Direct measurement of spectral shape of Cherenkov light using cosmic muons

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Abstract.

The spectral pulse shape of Cherenkov lights was directly measured by using cosmic muons. The observed decay times for early and late timing were 5.0 and 5.2ns, respectively. They were actually shorter than the time of scintillation lights which were also measured as 9.3ns and 9.2ns, respectively. However we could not see the difference of the rise time between scintillation and Cherenkov lights. This was due to the slow response of our DAQ equipment, photomultiplier and FADC digitizer.

keyword :

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）
Cosmic muons (宇宙線ミューオン）

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1. ZICOS experiment

ZICOS is a new experiment for neutrinoless double beta decay using ^{96}Zr isotope as a target[1]. 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 reduced by their lower energy.

Recently KamLAND-Zen[2] reported that there found backgrounds around 3.35 MeV, and those were events of ^{208}Tl beta decay which was adhere on the surface of inner balloon. KamLAND-Zen also used a liquid scintillator for outside of the balloon, therefore they succeeded to reduce ^{208}Tl decay events even though whose vertex remained within their fiducial volume due to measure all energy of ^{208}Tl decay (Q-value is 4.99 MeV).

On the other hand, ZICOS detector will use pure water instead of liquid scintillator for outside of inner balloon as shown in Fig.1. Therefore almost half of ^{208}Tl events observed in KamLAND-Zen should be reduced by missing the energy. However, another half will exist inside of the balloon. In order to remove those backgrounds to reach the sensitivity $T^{0\nu}_{1/2} \geq 2 \times 10^{26}$ years, we have been developed techniques which use Cherenkov light for discrimination of signals and backgrounds [1].

Basically ^{208}Tl decays into exited state of ^{208}Pb with beta emission, and the transition to the ground state with several gammas emission happens after the beta decay. At least, latter includes 2.6145 MeV gamma. This means that some electrons could emit Cherenkov light from different position. On the other hand, two electrons emitted by $0\nu\beta\beta$ are also able to release Cherenkov lights but from same position. This difference could be used for the reduction of ^{208}Tl backgrounds.

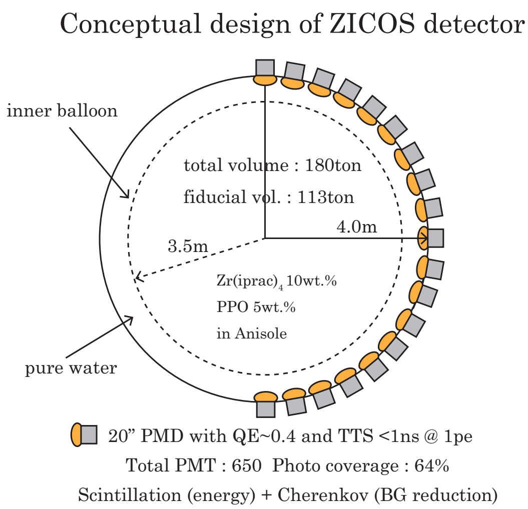

Figure 1. The left panel shows the global design of the ZICOS detector. The inner detector is located in pure water tank, and has 650 of 20 inch photomultiplier with 64 % of photo coverage. The right panel shows the conceptual design of the inner detector. The inner balloon will be filled with a liquid 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.

2. Discrimination of Cherenkov light using pulse shape

Generally speaking, it is possible to measure the energy of all events occurred in the scintillation detector if the detector has a large enough size. Since the scintillation photon emits isotropically, the reconstructed vertex of multi events should be located at the position with an energy weighted average of real positions. Therefore the scintillation detector basically is not able to distinguish the ^{208}Tl decay and $0\nu\beta\beta$ event using vertex information even though those have same energy.

Instead of vertex information using scintillation to distinguish signals and backgrounds, we better to consider the Cherenkov lights which basically have a directionality. 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, and we can reduce about 93 % of ^{208}Tl decay events with 78 % efficiency for $0\nu\beta\beta$ events as shown in right panel of Fig.2 using an adequate topological information from Cherenkov lights. On the other hand, ZICOS detector should measure the energy as precise as possible so that we have to use scintillation lights for the energy measurement. Therefore it is important to extract the hitted PMT by Cherenkov photon among the large yield of scintillation photon. In this points of view, we have to discriminate PMT whether including Cherenkov lights or not.

