Activity at Kamioka Double-Beta Decay Facility

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RCNP has the double beta decay facility at the Kamioka underground laboratory, ICRR, the University of Tokyo, for underground science such as double beta decay search and low background measurements.

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

Double beta decay is a phenomenon in which two beta decays occur simultaneously in a nucleus. The major decay mode, called two neutrino double beta decay, is associated with emission of two anti-neutrinos. On the other hand, the mode with no anti-neutrino emission is considered to be allowed in the particle theories beyond the standard model of the electro-weak interaction. In $0\nu\beta\beta$ the emitted anti-neutrino is converted to neutrino and is absorbed, and as a result there is no emitted anti-neutrino from the process. This means that the lepton number is not conserved. The lepton number non-conservation is one of the key points to solve the mystery why "matter" is far superior to "antimatter" in our universe. Thus $0\nu\beta\beta$ is acquiring great interest in fundamental physics.

The study for $0\nu\beta\beta$ is one of research projects in RCNP. RCNP is operating the CANDLES III system[1] for the measurement of $0\nu\beta\beta$ of ^{48}Ca. The CANDLES III system is a composite system by CaF_2(pure) scintillator and liquid scintillator. In the system, main detectors, which are CaF_2(pure) scintillators, are immersed in the liquid scintillator to aim a low background measurement[2]. By the liquid scintillator, external background events are vetoed and the system achieves low background condition for the $0\nu\beta\beta$ measurement.

By using the CANDLES III system, we performed a $0\nu\beta\beta$ measurement for 778 days with low background condition, and analyzed the data in 2019. The live time was more than twice as long as that of the previous measurement[3]. The criteria to select candidate events for $0\nu\beta\beta$ are given as follows.
(1) CaF_2 scintillator hit.
(2) No liquid scintillator hit. And position of the events are not in the liquid scintillator region.
(3) The events are not ^{212}Bi→ ^{212}Po events, which is due to radioactive contaminations inside the CaF_2 scintillators.
(4) The events are not candidate of the ^{208}Tl events, which is also due to radioactive contaminations inside the CaF_2 scintillators.
Details of the criteria are shown in ref.[3]. Figure 1 a) shows the energy spectra obtained with respective selections or cuts for background rejection. The green line shows the spectrum with the criteria (1)-(4). From this very preliminary analysis, 6 events were observed in the $0\nu\beta\beta$ window of 4.17 - 4.48 MeV[4]. On the other

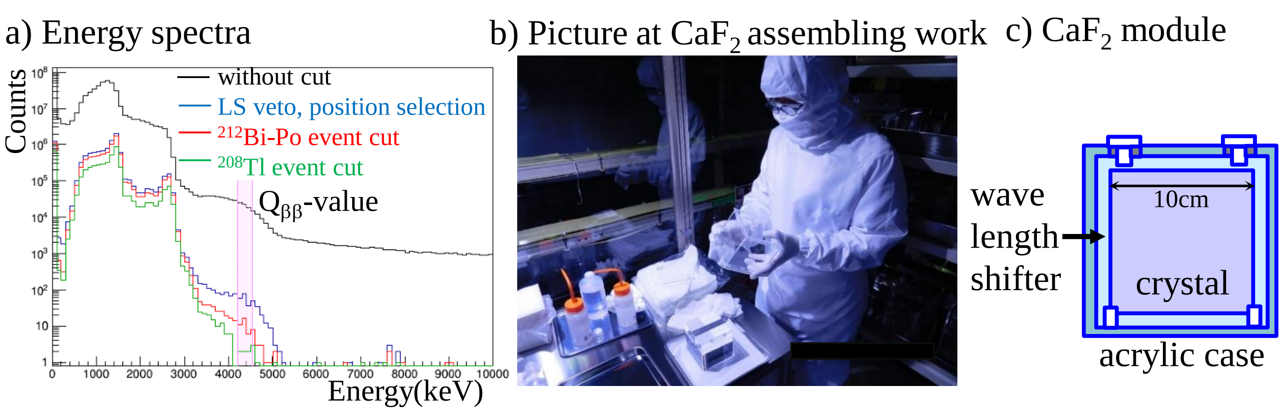

Figure 1: a) The energy spectra obtained with the event selections. 21 CaF_2 scintillators with higher purity were selected and used for this measurement. The measurement time was 778 days. After the event selections, 6 events remained in the $Q_{\beta\beta}$-value region. b) Picture of the work for assembling a CaF_2 module. The work was performed in a clean room. c) Schematic drawing of a CaF_2 module. The light in the UV region emitted by CaF_2 is converted by the wave length shifter to visible.

hand, we estimated number of background events from the simulation based on the radioactivities within the CaF_2 scintillators and rate of the high energy γ-rays due to (n, γ) reaction which is induced by environmental neutron. The expected value of 5.6 events from the simulation was consistent with the experimental value. After optimization of the cut condition for the background events, we will obtain new result for the $0\nu\beta\beta$ half-life of ^{48}Ca.

