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雑誌名	BULLETIN OF MIYAGI UNIVERSITY OF EDUCATION
巻	55
ページ	141-150
発行年	2021-01-29
URL	http://id.nii.ac.jp/1138/00001143/

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Abstract

With a liquid scintillation used for ZICOS experiment, we measured pulse shapes in case of several radio isotopes, ^{60}Co, ^{137}Cs, ^{133}Ba, and ^{57}Co. Taking FADC timing at 60 nsec for the peak position, FADC spectra from 58.5 nsec to 80 nsec were almost same shape for each RI, however, before 58.5 nsec, we have found that those were different shape. Especially, in case of ^{57}Co, the energy is lower than Cherenkov threshold, so that the spectra should not include Cherenkov light. Using those spectra between 57.0 nsec and 58.0 nsec (3 bins), we calculated simply χ^2 and it was clearly discriminated that $\chi^2 \geq 0.1$ should be include Cherenkov lights.

This was also confirmed by Compton electrons with fixed energy and fixed direction. Obtained detection inefficiency of Cherenkov lights was observed by 21.4 ± 9.6 %. According to Compton edge events which have almost same direction as the incident γ and backgrounds events which should have isotropic direction, the detection inefficiency were 10.4 ± 0.5 % and 49.1 ± 1.4 %, respectively. They were quite different values and the inefficiency of both fixed energy and Compton edge events were statistically same. This is a direct evidence that Cherenkov lights should keep their topology even if they are emitted by around 1 MeV electron.

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. Cherenkov lights

Cherenkov light is an electromagnetic radiation emitted by charged particle if the speed of the charged particle exceeds the phase speed of light in the material. The direction of Cherenkov lights is obtained by following formula;

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

here θ is the angle with respect to the direction of the charged particle, n is refractive index of the material, $\beta = \frac{v}{c}$, and v and c is the velocity of charged particle and light speed in vacuum, respectively. Refractive index of Anisole is 1.514, so that minimum value of β is 0.661 which corresponds to Cherenkov threshold (kinetic energy of electron is 170 keV).

For the measurement of ^{96}Zr neutrinoless double beta decay, the ultimate backgrounds from natural U/Th series is products of ^{208}Tl beta decay on the surface of balloon as observed by KamLAND-Zen [1], and they could contaminated to the energy region of interest.

As described in our previous paper [2], there was a difference of hit pattern of Cherenkov lights between ^{208}Tl backgrounds and $0\nu\beta\beta$ signals in Monte Carlo simulation, and we found that it could be reduced 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. Also, as we reported last year, the pulse shape of Cherenkov lights also has much faster rise time than that of scintillation [3]. Using V1751 FADC DES mode (2Gs/s), we have developed the method for pulse shape discrimination whether Cherenkov lights are included in scintillation signal or not.

2. Discrimination of Cherenkov light using several gamma sources

In order to develop the method of pulse shape discrimination whether Cherenkov lights are included in the observed scintillation signal or not, we have to confirm the difference of rise time between Cherenkov lights and scintillation again using 0.5 nsec binning at first. For this purpose, we measured the pulse shape of β electrons from ^{90}Sr which was same method as last year using V1751 double edge scan mode (2Gs/s with 4 channels).

Figure 1 shows those shapes for Cherenkov light and scintillation, respectively. Although the pulse shape obtained by our standard liquid scintillator, which does not include Zr(iPrac)$_4$, shows two structures for decay time, $\tau = 4.57$ nsec for first half and $\tau = 8.38$ nsec for latter half, respectively, there was also clear difference of the rising shape for both samples. The rise time was obtained as 0.75 nsec for Cherenkov lights and 1.45 nsec for scintillation, respectively. The timing of Cherenkov light in Fig,1 was adjusting first non-zero signal, therefore it might not be correct. Also the shape of rise time for scintillation included indeed small amount (a few % of scintillation) of Cherenkov light. Therefore, we would like to measure real difference for rising shape due to Cherenkov light.

To compare the spectral shape of rise time for any charge pulses, we defined the charge ratio Q_{time}/Q_{total}, here Q_{time} is FADC count at each timing and Q_{total} is summed FADC count between 55 nsec and 80 nsec. The timing of pulse is always located at 60 nsec for peak position.

