PROCEEDINGS OF SCIENCE

# Demonstration of Tl-208 background reduction using topological information of Cherenkov light and observation of Zr-96 two neutrino double beta decay

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An experiment has been planned to measure the half-life of double beta decay with two-neutrino emission for $^{96}$Zr nuclei. A newly designed $2\nu$-ZICOS detector will observe about 100 events of $^{96}$Zr double beta decay. The detector will use an ultra-pure quartz flask and 20 Hamamatsu H3378-50 photomultipliers in order to distinguish the signal shape of Cherenkov lights. The liquid scintillator containing 0.4 g of $^{96}$Zr will be filled in the ETFE cubic bag. The transparency of 50 $\mu$m thickness ETFE sheet for scintillation light was 97.5% at minimum. The constructions of a radiation shield using Pb blocks and the setup of $2\nu$-ZICOS detector will start in May 2024 at LAB-A in Kamioka mine, and the observation will start in next summer or autumn at the latest.

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## 1. $2\nu$-ZICOS experiment

ZICOS is one of the future experiments for $0\nu\beta\beta$. The target nuclei is $^{96}$Zr and the Q-value is 3.35 MeV, therefore the radioactive backgrounds such as $^{214}$Bi in Uranium series and $^{10}$C, which is spallation product of energetic cosmic muons, could be removed by their lower energy. The detector consists of spherical frame mounted by photomultipliers (PMTs), inner balloon filled with 113 tonnes of liquid scintillator containing tetrakis(isopropyl acetoacetato)zirconium ($Zr(iPrac)_4$), and pure Anisole for outside of the inner balloon. Therefore it has a structure almost similar to the KamLAND-Zen detector. As reported by KamLAND-Zen [1], non-negligible backgrounds were found around 3 - 4 MeV, and those were the decay products from $^{208}$Tl which was adhere on the surface of inner balloon. Those backgrounds are serious for ZICOS experiment, because of the overlap with Region of Interest for $0\nu\beta\beta$ of $^{96}$Zr. In order to obtain half-life of order $10^{27}$ to $10^{28}$ years, we have to enrich $^{96}$Zr to be 20 - 50% and reduce 95% of $^{208}$Tl background as observed in KamLAND-Zen. Those background events could be removed by the averaged angle which is topological information of Cherenkov lights as discussed in our previous papers [2].

We expect that 200 events of $2\nu\beta\beta$ using an order of 1 g for $^{96}$Zr nuclei. For the purpose, we are designing $2\nu$-ZICOS detector as shown in the left side panel of Fig. 1. This detector uses 16 cm diameter round bottom flask using an ultra-pure quartz (GE214) which has been produced by Asahi Glassplant inc., and 20 low-background fast rise-time 2 inch PMT Hamamatsu H3378-50, which will be used for pulse shape discrimination of Cherenkov lights, are mounted by the designed jig on the flask. A liter of liquid scintillator loaded 100 g of $Zr(iPrac)_4$, which will contain about 0.4 g of $^{96}$Zr, will be filled inside of inner bag. The expected number of signals from $2\nu\beta\beta$ is about 100 events per year among about 1 million background events. This detector will be located at LAB-A in Kamioka mine.

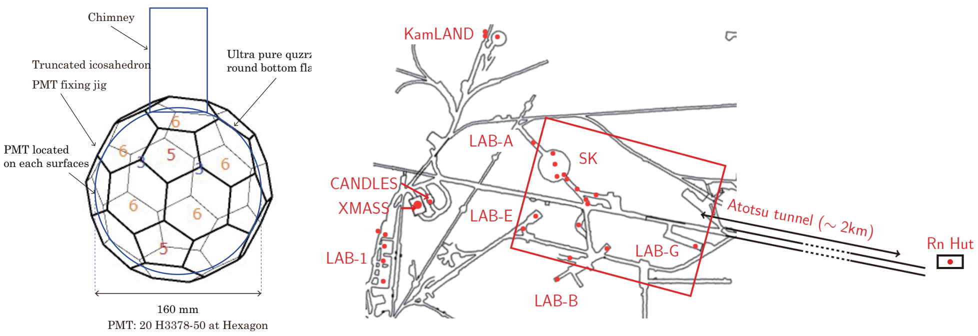


**Figure 1:** The left side panel shows the designed $2\nu$-ZICOS detector. The ultra-pure quartz round bottom flask and 20 Hamamatsu H3378-50 photomultipliers will be used for the observation of scintillation lights. The right side panel shows the map of underground laboratory in Kamioka mine.

The right panel of Fig. 1 shows the underground laboratory in Kamioka mine. LAB-A is just behind of LINAC control room, where locates beside of Super-Kamiokande detector. We will install our clean booth (class 1000) here and the radiation shields using these Pb blocks will be prepared. Inside this shield, we will construct $2\nu$-ZICOS detector in the early fiscal year 2024.

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## 2. U/Th contamination and simulation

The contamination of Uranium and Thorium for the ultra-pure quartz, Zr(iPrac)$_4$, and Zirconium tetrachloride ($ZrCl_4$), which is a material of zirconium complex, were measured by the ICP mass spectrometer. We found that most serious backgrounds come from quartz itself. The amounts are 15 ppb for Thorium and 29 ppb for Uranium, respectively. Those amounts correspond to $6 \times 10^{-5}$ Bq/g for Thorium, and $4 \times 10^{-4}$ Bq/g for Uranium. Assuming the radiation perpetual equilibrium, the expected number of background events from the quartz are 1 million events for $^{208}$Tl decay and 6 million events for $^{214}$Bi decay per year, respectively.

