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

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. The CANDLES III system consists of 96 CaF_2 scintillators with total mass of 305 kg and liquid scintillator with total volume of 2 m^3[2]. The CaF_2 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.

By using the CANDLES III system, we performed a $0\nu\beta\beta$ measurement for 131 days with low background condition and analyzed the data in 2017. The criteria to select candidate events for $0\nu\beta\beta$ are given as follows.
(1) CaF_2 scintillator hit.
(2) The events are not ^{212}Bi$\rightarrow$ ^{212}Po events, which is due to radioactive contaminations inside the CaF_2 scintillators.
(3) No liquid scintillator hit.
(4) The events are not candidate of the ^{208}Tl events, which is also due to radioactive contaminations inside the CaF_2 scintillators.
(5) Position of the events are not in the liquid scintillator region.
Criteria (1) and (3) are applied by using the pulse-shape difference between the CaF_2(pure) and liquid scintillators. Criteria (2) and (4) are described in refs [3, 4]. Criterion (5) is effective for rejection of the background events which hit multiple CaF_2 scintillators. By these analyses, the obtained energy spectra are shown in figure 1 a). In the red spectrum in figure 1 a), we found no events in the $0\nu\beta\beta$ window of 4.17 - 4.48 MeV. From the spectrum, the current lower limit of half-life is 6.2×10^{22} year, which is the world record of the $0\nu\beta\beta$ half-life limit of ^{48}Ca.

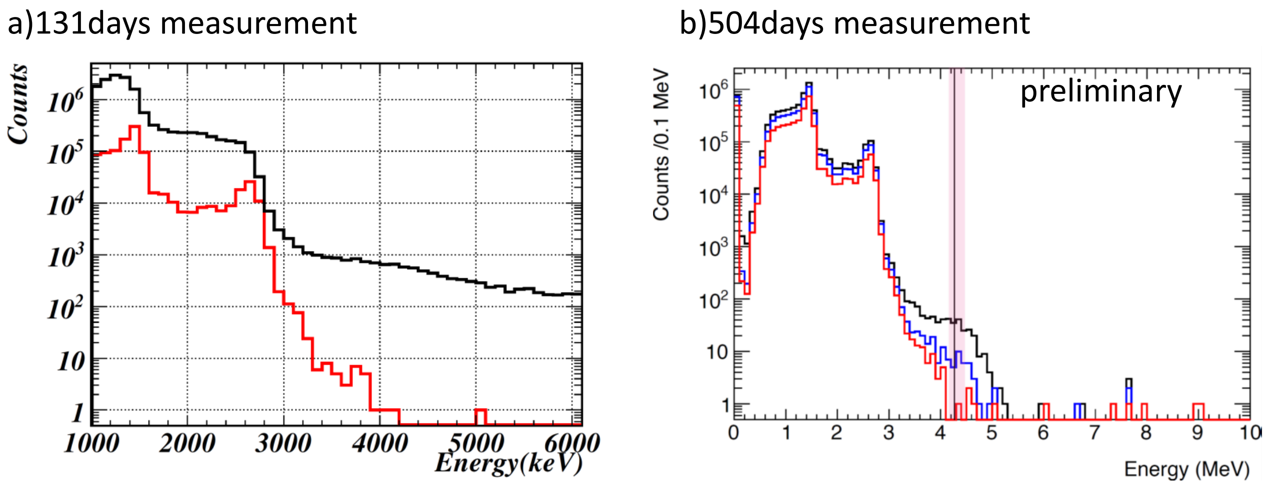

Figure 1: a) The obtained energy spectra with the event selections by using 27 CaF_2 scintillators. Details of the event selection are shown as criteria (1) $\sim$ (5) in text. Twenty-seven CaF_2 scintillators are selected as high purity scintillators. Measurement time is 131 days. After the event selections, there are no events in the $Q_{\beta\beta}$-value region. b) Energy spectra with the 504 days measurement. By rough analysis, we found that the background rate in $Q_{\beta\beta}$ region is proportional to the radioactivities of contaminations in CaF_2 crystals.

