Precise pulse shape measurement of Cherenkov light using sub-MeV electrons from Sr-90/Y-90 beta source

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Abstract

The precise spectral pulse shape from Cherenkov lights was directly measured by using sub-MeV electrons from ^{90}Sr/^{90}Y beta source. The observed shape was clearly different from the shape of scintillation light. 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 PMTs which receive Cherenkov lights, and the topological information due to Cherenkov light will be used for the reduction of backgrounds from ^{208}Tl beta decay which should be major backgrounds observed around Q-value (3.35MeV) of ^{96}Zr neutrinoless double beta decay.

Key words： Neutrinoless Double Beta Decay（ニュートリノを放出しない二重ベータ崩壊）
Liquid Scintillator（液体シンチレータ）
Cherenkov Light（チェレンコフ光）
Pulse Shape Discrimination（波形分別法）
Topological Information（位相幾何学情報）

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1. ZICOS experiment

ZICOS is one of the future experiments for neutrinoless double beta decay. The target nuclei is ^{96}Zr and the Q-value is 3.35MeV, 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 Fig.1. The detector consists of spherical frame mounted by 650 of 20 inch photomultiplier (PMT) and inner balloon filled with a liquid scintillator, therefore it is almost similar structure as KamLAND-Zen detector. As reported by KamLAND-Zen[2], 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 2.479MeV so that those were not major 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 $\mathrm{Zr(iPrac)_4}$ inside of inner balloon, and will use pure water for outside of inner balloon. Therefore almost half of ^{208}Tl events observed in KamLAND-Zen should be reduced by missing the energy. However, another half will be unavoidable backgrounds for ^{96}Zr $0\nu\beta\beta$ signal. In order to remove those backgrounds to reach the sensitivity $T^{0\nu}_{1/2} \geq 2 \times 10^{27}$ years, we have been developed the reduction technique using topological information from Cherenkov light [1].

2. Discrimination of Cherenkov light using pulse shape

As described in our previous paper [3], 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.

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 hitted 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. 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 hands, scintillation is the radiation from transition between the exited state and lower state of scintillator atoms, 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.

The possible pulse shape of Cherenkov lights using both 1MeV electron and cosmic muons were reported by our previous paper[3] and [4], and it actually had a shorter decay time than scintillation. At that time, however, we could not confirm that the difference of rise time was observed, because of loose timing resolution of our FADC digitizer.

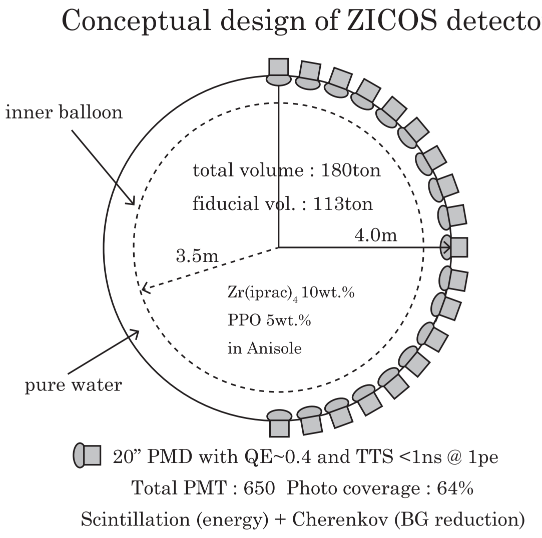

Figure 1. The conceptional design of ZICOS detector. The inner detector is located in pure water tank, and has 650 of 20 inch photomultiplier with 64 % photocoverage. The inner balloon will be filled with a liquid scintillator which contains 10 wt.% of $Zr(iPrac)_4$ and 5 wt.% of PPO. The outside of the inner balloon will be filled with an ultra pure water in order to reduce ^{208}Tl decay backgrounds.