Assuming those amounts, the energy distribution of each background events and expected signals from $2\nu\beta\beta$ are simulated by Monte Carlo as shown in left panels of Fig. 2. Top, middle, and bottom panels of show the case of $^{208}$Tl, $^{214}$Bi, and $^{40}$K, respectively. The solid line, dashed line, and dotted line show all events, events after fiducial volume cut which means the vertex position within 5 cm from center of the detector, and events after averaged angle cut which means the angle greater than 60 degree, respectively. The hatched spectrum indicated $2\nu\beta\beta$ signal. According to these figures, $^{40}$K affects only a part of double beta decay signal. $^{214}$Bi is significant background, but a small fraction of $2\nu\beta\beta$ signal should be observed after the fiducial volume cut and the averaged angle cut. However, $^{208}$Tl is the most dangerous for the detection of $2\nu\beta\beta$ even after those cuts. Only a few events for $2\nu\beta\beta$ might be observed. In this simulation, we used cubic bag for storing scintillator as described in next section.

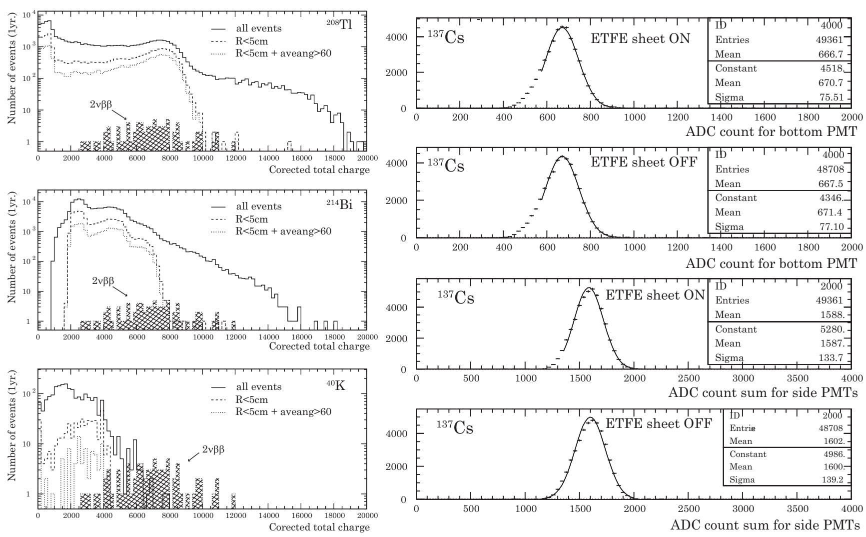


**Figure 2:** The left side figures show the energy distributions for background events and expected signals from $2\nu\beta\beta$ are simulated by Monte Carlo. Top, middle, and bottom panels show the case of $^{208}$Tl, $^{214}$Bi, and $^{40}$K, respectively. The solid, dashed, and dotted lines show all events, events after fiducial volume cut, and events after averaged angle cut, respectively. The hatched spectrum indicated $^{96}$Zr $2\nu\beta\beta$ signals. The right side figures show the charge distribution of photo peak for bottom PMT and side PMTs with of without the ETFE sheet using $^{137}$Cs 662 keV gamma.

## 3. Current status

The clean booth (class 1000) was constructed in the Laboratory of Miyagi University of Education for a preparation of the liquid scintillator and a mock up of $2\nu$-ZICOS detector. 200 g of Zr(iPrac)$_4$ has been synthesized by NARD institute, Ltd., and it is stored in the dry box located inside of the clean booth. The glove box with $N_2$ gas circulation for the preparation of liquid scintillator has been also installed. 12 Hamamatsu H3378-50 PMTs have been already arrived in last year, and stored in the clean booth. Remaining 8 PMTs were just delivered in September 2023.

The special made round bottom flask is also stored in the clean booth. Both PMT mounting jig and the inner bag for storing liquid scintillator are producing now. We used the ETFE transparent sheet (50 $\mu$m thickness) for inner cubic bag to store liquid scintillator. Outside of inner bag, pure Anisole will be filled in the detector. The ETFE is a kind of Fluoro resin against Anisole erosion, and no damage due to Anisole erosion was found in one month test.

The transparency of the ETFE sheet was directly measured by the scintillation lights from liquid scintillator. Using photon peak of the radio-active isotope $^{137}$Cs with or without the ETFE sheet, the transparency could be calculated the ratio of peak position using the side PMT. For the consistency check, we measured photon peak using the bottom PMT which has no ETFE sheet. The right panels of Fig. 2 show the energy spectra measured by $^{137}$Cs. The top two figures show in case of no ETFE sheet, and the bottom two figures shows in case of ETFE sheet on and off. The ratio of peak position is $1.0015 \pm 0.0018$ for bottom PMT and it is consistent with 1.0 within the statistical error. On the other hand, the ratio of peak position for the case with and without the ETFE sheet for side three PMTs was obtained by $0.9768 \pm 0.0014$, and only 2.5% light yield loss should be expected at maximum due to the ETFE sheet.

## 4. Future plan

The preparation of 1 little of ZICOS liquid scintillator has started in November 2023. The radiation shield using Pb blocks with the falling prevent wall is now designed. The inner size will be 80 cm cubic. The proto-type ETFE cubic bag has been produced by Taiyo Kogyo Corporation. Mock up for PMT mounting jig with flask will be done in the February 2024. After that, the installation of inner bag and introducing the liquid scintillator into the bag will be tested by using the ultra-pure water, not a scintillator in order to avoid the risk. The construction of the Pb shield and the setup of $2\nu$-ZICOS detector will start in May 2024 at LAB-A, and the observation will start in next summer or autumn at the latest.

## References

[1] A.Gando *et al.* (KamLAND-Zen Collaboration), Physical Review Letters **117** (2016) 082503.

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