Instead of βs from ^{90}Sr, we used γs from several radio isotope (RI) sources for the development of method for the pulse shape discrimination, because lower energy electrons might be multiply

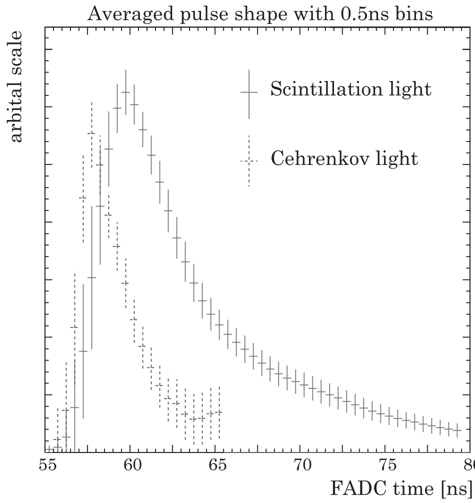

Figure 1. The averaged pulse shape for scintillation and Cherenkov light measured by V1751 DES mode. In this figure, the amount of Cherenkov light was scaled at same peak height as scintillation.

scattered and the topological information of Cherenkov light should be lost. This means that the spectral shape at rise time could be different between lower and higher energy electrons. We used ^{60}Co, ^{137}Cs, ^{133}Ba, and ^{57}Co for γ RI sources in this time.

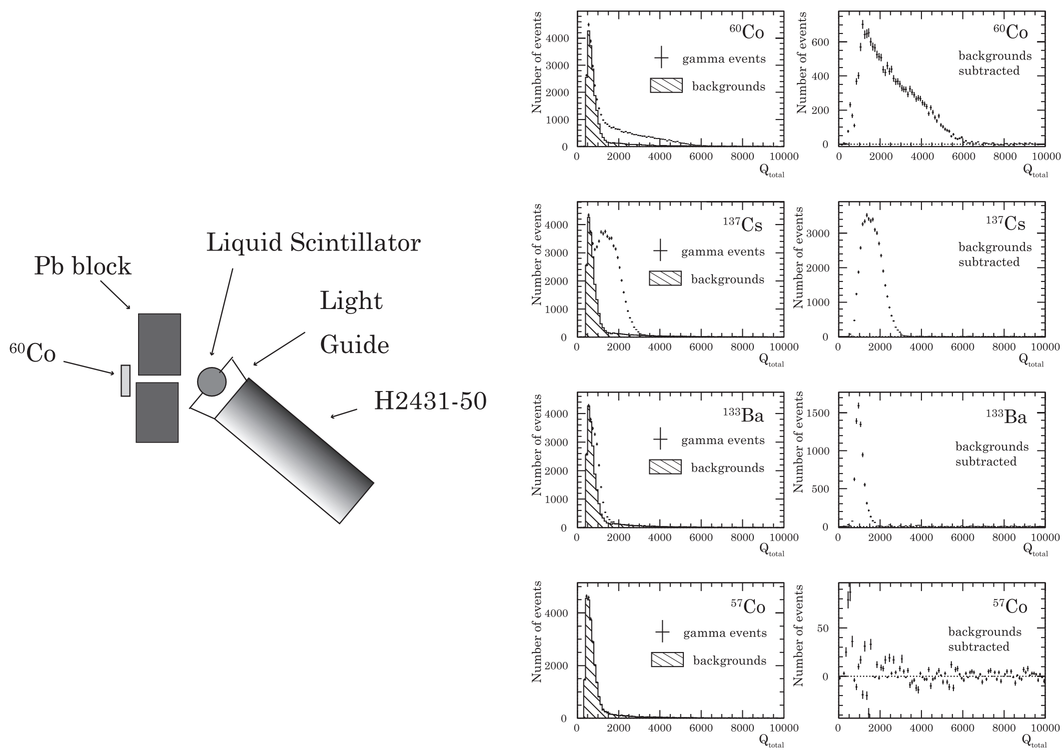

Figure 2. The left side figure shows the setup for measurement of Cherenkov and scintillation lights of Compton scattering electrons from several RI sources. The right side figures show their total charge distribution. The shaded distributions show backgrounds.