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

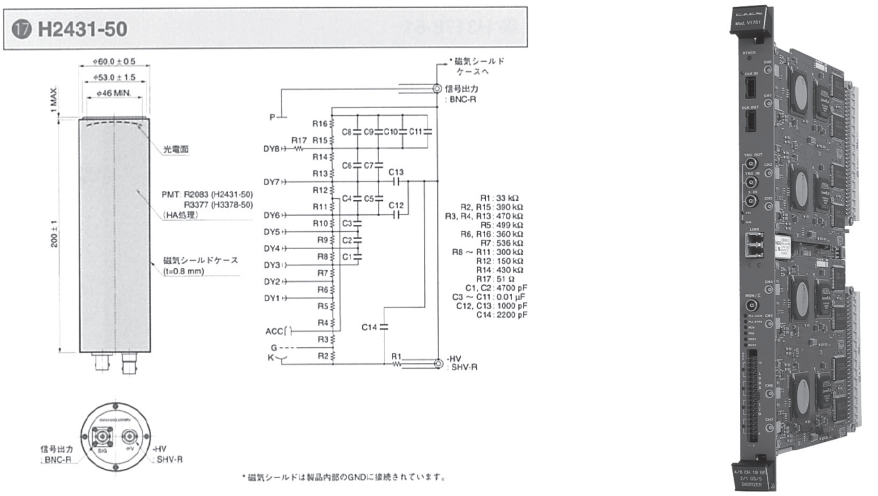

Figure 2. Left panel shows the dimensional outline and circuit diagrams for Hamamatsu H2431-50 photomultiplier[5]. The rise time and time transit spread (TTS) is 0.7 ns and 0.37 ns, respectively. Right photograph shows V1751 FADC digitizer [6]. In this paper, we used 1 GS/s ADC for scan sampling which corresponds to 1 ns for 1bin.

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). So far we have used Hamamatsu H6410 (R329) which has 400K for spectral response, 12 linear focused dinodes for R structure, 2000 V for high voltage, 3.0×10^6 for gain, 10 nA for dark currents, and 2.7 ns and 1.1 ns for rise time and TTS, respectively. On the other hands, in this time, we chose Hamamatsu H2431-50 (R2083) and it has same spectral response, 8 linear focused dinodes for the structure, 3000 V for high voltage, 2.5×10^6 for gain, 100 nA for dark currents. and 0.7 ns and 0.37 ns for rise time and TTS, respectively.

Another is FADC digitizer. We have used CAEN V1721 digitizer, which has 8 channel, 8 bit 500 MS/s ADC, and 2 MS/ch maximum for memory buffer, respectively. This means that one time bin corresponds to 2 ns. In this time, we have borrowed CAEN V1751 digitizer from XMASS experiment. This digitizer has 4/8 channel, 10 bit 2 GS/s (interleaved) 1 GS/s ADC, 14.4 MS/ch (28.8 MS/ch for 2 GS/S) maximum for memory buffer, respectively. One time bin corresponds to 1 ns for 1 GS/s and 0.5 ns for 2 GS/s. In this paper, we used 1 GS/s ADC for Zero Length Encording (DPP-ZLEplus) which was default firmware for XMASS experiment. These two fast timing spectral measurement 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 as shown in left panel of Fig.3. Using electrons above 0.679 MeV, we measured the pulse shape for Cherenkov light.

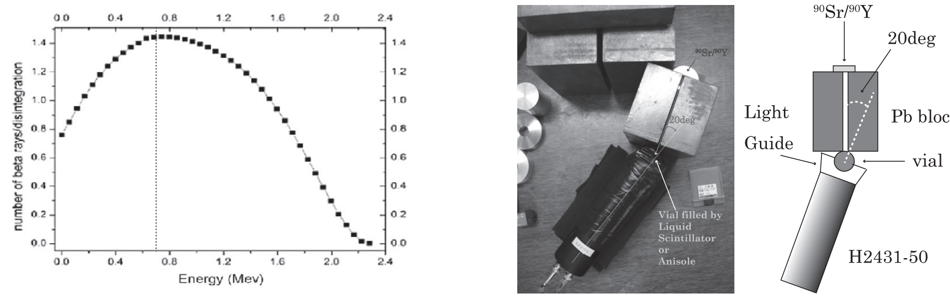

Figure 3. Left panel shows an energy spectrum of ^{90}Y beta decay [7]. End point energy is 2.280 MeV so that all electrons whose energy above 0.679 MeV could emit Cherenkov light. Middle photograph and right figure show the setup for pulse shape measurement. The ^{90}Sr/^{90}Y source was located behind the Lead block shield which was used for colimater. The incident electrons were selected by the colimater and the direction was fixed by 20 degree with respect to the direction of PMT.

