ZICOS - Neutrinoless Double Beta Decay experiment using Zr-96 with an organic liquid scintillator -

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Abstract. A liquid scintillator containing a tetrakis(isopropyl acetoacetato)zirconium has been developed for ZICOS experiment. In order to reach the sensitivity $T_{1/2}^{0
\nu} \geq 10^{27}$ years, we have to use tone scale of $^{96}$Zr and have to reduce 95% of backgrounds from $^{208}$Tl decay, which should be major backgrounds observed around Q-value (3.35 MeV) of $^{96}$Zr neutrinoless double beta decay. According to the Monte Carlo simulation, we demonstrated that new method using the topological information of Cherenkov light could reduce 93% of $^{208}$Tl background with 78% efficiency for $0\nu$ signal. For an identification of Cherenkov light, the precise spectral pulse shape from both Cherenkov and scintillation was directly measured by using sub-MeV electrons from $^{90}$Sr/$^{90}$Y beta source. The observed pulse rise and fall (decay) time for Cherenkov light were 0.8 ns and 2.5 ns, respectively. They were actually shorter than those times of scintillation light which were also measured by 1.6 ns and 6.5 ns, respectively. This clear difference of rise time will be used for the pulse shape discrimination in order to select photomultiplier tube which receives Cherenkov lights, and the topological information of Cherenkov light will be used for the reduction of backgrounds from $^{208}$Tl decay.

1. ZICOS experiment

ZICOS is one of the future experiment for neutrinoless double beta decay. 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 conceptional design of ZICOS detector is shown in the left side and the center of Fig.1. The detector consists of spherical container mounted by 650 of 20 inch photomultiplier tube (PMT) and inner balloon filled with a liquid scintillator, therefore it is almost similar structure as KamLAND-Zen detector. As reported by KamLAND-Zen[1], non-negligible events were found around 3 - 4 MeV, and those were the decay products from $^{208}$Tl which was adhere
on the surface of inner balloon. Fortunately the Q-value of $^{136}$Xe is 2.479 MeV so that those were not backgrounds due to out of range for signal region.

However those events should be quite serious backgrounds for ZICOS experiment. The ZICOS detector will use liquid scintillator containing a tetrakis(isopropyl acetoacetato)zirconium ($\text{Zr}(\text{iPrac})_4$) inside of inner balloon, and will use pure water for outside of inner balloon as shown in the left side of Fig.1. Therefore almost half of $^{208}$Tl events observed in KamLAND-Zen should be reduced by missing their energy, but the another half will be unavoidable backgrounds for $^{96}$Zr $0\nu\beta\beta$ signal. In order to reach the sensitivity $T^{0\nu}_{1/2} \geq 2 \times 10^{27}$ years, we have been developed the reduction technique using a topological information of Cherenkov light [2].

Figure 1. The conceptual design of ZICOS detector, and the expected averaged angle distribution for $0\nu\beta\beta$ signal and $^{208}$Tl background obtained by EGS4 simulation.

2. Background reduction using topological information of Cherenkov light

As described in our previous papers [3] [4], there is a difference of hit pattern of Cherenkov lights between $^{208}$Tl backgrounds and $0\nu\beta\beta$ signals in case of Monte Carlo simulation, and we could reduce about 93% of $^{208}$Tl beta decay events with 78% efficiency for $0\nu\beta\beta$ events using an adequate topological information (defined by averaged angle) from Cherenkov light as shown in the right panel of Fig.1.

ZICOS detector also should measure the energy as precise as possible in order to reduce background from $2\nu\beta\beta$ signals, so that we have to observe scintillation lights for the precise energy measurement. Therefore it is necessary to extract the hit PMT by Cherenkov light among the large yield of scintillation. In this points of view, we have to discriminate PMT whether including Cherenkov light or not using the pulse shape. Generally speaking, Cherenkov radiation is generated by the vibration of an electromagnetic dipole moment, so that the timing spreads during passing time of the charged particle (a few 100 pico seconds). On the other hand, scintillation is the radiation from transition between the exited state and lower state of scintillator molecule, therefore the timing should be decided by nuclear property with a few tenth of nano seconds. This difference of spectral shape at both rise and decay time could be observed. In particular, the difference of rise time should be important because of poor amount of photon from Cherenkov light.

3. Pulse shape of Cherenkov light and Scintillation using sub-MeV electrons

In order to observe the rise time of pulse shape precisely, we introduced two equipments. One is photomultiplier which should have a fast timing response for both rise time and transit time spread (TTS). The another is FADC digitizer which has a fast timing resolution. We used PMT Hamamatsu H2431-50 (R2083) and CAEN V1721 digitizer for this measurement. They would separate the shape of rise time between Cherenkov light and scintillation clearly.
We used 1 MBq $^{90}$Sr (half life 28.79 year) for sub-MeV electrons source. The end point energy of electrons from $^{90}$Sr is 0.546 MeV so that all electrons could not emit Cherenkov light because of under Cherenkov threshold. On the other hand, $^{90}$Y (half life 64 hour) beta decay should be a radioactive equilibrium, then same radiation yield could be expected. The end point energy of electrons from $^{90}$Y is 2.280 MeV, so that about half of electrons could emit Cherenkov lights. Using electrons above 0.679 MeV, we measured the pulse shape for Cherenkov light.