The left side figure of Fig.2 shows the setup for measurement of Cherenkov lights from Compton scattering electrons. The γs were collimated by Pb block, and the scattered electrons in liquid scintillator emit both scintillation and Cherenkov lights. Those lights were detected by photo multiplier H2431-50. This PMT was located at 40 degree with respect to the incident γ because of Cherenkov angle for electrons with an energy at near Compton edge.

The right side panels of Fig.2 show the total charge distribution of Compton scattered electrons from each γ source. The shaded region shown in the panels corresponds to backgrounds which means no source, and the total charge distribution subtracted background were also shown in right panels. The Compton edge is 0.96/1.12MeV for ^{60}Co, 478keV for ^{137}Cs and 207keV for ^{133}Ba. Those energies are above the Cherenkov threshold, however the energy of γ from ^{57}Co is below the Cherenkov threshold. Also the yield of scintillation of ^{57}Co and backgrounds was almost same, and the radioactivity of ^{57}Co was weak, therefore the observed spectrum is quite small compared to large amount of backgrounds.

3. Development of method for pulse shape discrimination

Using the charge ratio defined at previous section, we plot the charge ratio distribution for each timing of each RI source as shown in Fig.3. The distribution have already been subtracted by background distribution. The timing are also shown in left side in this figure.

The charge ratio distributions after 58.0 nsec is almost same shape for each RI source. This is due to scintillation is dominant compared to the Cherenkov lights. On the other hands, before 58.0 nsec, there seems to exist some differences of the distribution for each source. For instance, the Mean value for distribution of ^{60}Co and ^{57}Co at 57.5 nsec are 0.02212 and 0.00178, respectively. As already explained previous section, the energy of γ from ^{57}Co is below the Cherenkov threshold, therefore only scintillation signal should be observed. The spectral differences between ^{57}Co and other sources before 58.0 nsec should be caused by the Cherenkov lights. If Cherenkov lights might make such a difference, the charge ratio for scintillation at earlier timing should be almost zero, because of their slow rise time.

Moreover the shape of charge ratio distribution at earlier timing should depend on the energy of Compton electron, because lower energy electrons could be scattered multiply and then the topological information of Cherenkov light might be lost. Looking at charge ratio distribution of ^{133}Ba, ^{137}Cs and ^{60}Co between 57.0 and 58.0 nsec, ^{133}Ba is smaller amount of charge ratio above zero than others. Therefore we concluded that Cherenkov light was dominant for the charge ratio distribution before 58.0 nsec for FADC timing.

Here we adopted the template waveform of scintillation between 56.5 and 57.5 nsec for ^{57}Co. Table 8 shows the Mean and RMS for each FADC timing. Using these Mean and RMS values, we could calculate $\chi^2 = \Sigma \frac{(Mean(t) - FADCcount(t))^2}{RMS(t)^2}$ event by event. Figure 4 shows the χ^2 distribution for each source. Shaded region in this figure shows χ^2 distribution of backgrounds.

FADC timing (nsec)	Mean	RMS
56.5	0.00025	0.00735
57.0	0.00074	0.00776
57.5	0.00178	0.01098

Table 1. Mean and RMS value obtained the charge ratio distribution of ^{57}Co source.

Clearly the small χ^2 of Compton electron is consistent with backgrounds. Majority of backgrounds could be low energy electrons from natural radio isotopes in liquid scintillator,