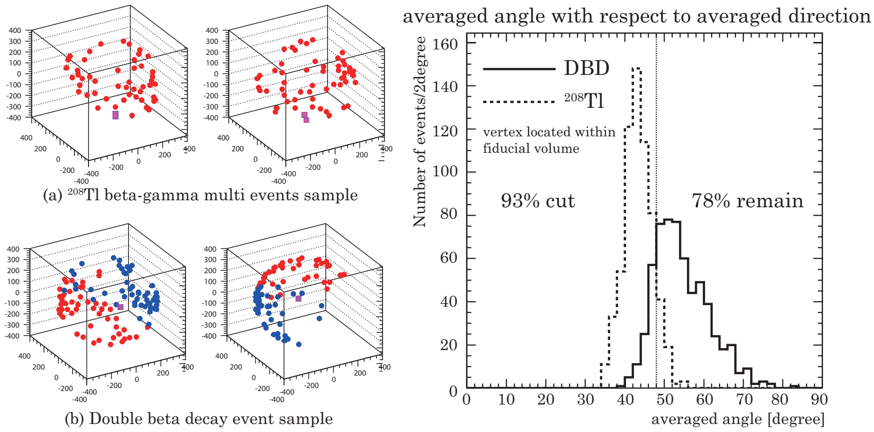

Figure 2. The left panel shows PMT hit pattern of Cherenkov lights for typical (a) ^{208}Tl decay and (b) $0\nu\beta\beta$ in case of vertex located within the fiducial volume. The right panel shows that the averaged angle distribution for each case. If we set 48 degree as a cut point, we can reduce 93 % of ^{208}Tl backgrounds with 78 % efficiency for $0\nu\beta\beta$ signal.

The discrimination of pulse shape whether including Cherenkov lights in PMT signal is possible, because of the difference of photon emission mechanism. 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 100ps). On the other hands, scintillation is the radiation from transition between the exited state and lower state of scintillator atoms, therefore the timing spreads with a few tenth of nano seconds. Therefore the difference of spectral shape at both rise and decay time could be considerable.

The possible pulse shape of Cherenkov lights using both 1MeV electron and single PMT was reported by our previous paper[3], and it might seem to have a shorter decay time than scintillation as shown in right panel of Fig.3. In this time, however, we could not confirm that the pulse shape was occurred actually by Cherenkov lights, because of no information from other than the energy of back scattered gammas.

3. Observation of Cherenkov light using cosmic muons

In order to confirm the spectral shape of actual Cherenkov lights, we better to use obvious Cherenkov photons emitted by cosmic muons, which go straight through the materials. Emitted

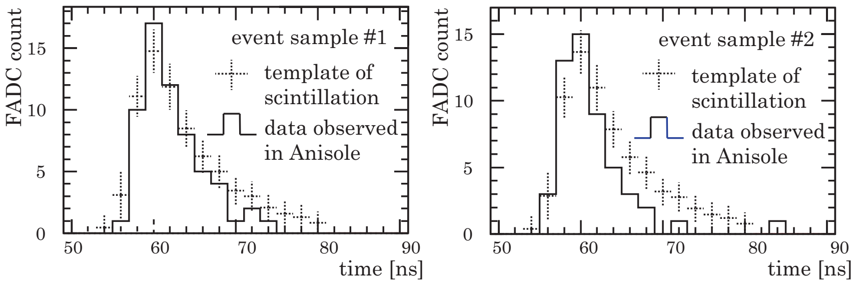

Figure 3. Observed timing pulse shape in Anisole using 1MeV electron. The pulse shale of left panel was consistent with template of scintillation, however number of those events was quite small. On the other hands, the pulse shape of right panel showed inconsistent with the template of scintillation, and most of events had a similar shape.