Middle photograph and right figure of Fig.3 show the setup for this measurement. The incident electrons were colimated 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. For the measurement of scintillation, this setup was same even though Cherenkov photon was induced to PMT, because of large amount of light yield of scintillation.

4. Averaged Pulse shape of Cherenkov light and Scintillation

In order to obtain the spectral shape, we have to collect signal events and have to make a distribution of FADC counts for each timing bin.Of course, same distribution for backgrounds in case of no source should be subtracted in each timing bin.

At first, we have to define the summed FADC counts, which is treated as light yield. We summed FADC counts between timing 57 ns and 80 ns in case of the peak at 60 ns always. Left top panel of Fig.4 shows that summed FADC counts distribution for scintillation in case of on-source and off-source. No source events came from environmental backgrounds detected by liquid scintillator. We selected events with summed FADC counts between 650 and 750 for making an averaged pulse shape because of height statistics and almost same pulse shape. Actually left bottom figures of Fig.4 show some sample waveform of those selected events.

Right panel of Fig.4 shows that FADC count distribution for each timing for selected events. For making averaged pulse shape for scintillation, we took mean and RMS for each distribution.

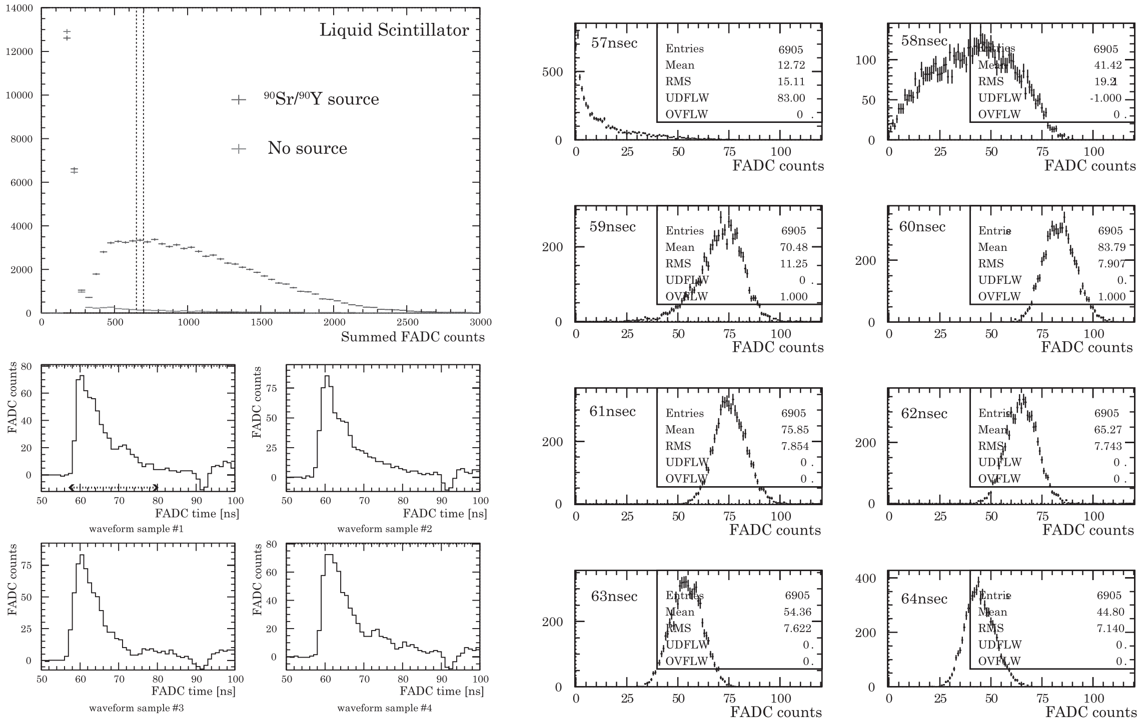

Figure 4. Left top panel shows the summed FADC counts distribution for scintillation. Dotted line corresponds to lower and upper bound of event selection for the making averaged pulse shape. Left bottom figures shows sample waveform for selected events. Right panels shown FADC count distribution for each timing. Taking mean and RMS value, an averaged pulse shape for scintillation is shown in Fig.6.

Next we measured the pulse shape from Cherenkov light. In this time, the vial which was filled with only Anisole 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 photons above 400 nm should be observed.

Top left panel of Fig.5 shows whole distribution of summed FADC counts for Cherenkov light. Due to environmental backgrounds, we have selected events with summed FADC counts between 250 and 300 for signal and background as shown in top right panel of Fig.5. Left bottom figures of Fig.5 shows some sample waveform for selected events. As shown in right figures of Fig.5, again FADC count distribution for each timing in case of Cherenkov light, and those distributions were obtained by subtracting the distribution from no source. In this case, we have to evaluate the spectrum separately for fast and slow component. For instance, according to the distribution of timing 62 ns in right panels of Fig.5, the distribution looks have two structures around FADC counts 27. If we select events in case of greater than 27 and less than 27 at timing 62 ns, then FADC count distributions were separated as shown in right 2 figures as fast and slow component at each timing. This is because that the time resolution (1ns) was wider than the rise time of Cherenkov light. Using mean and RMS for each distribution, we made averaged pulse shape of Cherenkov light for fast and slow component, respectively.