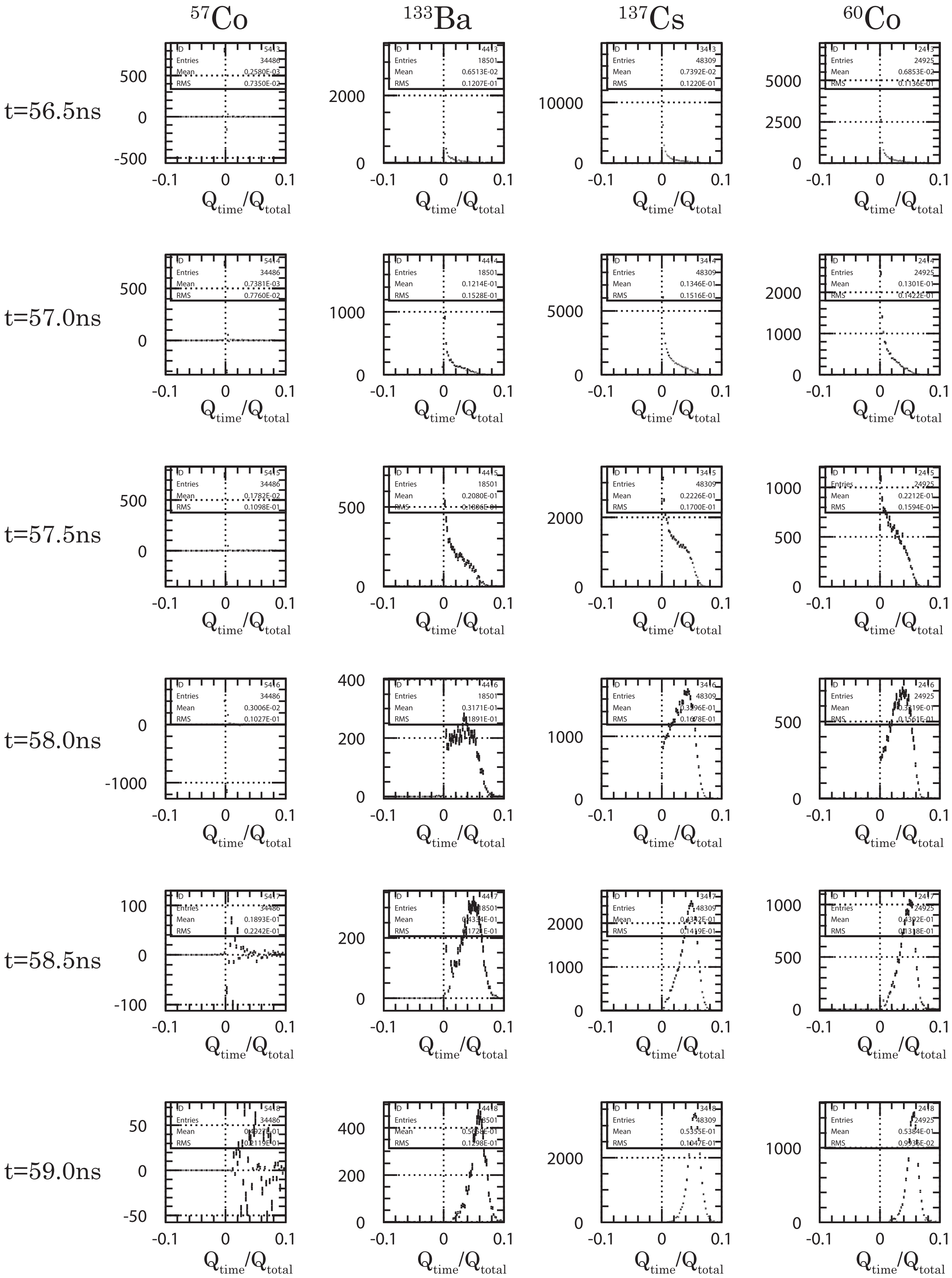

Figure 3. The charge ratio distribution of each FADC timing for each RI source. All data have been subtracted by background. FADC timing is also shown in left side.

in environment and in PMT materials, and their energies are almost below the Cherenkov threshold. Also the direction of those events should be isotropic.

On the other hands, the Compton electron scattered by γ observed in ^{60}Co, ^{137}Cs and ^{133}Ba

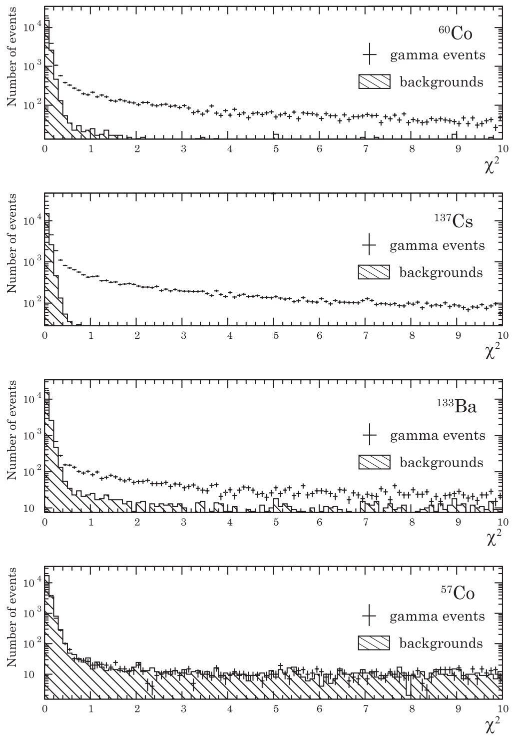

Figure 4. The χ^2 distribution for each RI source. The shaded region indicated the background distribution. Most of backgrounds have low χ^2 values.