In 2018, we analyzed additional data for 373 days. Figure 1 b) shows the energy spectra obtained from high purity 21 CaF_2 scintillators. In figure 1 b), the lowest spectrum shows the result of the event selections by criteria (1) $\sim$ (5). As the result, we observed 1 event in the $0\nu\beta\beta$ window of 4.17 - 4.48 MeV with rough analysis. This event rate is consistent with the estimated background rate from the radioactivities of contaminations in the CaF_2 scintillators. 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.

Measurement of neutron flux at Kamioka underground laboratory

Environmental neutron is one of background origins for measurements of rare nuclear processes such as double beta decay measurement, dark matter search at underground laboratory, even if neutron flux at the underground laboratory is two order of the magnitude smaller than one at sea level laboratories. In fact, in the CANDLES system for the double beta decay measurement, high energy γ-rays from (n, γ) reaction were found to be the most serious backgrounds[5]. Thus we have to know the neutron flux at the laboratory in order to estimate the background rate.

Many measurements of the environmental neutron flux have been carried out in underground laboratories. The neutron flux in the Kamioka underground laboratory was measured in 2004[6] by using a ^{3}He proportional counter, which is sensitive to thermal neutrons. However an energy spectrum was not considered in this measurement, because the energy spectrum of neutrons is not directly measured by ^{3}He proportional counters.

In order to estimate the energy spectrum of neutrons, we performed the neutron flux measurements with different detector setups and simulated the energy spectrum of environmental neutron. Figure 2 shows detector setups of our measurements without/with a polyethylene moderator and ^{10}B sheets. Setups A and B are mainly sensitive to thermal and fast neutrons, respectively. Figure 3 a) shows the obtained energy spectrum from the measurement with setup B. In this spectrum, events in low energy region less than 0.5 MeV are due to electrical noise. Thus we obtained event rates from the region between 0.5 MeV and 0.85 MeV. Table 1 shows the event rates with setups A/B.

Next we consider the natural sources of environmental neutrons by using Monte Carlo simulation to estimate the shape of the neutron energy spectrum. One of the natural sources was spontaneous ^{238}U fission. The other source was assumed (α, n) reactions of the ^{238}U and ^{232}Th series, which were contained in the wall rock. In order to measure chemical composition of the wall rock, X-ray fluorescence (XRF) was used. By using the chemical composition and radioactivities of the ^{238}U and ^{232}Th series, the energy spectra for spontaneous ^{238}U fission and for the (α, n) reactions of the U series are obtained as shown in figure 3 of reference [7]. The energy spectra are not yet realistic, since moderators such as hydrogen in the rock have not been taken into account. XRF, however, is not sensitive to hydrogen. Thus the percentage of hydrogen needs to be experimentally determined by using the ratio of the count rates with setups A and B (R_A/R_B). R_A/R_B from the experimental data R_A and R_B, which are shown in table 1, is $2.90 \pm 0.14\ ^{+0.04}_{-0.03}$. On the other hand, simulated R_A/R_B values with 0, 3, and 6% addition of hydrogen were obtained to be 1.15, 2.91, and 3.29, respectively. In this way, there is a large difference between R_A/R_B values with 0, 3, and 6% addition of hydrogen. Therefore, it can be determined by comparing the measured and simulated R_A/R_B.

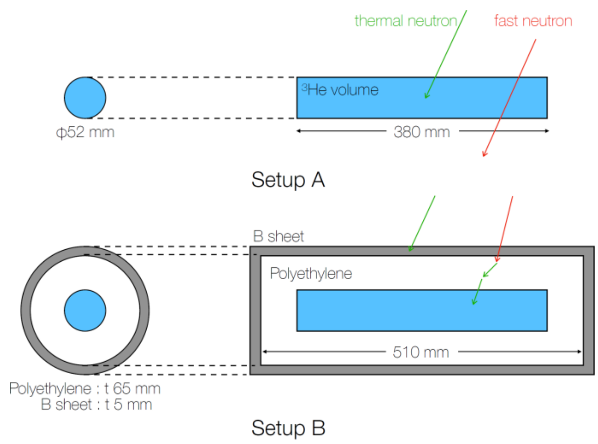

Figure 2: The experimental setups for the neutron measurements. In setup B, a polyethylene moderator and ^{10}B sheets are installed. By the moderator and ^{10}B sheets, setup B is mainly sensitive to fast neutrons.