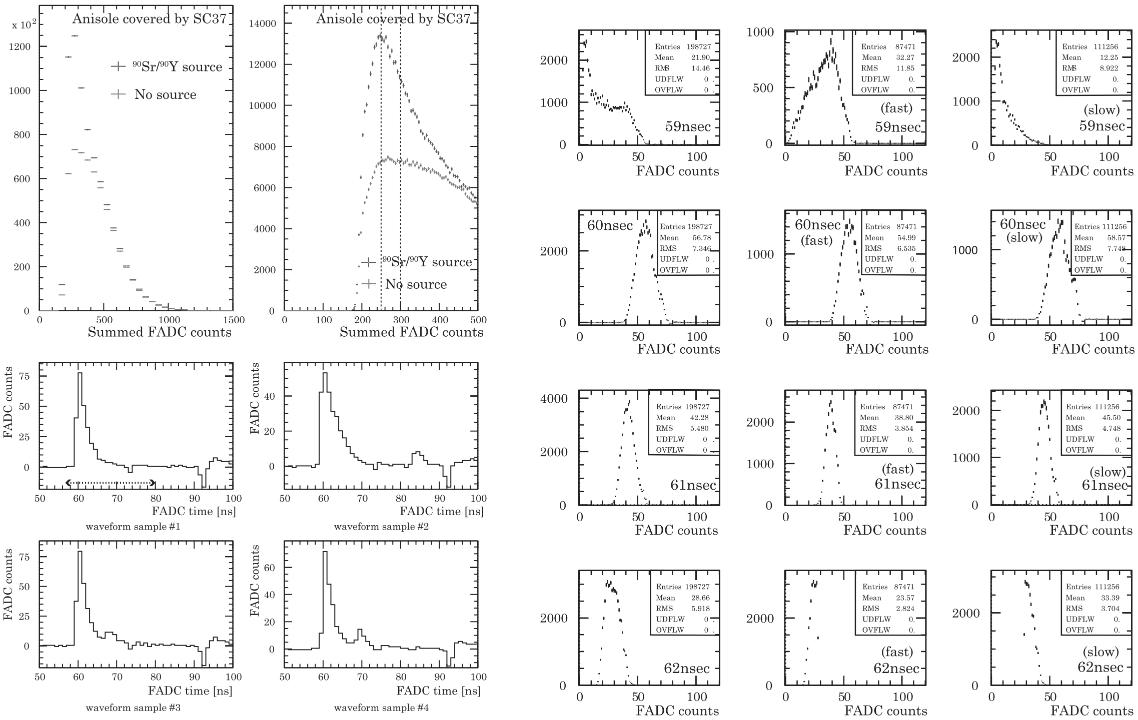

Figure 5. Left top panels show the summed FADC counts distribution for Cherenkov light. Dotted line corresponds to lower and upper bound of event selection for the making averaged pulse shape. Left bottom figures shows sample waveform for selected events. Right panels shown FADC count distribution for each timing. In this case, events were separately selected as fast and slow component. Using mean and RMS value of each timing, an averaged pulse shape for Cherenkov light as shown in Fig.6.

Figure 6 shows the averaged pulse shape for scintillation and Cherenkov light, respectively. Left and right panel of Fig.6 show fast and slow component, respectively. In this figure, the shape of Cherenkov light was scaled to 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 receive Cherenkov lights, and the topological information such as averaged angle which was described in our previous paper [3] will be used for the reduction 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.

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

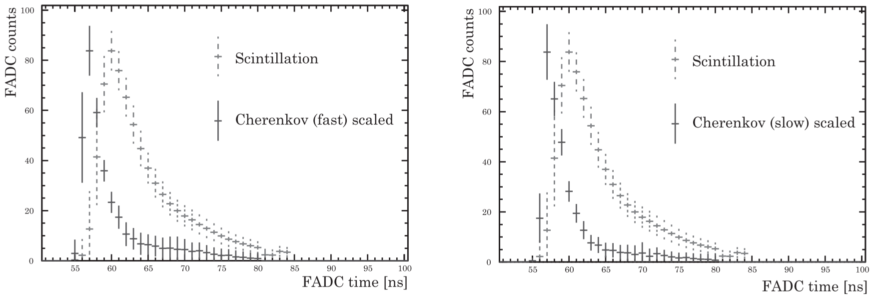

Figure 6. The averaged pulse shape for scintillation and Cherenkov light. Left and right panel show fast and slow component, respectively. In this figure, the shape of Cherenkov light was scaled to same peak height as scintillation.

