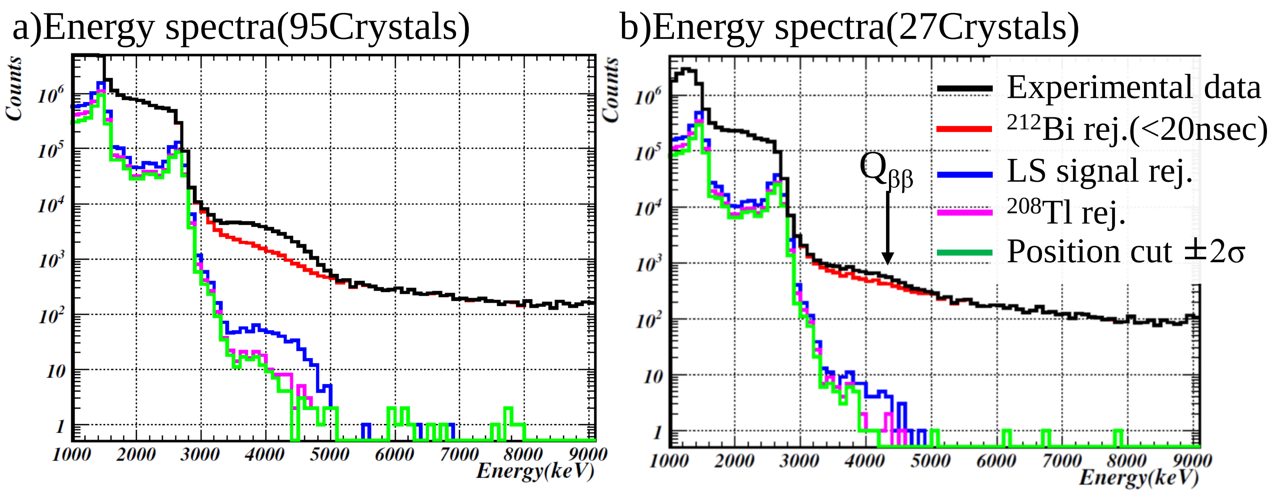

Figure 2: a) and b) Obtained energy spectra with each event selection by using 95/27 CaF_2(pure) scintillators. Details of the event selection are shown as criteria (1) $\sim$ (5) in text. 27 CaF_2(pure) scintillators are selected as high purity scintillators. Measurement time is 131 days. After the event selections, there are no events in the $Q_{\beta\beta}$-value region.

Measurement of radioactive contaminations in scintillation crystals

Radioactive contaminations in a detector deteriorate its sensitivity when the detector is used for low-background measurements. Even if the concentrations in the detector are less than a few ppb, they are serious sources of background in measurements of rare nuclear processes, for instance, double beta decays and dark matter-nuclear interactions. Since the event rate of double beta decay may be less than the order of 1 event/ton/year, there is a need for a detector whose contamination is as low as possible. Radioactive contaminations in the detector are mostly composed of U- and Th-chain isotopes. Thus we need to measure the concentration of these isotopes.

The delayed coincidence method is a powerful tool for measuring the concentrations of these isotopes. This method is especially effective when extracting successive decays with short half-lives. For measurement of radioactive contaminations, we have operated the low background detector. By using the system, two consecutive decays of ^{214}Bi $\underset{\beta}{\longrightarrow}$ ^{214}Po ($T_{1/2}$= 164 μsec) $\underset{\alpha}{\longrightarrow}$ ^{210}Pb(U-chain) and ^{220}Rn $\underset{\beta}{\longrightarrow}$ ^{216}Po ($T_{1/2}$= 145 msec) $\underset{\alpha}{\longrightarrow}$ ^{212}Pb(Th-chain) were measured as correlated events by means of the delayed coincidence method.

Figure 3 a) shows the low background system for measurement of radioactive contaminations in scintillation crystals. The detector was shielded from environmental radiations with oxygen-free high-conductive(OFHC) copper bricks of 10cm in thickness and lead bricks of 10cm in thickness. Black/blue/red lines in figure 3 b) shows background spectra with a NaI(Tl) scintillator at sea-level laboratory(no shield)/underground laboratory(no shield)/ underground laboratory(with shield). Cosmic-ray events above 3 MeV were reduced by using the underground laboratory and γ-ray events bellow 3 MeV were by the OFHC copper and lead shieldings. Figure 3 c) shows the result of measurement of Th-chain contaminations within a CaF$_2$(pure) scintillator. Sensitivity of this measurement depends on the event rate of the chance-coincidence in the energy region in which the delayed α-rays are observed. The sensitivity of the system is $\sim$ 5 μBq/kg. The system will be used for development of high purity crystals.

References

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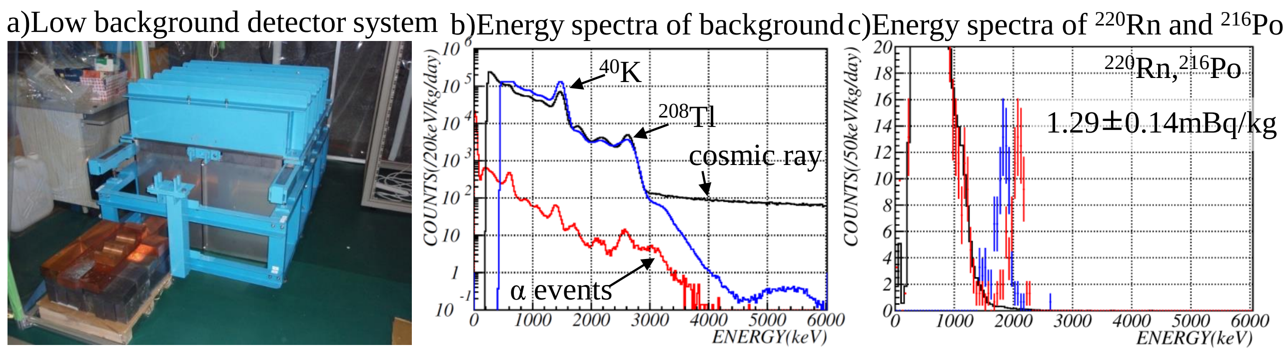

Figure 3: a)The low background detector system for measurement of radioactive contaminations in scintillator crystals. b) Background spectra obtained by a NaI(Tl) scintillator. Black/blue/red lines in figure 3 b) shows background spectra at sea-level laboratory(no shield)/underground laboratory(no shield)/ underground laboratory(with shield). c) Obtained energy spectra of ^{220}Rn and ^{216}Po by the delayed coincidence method. Measured radioactivity of ^{220}Rn is 1.29 $\pm$ 0.14 mBq/kg.