Table 1: Count rates obtained with setup A/B.

Setup	Rate $\pm stat. \pm sys.$ (10^{-3}cps)
Count rate R_A (setup A)	$1.295 \pm 0.034^{+0.039}_{-0.033}$
Count rate R_B (setup B)	$0.446 \pm 0.018^{+0.013}_{-0.011}$

Figure 3 b) shows three spectra of environment neutrons produced by (α, n) reactions and the spontaneous fission at the Kamioka Observatory. In this figure, the rock sample was assumed to include 2%∼4% addition of hydrogen. However the differences between the three spectra are unrecognizable. This means that the neutron spectrum is not affected by the percentage of hydrogen. From this measurements and simulations, we obtained the neutron flux and energy spectrum. Obtained total neutron flux is $(23.5 \pm 0.7_{stat.} \, {}^{+1.9}_{-2.1} \, {}_{syst.}) \times 10^{-6}$ cm^{-2} s^{-1}. Details of the measurements and analyses are shown in reference [7]. These results can help to estimate the background rate in measurements of search for the nuclear rare processes.

References

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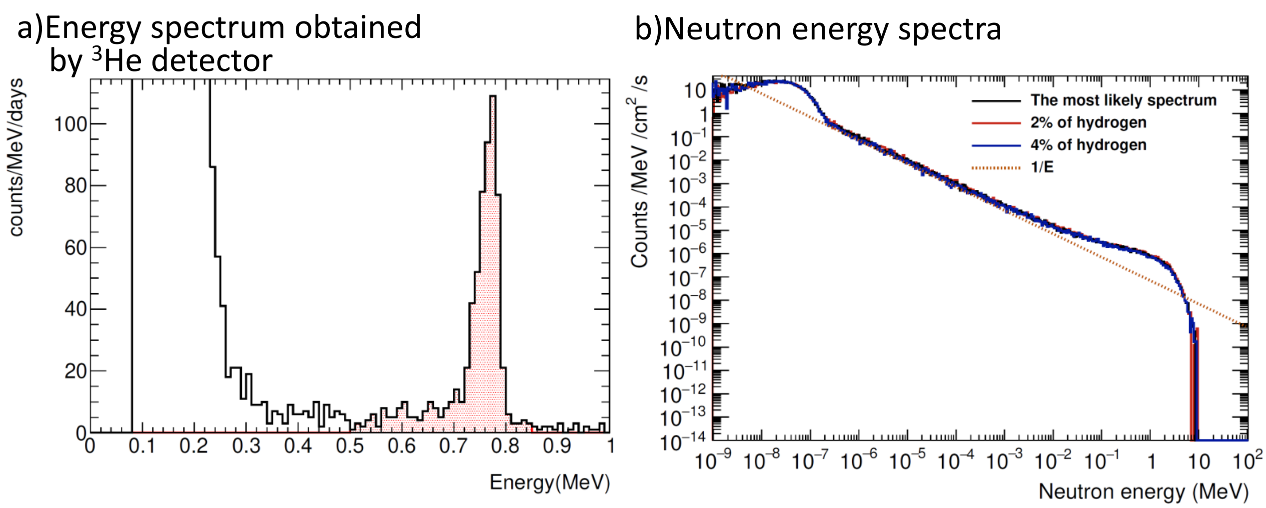

Figure 3: a) The energy spectrum of the ^{3}He detector. This is obtained from the measurement with setup B. b) The energy spectra estimated from ^{3}He measurements and assumption of the natural neutron sources. Three spectra of environment neutrons were produced by simulating of (α, n) reactions and the spontaneous fission at the Kamioka Observatory.