actually shorter than those times of scintillation. However, the information of rise time in this time is slightly poor, because of a few bins. We will rearrange CAEN V1751 to set original firmware and will measure same pulse shape with 0.5 ns timing bin to get more clear difference. After that, we will develop the pulse shape discrimination in order to distinguish PMTs whether receive Cherenkov light or not within 2019 fiscal year.

Also we are going to measure an actual energy resolution using special light guide as shown in Fig.7 which has almost 60 % photocoverage, and will measure the topological information using hemispherical detector HUNI-ZICOS as shown in Fig.8 to directly obtain an averaged angle of monochromatic energy (1.03 MeV) electrons with fixed direction.

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References

[1] Y.Fukuda, Journal of Physics: Conference Series **718** (2016) 062019.

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

[3] Y.Fukuda, Y.Kamei, Narengerile, A.Obata, S.Moriyama, I.Ogawa, T.Gunji, R.Hayami, S.Tsukada, Bulletin of Miyagi University of Education **52** (2017) 139-147.

[4] Y.Fukuda, Y.Kamei, Narengerile, A.Obata, S.Moriyama, K.HIraide, I.Ogawa, T.Gunji, R.Hayami, S.Tsukada, S.Kurosawa Bulletin of Miyagi University of Education **53** (2018) 183-192.

[5] Photomultiplier tubes and assembles for scintillation counting and high energy physics, Hamamatsu Photonics K.K., Electron Tube Division, revised Apr,2017.

[6] https://www.caen.it/products/v1751/

[7] L.Mostafa *et al.*, Physica Medica **32** (2016) 1007-1018.