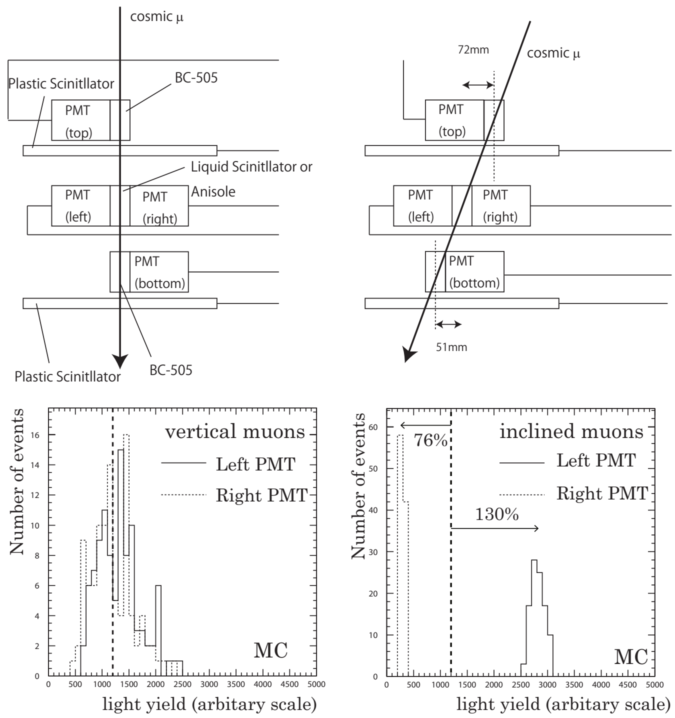

Figure 4. Top panel shows that the setup of the measurement of pulse shape using vertical (left) and inclined (right) muons. The bottom panel shows that the expected charge distribution for Left (solid line) and Right (dotted line) PMT, respectively. The averaged charge is almost same for left and right PMT in case of vertical muons. On the other hands, the charge for Left PMT moved about 130% but the charge for Right PMT was decreased about 76%. This is due to the directionality of Cherenkov lights.

Cherenkov photon has a directional angle θ_c with respect to the direction of muons as shown in following formula,

$$\cos\theta_c = \frac{1}{n\beta} \tag{1}$$

where n is a refractive index of material, and β is a relative velocity of muons to the light velocity. Therefore the emitted Cherenkov photon from cosmic muons should have a strong directionality.

According to the simple simulation using a vertical and inclined muons as shown in top figures of Fig.4, an observed Cherenkov light yield for Right and Left PMT should be varied as shown in bottom figures of Fig.4, respectively. Using this variation of lights yield, we will be able to measure the pulse shape of actual Cherenkov lights. The events were triggered by the coincidence for both top and bottom trigger counter, and we measured those charge simultaneously.

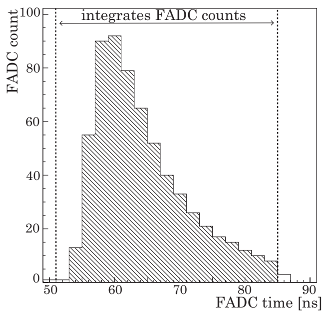

Figure 5. Definition of charge (Q using FADC pulse shape. The charge was obtained by integration between 52ns and 84ns where the peak always stay at 30ns.

Before the measurement of Cherenkov light from cosmic muons, we would like to demonstrate that a scintillation light emitted by cosmic muons should be same amount of light yield between vertical and inclined muons. We used our standard liquid scintillator which consist of PPO/POPOP and Anisole for the target. No Zr(iPrac)$_4$ was solved. In order to obtain a charge of pulse, we integrated FADC pulse counts between 52ns and 84ns as shown in Fig.5. Always every pulse shapes have a peak at 60ns.