![Figure 2. The setup for measurement of pulse shape for Cherenkov light and scintillation using $^{90}$Sr beta source, and obtained each pulse shape (scaled by same height)](image)

The left side and the center of Fig.2 show the setup for this measurement. The incident electrons were collimated by Lead block and the direction was fixed by 20 degree with respect to the direction of PMT, because it is easy to induce Cherenkov photon to the PMT. The vial was filled with only Anisole for the measurement of Cherenkov light, and it was covered by SC-37 filter in order to observe Cherenkov photons only above 400 nm. For real experiment, Cherenkov photons below 400 nm should be absorbed by the secondary scintillator such as PPO, therefore only Cherenkov photons above 400 nm should be observed. For the measurement of scintillation, this setup was same except the vial filled with ZICOS liquid scintillator, even though Cherenkov photon was also induced to PMT, because of large amount of scintillation light yield.

In order to obtain the spectral shape scintillation, we have to collect signal events and have to make a distribution of FADC counts for each timing bin. Because of high statistics of scintillation, we could easily select events with almost same pulse height, and no background subtraction was done. For the measurement of the pulse shape from Cherenkov light, we have selected events with almost same pulse height for both signal and noise due to the environmental backgrounds. Again the distribution of FADC counts for each timing in case of Cherenkov light were obtained by subtracting the distribution for noise. Using mean and RMS for each timing, we made averaged pulse shape of both scintillation and Cherenkov light.

The right panel of Fig.2 shows the averaged pulse shape for scintillation and Cherenkov light, respectively. In this figure, the shape of Cherenkov light was scaled by same peak height as scintillation. The observed Cherenkov pulse shape was clearly different from the shape of scintillation. The pulse rise and fall (decay) time for Cherenkov light were 0.8 ns and 2.5 ns, respectively. They were actually shorter than those times of scintillation light which were also measured by 1.6 ns and 6.5 ns, respectively. This clear difference of rise time will be used for the pulse shape discrimination in order to select PMT which receives Cherenkov lights, and the topological information such as an averaged angle which was described in our previous paper [3] will be used for the reduction of backgrounds from $^{208}$Tl decay.

4. Direct measurement of topological information using beta-gamma events

For the measurement of such a topological information of single electron, an averaged angle will be measured by HUNI-ZICOS detector, which has 5 cm diameter Hemispherical container with 28 Hamamatsu H3146-12 3/8 inch PMTs, using monochromatic energy and fixed directional Compton electrons scattered by gamma from $^{60}$Co as shown in the left side of Fig.3. This
plan has been already funded and will start in next fiscal year. In order to demonstrate the background rejection using an averaged angle, we have to measure it directly using real beta-gamma events emitted from the radioactive nucleus such as $^{60}$Co, because of $^{208}$Tl beta decay with gamma emission. For 99.88% of $^{60}$Co decay, the beta should have a maximum energy of 0.31 MeV and the excited state of $^{60}$Ni decays with emission of two gammas with an energy of 1.17 and 1.33 MeV. Moreover the residual 0.12% of $^{60}$Co emits beta with maximum energy of 1.48 MeV and single 1.33 MeV gamma. Using latter events, we can measure the averaged angle of Cherenkov light emitted from both beta and gamma. The center of Fig.3 shows the conceptual design of UNI-ZICOS detector which will have 5 cm diameter spherical container with 48 H3146-12 PMTs. The 10 kBq $^{60}$Co beta source will be located at the edge of detector. In order to observe latter events, a thin aluminum plate (t=0.03cm) will be sorted between $^{60}$Co source and Si APD. A trigger from this APD makes us possible to observe Cherenkov light from both beta and gamma. According to the simulation of UNI-ZICOS, the averaged angle distribution for each single electron and $^{60}$Co beta-gamma event will be obtained as shown in the right panel of Fig.3, respectively. Those shapes are quite different from each other, so that we can verify that an averaged angle will be used for the background reduction of $^{208}$Tl decay.

Figure 3. The conceptual design of HUNI-ZICOS (left) and UNI-ZICOS (center) detector. The expected averaged angle distributions from $^{60}$Co source are also shown in the right panel.

5. Conclusion
Using sub-MeV electron from $^{90}$Sr/$^{90}$Y beta source, we successfully measured the actual pulse shapes of Cherenkov light. The measured pulse rise and decay time for Cherenkov light were actually shorter than those times of scintillation. Using this feature, we will develop the pulse shape discrimination in order to distinguish PMT whether receives Cherenkov light or not within this fiscal year. Also we are going to measure the topological information such as an averaged angle of single electron using HUNI-ZICOS detector in the next fiscal year. Furthermore we will try to measure an averaged angle for beta-gamma events from $^{60}$Co beta source in order to verify the effective reduction of $^{208}$Tl backgrounds. After the confirmation, we will start the physics program using proto-type ZICOS detector, which has 35cm radius container with 300 H2431-50 PMTs, filled with 180 L of ZICOS liquid scintillator containing 80 g of natural $^{96}$Zr in order to measure the half life of 2$\nu \beta \beta$ and to update NEMO3 limits of 0$\nu \beta \beta$.

References
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