have much higher energy than Cherenkov threshold. Therefore χ^2 value should be also larger than the background. The results from Fig.4 are consistent with this assumption. Of course, the backgrounds include small amount of higher energy events and large χ^2 event also could be observed.

In order to confirm χ^2 value for events include Cherenkov lights. we have to measure the χ^2 using well known physics events. For that purpose, we used electrons for fixed direction and fixed energy (FDFE) using the setup as shown in the left figure of Fig.5. This was an usual method which we have measured the energy resolution in our previous paper [4]. The trigger from the liquid scintillator and La-GPS scintillator was taken with coincidence, then we could select events which the energy of La-GPS to be around 418 keV. At this time, FDFE events were generated by Compton scattering with the energy of 835 keV in the liquid scintillator. The PMT H2431-50 was located at 40 degree with respect to the direction of FDFE events. Backgrounds (accidental coincidence events) were also measured with same setup but La-GPS was located another position where Compton γ did not come in.

The right side panels of Fig.5 show total charge distribution and χ^2 distribution for FDFE events and backgrounds,respectively. We observed 31 events in total for this measurement. In those events, number of events with $\chi^2 \geq 0.1$ was 22 events. On the other hands, the observed number of backgrounds was 3 events and all events have $\chi^2 \leq 0.1$. Therefore, the condition of $\chi^2 \geq 0.1$ was reasonable to assume that the signal included Cherenkov lights. Considering backgrounds, the inefficiency for detection of Cherenkov light with most preferable position was obtained by 21.4 ± 9.6 %. We have to compare this number with an another method.

Using the Compton scattering electron with the energy near Compton edge from ^{60}Co and backgrounds with lower energy but above the Cherenkov threshold in same setup in Fig.2, we estimated the detection inefficiency of Cherenkov lights. The left panels of Fig.6 show the