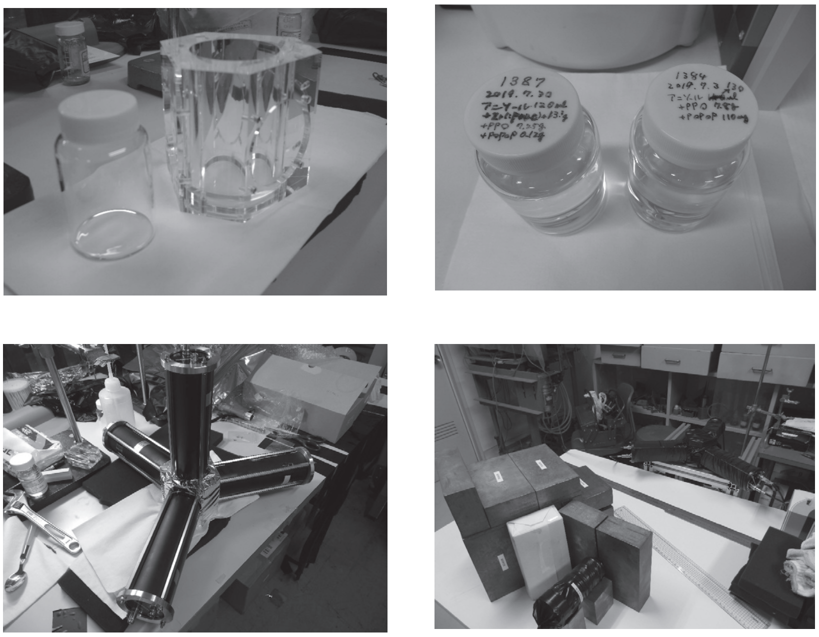

Figure 7. Precise measurement of an energy resolution using 60 % photocoverage light guide. The vial is changed by 120 mL size, and 10 MBq ^{60}Co source is used for monochromatic energy (1.03 MeV) electrons with fixed direction.

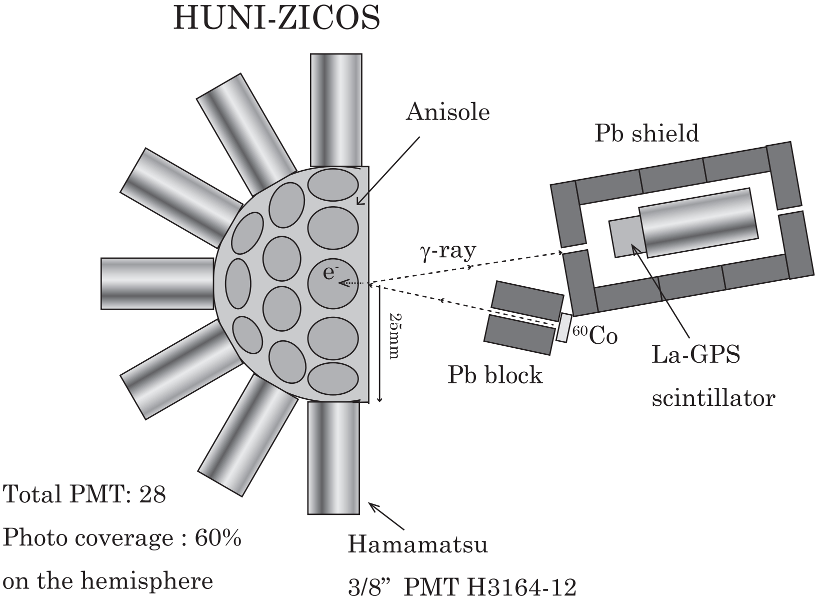

Figure 8. Approved plan to measure the averaged angle using HUNI-ZICOS detector. We will use 28 photomultipliers (H3164-12) to get averaged angle. We also plan to use CAEN V1742 (32+2 ch 12bit 5GS/s Switched-Capacitor digitizer) for discrimination of Cherenkov light using monochromatic energy electrons with fixed direction.

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