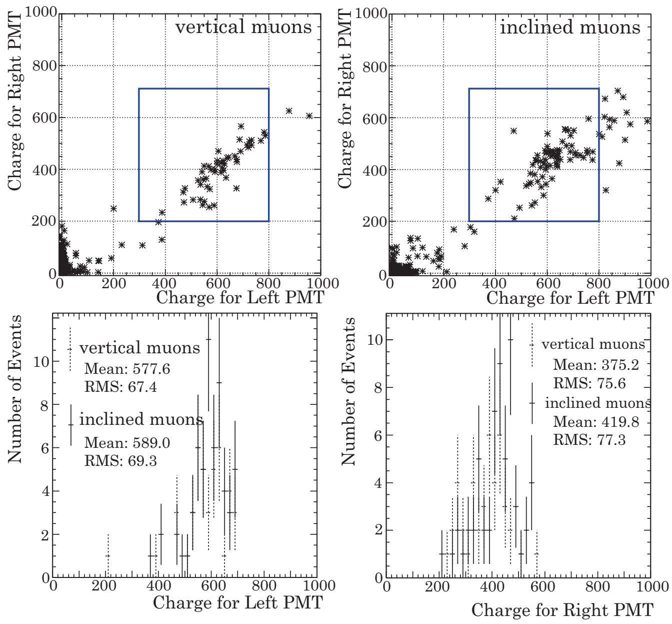

Figure 6. Top panel shows that correlation of charge for Left PMT and Right PMT in case of vertical (left side) and inclined (Right side) muons. Bottom panel shows that the charge distribution for Left PMT (left side) and Right PMT (right side) in case of vertical (dotted line) and inclined (solid line) muons. No change was observed in each case of muons, because of isotropic emission of scintillation lights.

Using this charge for Left and Right PMT, we obtained correlation in case of vertical and inclined muons as shown in top panel of Fig.6. Events located in box indicated in the figure correspond to the cosmic muons which penetrated in liquid scintillation located at center position. These events were confirmed by charge of top and bottom trigger counter. Other events located at lower charge region could be occurred by muons, which passed through the light guide of center liquid scintillator. Both charge of Left and Right PMT at center liquid scintillator did not change in case of both vertical and inclined muons as shown in bottom panel of Fig.6, because of isotropic emission of scintillation photon.

Of cause, Cherenkov lights should be observed in this case, however the amount of light yield might be very small (∼1%) compared to the scintillation lights, therefore the effect of Cherenkov light should be negligible.

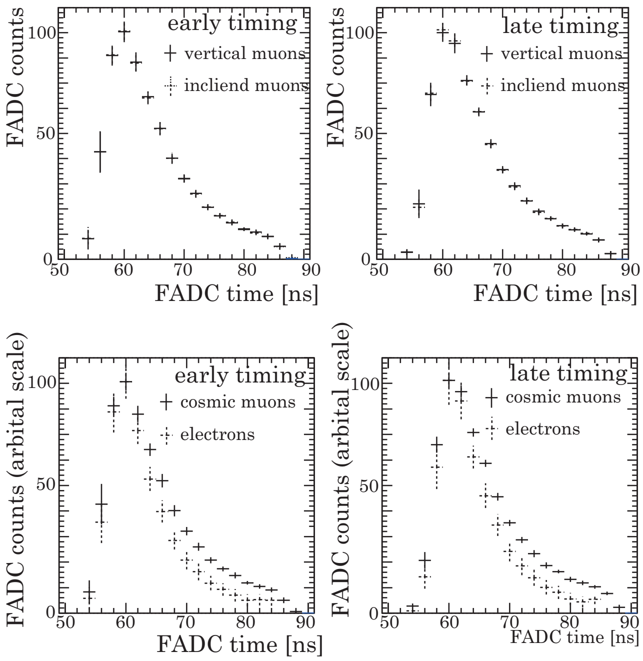

Figure 7. Top panel shows that an averaged pulse shape using selected events in the box of Fig.6 in case of vertical (solid line) and inclined (dotted line) muons, respectively. There is two figures for early and late timing with with the trigger pulse, because of resolution of FADC time binning (2ns). Bottom panel shows the comparison of averaged pulse shape of scintillation lights observed by electrons for early and late timing, respectively.