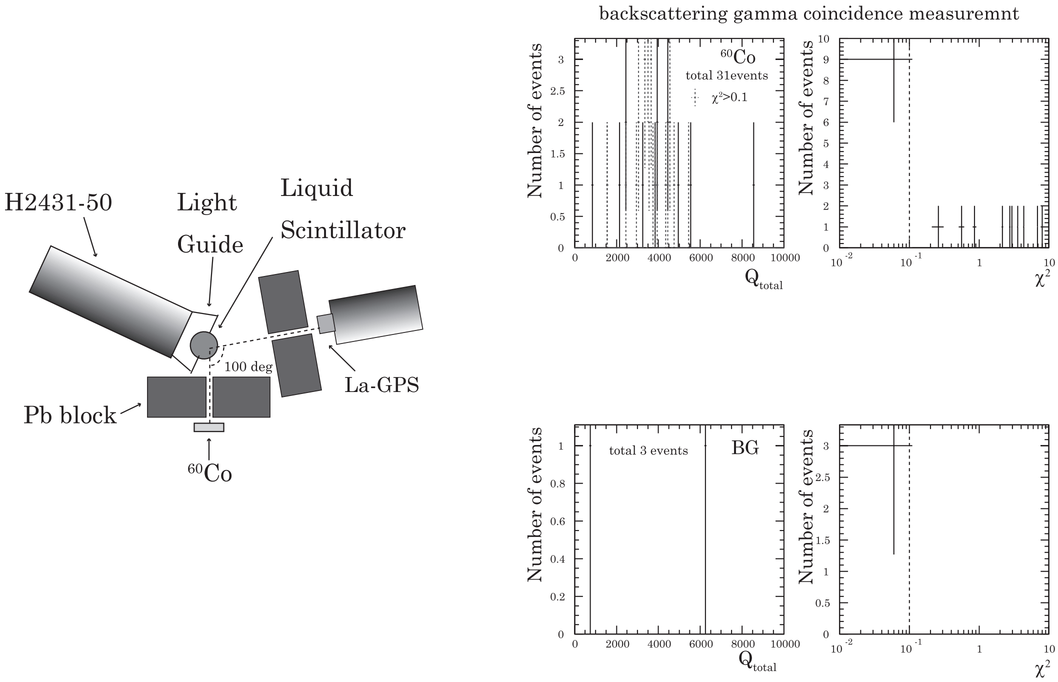

Figure 5. The left side figure show the setup for measurement of fixed direction and fixed energy (FDFE) electrons scattered by Compton γ which was detected by La-GPS scintillation detector. The right side panels show total charge and χ^2 distribution for FDFE events and accidental coincident backgrounds.

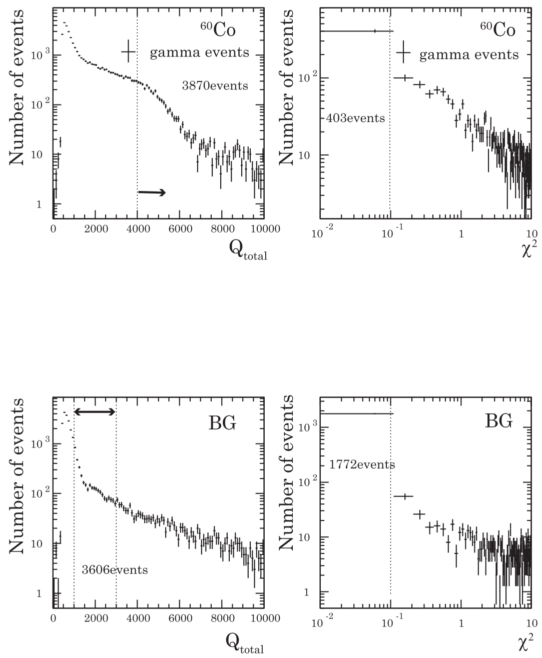

Figure 6. The left side panels show the total charge distribution for ^{60}Co and background. The right side panels shows χ^2 distribution for selected events.

total charge distribution of ^{60}Co and backgrounds. we selected near Compton edge event as $Q_{total} \geq 4000$ and backgrounds as $1000 \leq Q_{total} \leq 3000$. The selected number of events are 3870 and 3606, respectively. For those events, the right side panels show χ^2 distribution. If we adopted no Cherenkov light events as $\chi^2 \leq 0.1$, the number of events for near Compton edge events and backgrounds were 403 and 1772 events, respectively. Therefore the detection inefficiency of near Compton edge event and low energy background above Cherenkov threshold were also obtained by 10.4 ± 0.5 % and 49.1 ± 1.4 %, respectively.

Considering the isotropic direction and the multiple scattering for low energy backgrounds, it is naturally understood that almost half of Cherenkov are detected by PMT, and the detection inefficiency of near Compton edge events are quite different statistically. On the other hands, the detection inefficiency of both near Compton edge events and FDFE events are consistent within statistical error, This results confirmed that we can select PMT whether Cherenkov lights include event by event, therefore the pulse shape discrimination method has been established. Also it is very important evidence that Cherenkov lights should keep their topology even if they were emitted by around 1 MeV electrons.

4. Development for pulse shape discrimination for H3164-12

Same pulse shape discrimination for PMT H3164-12 which will be used for HUNI-ZICOS and UNI-ZICOS experiment as explained in our previous paper [3] was developed. TTS and rise time of this PMT is 0.5 nsec and 0.8 nsec, respectively, and they are almost same number as those of H2431-50. However the area of photo cathode of H3164-12 is quite smaller than that of H2431-50, we have to use multiple PMTs to detect Cherenkov lights and scintillation as shown in the left photograph of Fig.7.