After the measurement for 778 days, we made an upgrade to the CANDLES system by replacement of CaF_2 scintillators. As mentioned above, we estimated the background origins, and the background from the radioactivities is more than 90% of total background. Thus we can improve the detector sensitivity by replacing the contaminated CaF_2 scintillators with the high purity ones. New 14 CaF_2 scintillators were selected by the result of radioactivity measurements, which are described in next section. Each CaF_2 scintillator was placed in each CaF_2 module, which is shown in figure 1 c). Here the light emission spectrum of CaF_2 scintillator has a peak at the ultraviolet(UV) region. On the other hand, the quantum efficiency of the large photomultiplier tube becomes maximum at $\sim$400 nm. Therefore the light in the UV region emitted by CaF_2 must be converted by the wave length shifter to visible. Thus the acrylic cases in figure 1 c) are filled by wave length shifter. Figure 1 b) is a picture taken during the CaF_2 assembling work. The work was performed in a clean room in order to avoid dust in atmosphere. The measurement of the radioactivities of the new CaF_2 scintillators was started with the CANDLES system at November, 2019. By this upgrade, we will improve the detector sensitivity for the $0\nu\beta\beta$ half-life of ^{48}Ca.

Detector system for measurement of radioactive contaminations

Radioactive contaminants in a detector deteriorate its sensitivity when the detector is used for low-background measurements such as double beta decay, dark matter search and so on. Even if the concentrations of radioactivities in the detector are less than 1 mBq/kg, they are serious background sources for the low-background measurements of rare nuclear processes.

RCNP offers a detector system for measurement of radioactive contaminations as the joint usage/research. In this study, the detector system has been applied to develop the high purity CaF_2 crystals for double beta decay study. As mentioned in previous section, we have used CaF_2 scintillators to search for double beta decay. The CaF_2 scintillators exactly need to reduce the concentrations of radioactivities within itself. In this section, we will report the study of development of the high purity CaF_2 crystals and performance of the detector system.

Radioactive contaminations are mainly composed of U- and Th-chain isotopes. Since the detector itself contains these isotopes, it is essential that the concentrations of the radioactive contaminations should be measured in order to determine their effects on the double beta decay measurement. Actually, we know that the serious background sources for the study of $\beta\beta$ decay with the CANDLES system are radioactive contaminations within CaF_2 crystals, because external backgrounds can be much reduced by the 4π active shield of the CANDLES

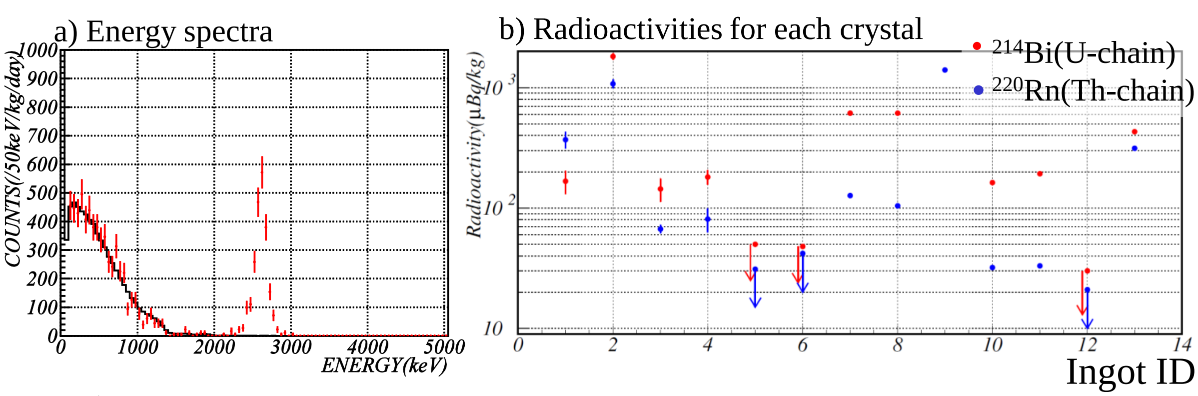

Figure 2: a)Typical energy spectra obtained by the delayed coincidence measurement. Closed circles and solid line show the the delayed events and chance-coincidence events, respectively. b)Distribution of radioactivities of each CaF_2 ingot. Red/blue circles show ^{214}Bi(U-chain) and ^{220}Rn(Th-chain), respectively. We selected 3 CaF_2 ingots to cut out the 14 CaF_2 scintillators for the CANDLES III system.