Using these events, we could make an averaged pulse shape for scintillation lights as shown in top panel of Fig.7 in both case of vertical and inclined muons. There are two shapes for early and late timing due to FADC time resolution (1bin corresponds to 2ns). Comparing to the shape obtained by electrons, they have almost same rise time, however the decay time seems to be different (7.4ns (e) and 9.2ns (μ) for early timing and 7.6ns (e) and 9.3ns (μ) for late timing) as shown in bottom panel of Fig.7. There is no obvious reason to explain this difference, but it should be caused by kind of charged particle.

Instead of our standard liquid scintillator, we used only Anisole (without any additive scintillator such as PPO and POPOP) for the target wind the UV cut filter SC-37 in order to minimize the effect of scintillation lights. The light measured through the SC-37 should be mainly Cherenkov lights with wavelength above 400nm, because of shorter wavelength of scintillation for Anisole (peak at ∼300nm). The measured light yield for both Left and Right

PMT in case of both vertical and inclined muons is shown in top panel of Fig.8. The events

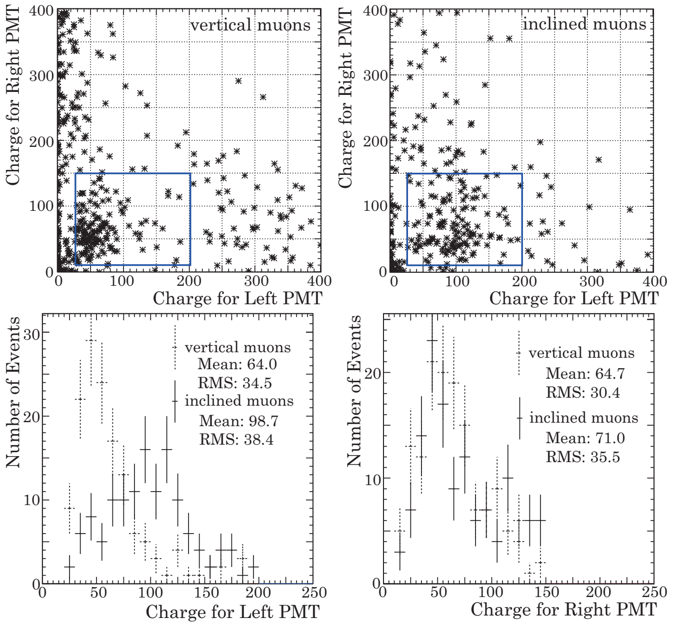

Figure 8. Top panel shows that the correlation of charge between Left and Right PMT in case of both vertical (left side) and inclined (right side) muons. Bottom panel shows the charge distribution of Left PMT (left side) and Right PMT (right) using events located in box of above panel in case of vertical (dotted line) and inclined (solid line) muons. Obviously the charge of Left PMT was increased in case of vertical muons.

located in box indicated in top panel of Fig.8 are occurred by cosmic muons passing through the central scintillator vial which was filled with Anisole. In this figure, the charge of PMTs is not same as shown in Fig.6, since the signal was attenuated due to large amount of light yield in case of liquid scintillator. Other events located at lower charge region should be occurred by muons passing through the light guide as described above or the accidental coincidence. The another events located at larger charge was unknown, but it might be caused by multiple muons since the trigger counter did not have proper charge.

According to top panel of Fig.8, the charge of Left PMT seemed to increase in case of inclined muons. Using events located inside of the box, the charge distribution for Left PMT actually indicated that increasing of charge as shown in bottom panel of Fig.8. In fact, a mean values for vertical and inclined muons for Left PMT were 64.0 and 98.7, respectively. The charge for Left PMT increased statistically enough, however the charge for Right PMT was almost same in both case.

This could be explained by following. Observed lights consist not only Cherenkov lights but also scintillation lights. A large amount of scintillation from Anisole should not be negligible even though the lights below 400nm was attenuated by SC-37 UV cut filter. Using the ratio indicated by values from the simulation as shown in Fig.4, the amount of scintillation and Cherenkov lights are expected as 37 and 27, respectively. In case of Right PMT, an expected charge is 52 in case of inclined muons, however since the distribution spread so wide that the decreasing of charge could not be observed clearly. Actually it is impossible to discriminate the difference between 64 and 52 as shown in bottom panel of Fig.8. Anyway, in this case, we have to subtracted the charge of Left PMT in order to eliminate the effect of scintillation for the extraction of the pulse shape of actual Cherenkov lights as shown in Fig.9.