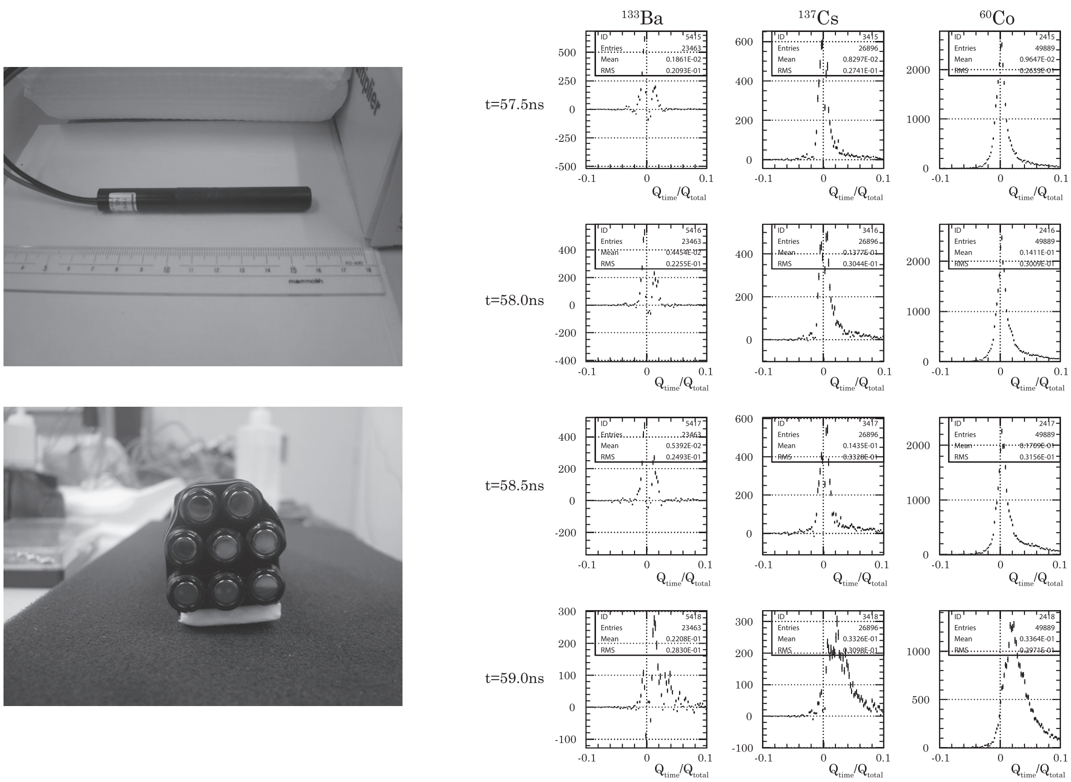

Figure 7. The left side photograph show H3164-12 photo multipliers and the right side panels shows χ^2 distribution between FADC timing for each RI source.

In this time, total 4 PMTs were used simultaneously for the measurement of pulse shape using V1751 DES mode. Therefore, we accumulate the total charge of each PMT as $Q_{total} = \Sigma Q_{total(PMT)}$. The right panels of Fig.7 shows the charge ratio of one PMT at each FADC timing for several RI sources. According to the case of H2431-50, the template of scintillation shape is almost same as low energy background. Therefore, we adopted the background shape as a scintillation template in case of H3164-12.