Table 1: A list of sample CaF_2 crystals from each ingot.

Ingot	Dimension	CaF_2 material	Size(kg)
ID 1	50×50×50 mm^3		
ID 2	50×50×50 mm^3		
ID 3	50×50×50 mm^3		
ID 4	50×50×50 mm^3	A	74.9
ID 5	50×50×50 mm^3	A	49.4
ID 6	50×50×50 mm^3	A	59.2
ID 7	50×50×50 mm^3	A	57.6
ID 8	50×50×50 mm^3	A	97.2
ID 9	50×50×50 mm^3	Recycle	64.0
ID 10	50×50×50 mm^3	A	82.0
ID 11	50×50×50 mm^3	A	50.0
ID 12	50×50×50 mm^3	A	90.1
ID 13	50×50×50 mm^3	Recycle	91.5

system. The remaining backgrounds are following processes:
(a) the pile-up events
$^{212}\mathrm{Bi} \xrightarrow[\beta]{} {}^{212}\mathrm{Po} \xrightarrow[\alpha]{} {}^{208}\mathrm{Pb}$ (Th-chain)
$^{214}\mathrm{Bi} \xrightarrow[\beta]{} {}^{214}\mathrm{Po} \xrightarrow[\alpha]{} {}^{210}\mathrm{Pb}$ (U-chain)
(b) ^{208}Tl events
$^{208}\mathrm{Tl} \xrightarrow[\beta]{} {}^{208}\mathrm{Pb}$(Th-chain)

The delayed coincidence method is a powerful tool for measuring the concentrations of radioactive contaminants. This method is especially effective when extracting successive decays with short half-lives. In the present work, the β-α delayed coincidence method was applied to extract the successive decay of the following processes:
(A) $^{214}\mathrm{Bi} \xrightarrow[\beta]{} {}^{214}\mathrm{Po}(T_{1/2} = 164\ \mu\mathrm{sec}) \xrightarrow[\alpha]{} {}^{210}\mathrm{Pb}$ (U-chain)
(B) $^{220}\mathrm{Rn} \xrightarrow[\alpha]{} {}^{216}\mathrm{Po}(T_{1/2} = 145\ \mathrm{msec}) \xrightarrow[\alpha]{} {}^{212}\mathrm{Pb}$ (Th-chain)
Since the ^{214}Po and ^{216}Po nuclei have short half-lives of 164 μsec and 145 msec, respectively, the delayed coincidence method effectively extracts the ^{214}Bi decay and the ^{220}Rn decay, which are prompt decays of ^{214}Po and ^{216}Po, from a huge number of background events. Figure 2 a) shows a typical energy spectrum of ^{214}Po events extracted by the delayed coincidence method. Background rate for ^{214}Po peak is almost 0 and sensitivities of the detector system for processes (A) and (B) are $\sim$ 50 μBq/kg with 5×5×5 cm^3 for 10 days measurement.

By using this method, we measured the radioactivities of 13 CaF_2 crystals in order to select high purity CaF_2 crystals. Each CaF_2 crystal was grown in the same manufacturer and we cut out 5 cm cube CaF_2 from the different ingots. These crystals are listed in table 1. Figure 2 b) shows radioactivities of U- and Th-chain for each crystal. From the results, we selected 3 CaF_2 ingots to cut out the 14 CaF_2 scintillators with 10 cm cube. As mentioned above, the new scintillators were installed in the CANDLES III system and measurement of the radioactivities within new CaF_2 scintillators was started at November, 2019. From a rough analysis, we found the radioactivities of the new 14 CaF_2 scintillators are less than 10 μBq/kg. This means we can estimate the radioactivities of the CaF_2 scintillators by the measurements of small parts from CaF_2 ingots, and the measurement by the detector system is effective for development of high purity crystals.

References

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[2] T. Iida et al., Journal of Physics : Conference Series, 718 (2016) 062026.

[3] S. Umehara et al., RCNP Annual Report 2018: Kamioka Double-Beta Decay Facility, http://www.rcnp.osaka-u.ac.jp/~annurep/2018/Highlights/2018_RCNP_Kamioka-ver2%20.pdf, 2018.

[4] T. Iga et al., presentation in JPS 2019 autumn meeting.