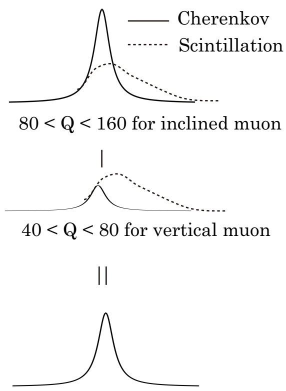

Figure 9. Explanation to obtain the pulse shape due to pure Cherenkov lights. An averaged pulse shape obtained by vertical muons should have small effect from scintillation even through shorter wavelength and SC-37 UV cut filter. Subtracted the averaged pulse shape should be made by pure Cherenkov lights.

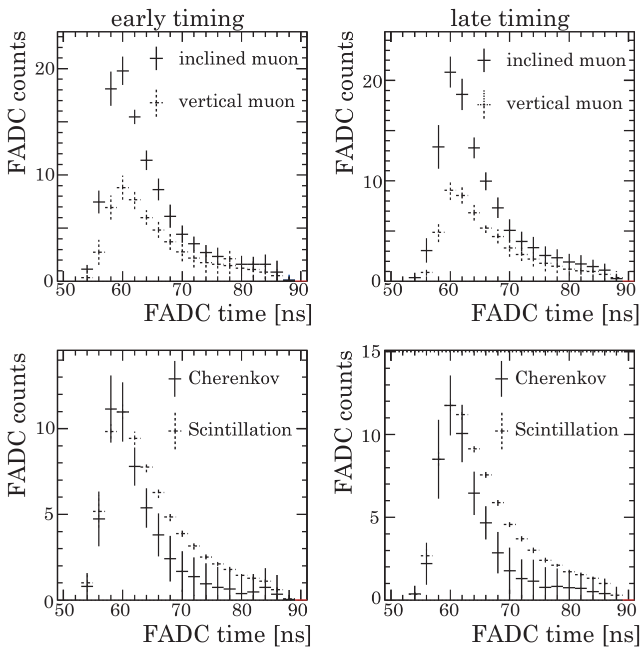

Figure 10. Top panel shows an averaged pulse shape obtained by events with $40 \leq Q \leq 80$ for vertical muons(dotted line) and $80 \leq Q \leq 160$ for inclined (solid line) muons in each timing. The bottom panel shows the subtracted averaged pulse shape (solid line) for corresponding timing. This should consist of pure Cherenkov photon. Dotted line shows the pulse shape of scintillation which is same as the bottom panel of Fig.6.

In this time, we subtracted an averaged pulse shape using $80 \leq Q \leq 160$ in case of inclined muons to an averaged pulse shape using $40 \leq Q \leq 80$ in case of vertical muons, then we obtained an averaged pulse shape due to pure Cherenkov lights as shown in bottom panel of Fig.10. Obtained pulse shape due to Cherenkov lights has almost same rise time as scintillation light, but the obvious shorter decay time (5.4ns and 5.0ns for early and late timing, respectively) than scintillation (9.3ns and 9.2ns for those timing). Therefore, we concluded that the obtained averaged pulse shape consisted only Cherenkov lights.

4. Conclusion

Using cosmic muons, we could obtain the actual pulse shapes of Cherenkov light and they had shorter decay time than scintillation. However, we could not see the difference of rise time in case of Cherenkov and scintillation. This is due to slow response of our equipment such as Hamamatsu photomultiplier H6410 (rise time is 2.7ns and TTS is 1.1ns) and CAEN digitizer V1721 (500MS/S). In order to confirm the discrimination ability using a rise time of pulse shape, we will use faster PMT such as Hamamatsu H2431-50 (rise time is 0.7ns and TTS is 0.37ns) and FADC such as CAEN digitizer V1751 (2GS/s which corresponds to 0.5ns/bin).

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