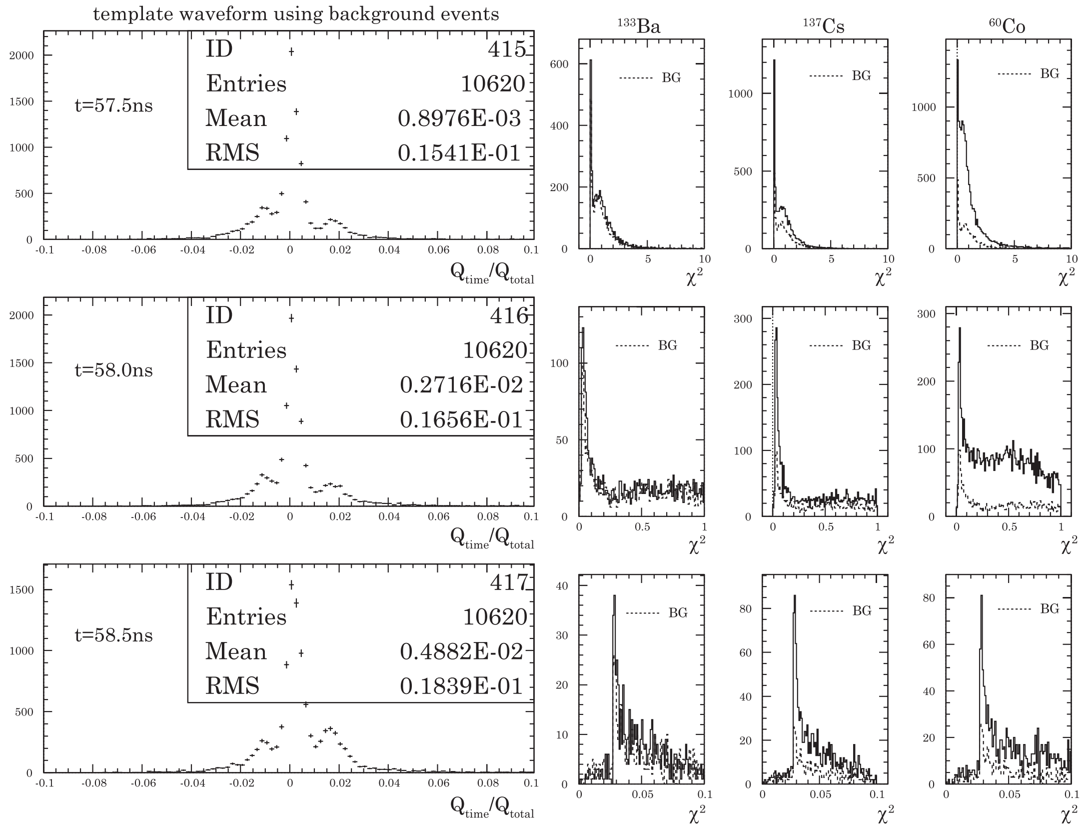

Figure 8. The left side panels show the total charge distribution for backgrounds as a template for scintillation. The right side panels shows χ^2 distribution for Compton electrons from each γ RI source.

The left side panels in Fig.8 shows the charge ratio of backgrounds as a template pulse shape of scintillation, and right side panels of Fig.8 show the $\chi 2$ distribution of the both Compton scattering events and backgrounds for one PMT. Some backgrounds could be identified as low χ^2 values, however it was not perfect yet. The pulse shape discrimination for H3164-12 could be possible, but still we need more tuning. HUNI-ZICOS will use only Anisole in order to measure the topological information of Cherenkov lights, so that we will not use the pulse shape discrimination. However many pulse shape information for Cherenkov lights will be accumulated at the measurement. So we will make a tune the method for pulse shape discrimination using H3164-12 in next year for UNI-ZICOS.

5. Conclusion

Using a liquid scintillation used for ZICOS experiment, we measured pulse shapes in case of several radio isotopes, ^{60}Co, ^{137}Cs, ^{133}Ba, and ^{57}Co. Taking FADC time at 60 nsec for the peak position, FADC spectra from 58.5 nsec to 80 nsec were almost same shape for each RI source, however, before 58.5 nsec, we have found that those had different shape. Especially, in case of ^{57}Co, the energy is lower than Cherenkov threshold, so that the spectra should not include Cherenkov light. Using those spectra between 56.5 nsec and 57.5 nsec (3 bins), we calculated simply χ^2. It is clearly discriminated that $\chi^2 \geq 0.1$ should be include Cherenkov lights.

This is also confirmed by Compton electrons with fixed energy and fixed direction. According to both Compton edge events which have almost same direction to the incident γ and backgrounds which should have isotropic direction, the detection inefficiency which did not include Cherenkov lights were 10.4 ± 0.5 % and 49.1 ± 1.4 %, respectively. This is a direct evidence that Cherenkov lights should keep their topology even if they are emitted by around 1 MeV electrons.

Acknowledgments

This work was supported by a Grant-in-Aid for Scientific Research on Innovative Areas (No.24104501, No.26105502, No.19H05093, and 20H05241) from the Ministry of Education, Culture, Sports, Science and Technology (MEXT), a Grant-in-Aid for Scientific Research (C) (No.18K03664) from the Japanese Society for the Promotion of Science (JSPS), and the Foundation for High Energy Accelerator Science.

References

[1] A.Gando *et al.* (KamLAND-Zen collaboration), Physical Review Letters **117** (2016) 082503.
[2] 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.
[3] 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 **54** (2019) 169-176. Y.Fukuda *et al.* Journal of Physics: Conference Series **1468** (2020) 012139.
[4] Y.Fukuda, Journal of Physics: Conference Series **718** (2016) 062019.