Direct measurement of topological information for Cherenkov lights using HUNI-ZICOS detector

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Abstract.

The topological information of Cherenkov light from low energy electron was directly measured by HUNI-ZICOS detector. A 1.484 MeV electron with fixed direction to the center of hemispherical surface of the detector was generated by Compton back scattering with 100 degree from ^{88}Y 1.836 MeV gamma. The observed averaged angle of Cherenkov light emitted from this electron was clustered around 40 degree assuming the vertex position to be at the center of truncated icosahedron photomultiplier jig. It was not Cherenkov angle around 47 degree as obtained by old simulation and the vertex to be the center of light yield for hitted photomultiplier. According to the HUNI-ZICOS simulation, the averaged angle of Cherenkov light was also clustered around 40 degree. On the other hands, the simulated averaged angle of scintillation was clustered around 49 degree, which is consistent with the averaged value of angle between the direction to center of hemisphere surface and each photomultiplier from the center of the jig. The obtained hitmap seemed to have same non flat structure as that of simulation due to Cherenkov ring. This is an evidence that Cherenkov lights emitted from 1.484 MeV electron should really have their topology. Therefore, we concluded that we will be able to reduce ^{208}Tl background using the averaged angle for ^{96}Zr neutrinoless double beta decay search.

Key words : Neutrinoless Double Beta Decay, Liquid Scintillator, Cherenkov Light, Pulse Shape Discrimination, Topological Information

1. Cherenkov lights

Cherenkov light is an electromagnetic radiation emitted by charged particle if the speed of the charged particle exceeds phase speed of light in the material, and is radiated in a conical shape with respect to the travel direction of the charged particle. Cherenkov angle θ, which is half of opening angle, is obtained by following formula;

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

here n is refractive index of the material, $\beta = \frac{v}{c}$, and v and c is the velocity of charged particle and light

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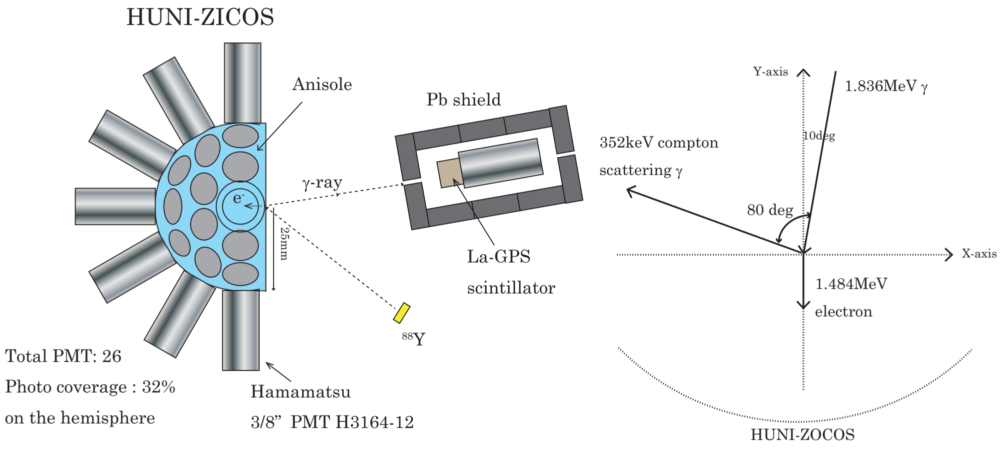

Figure 1. The conceptional design to measure the averaged angle using HUNI-ZICOS detector. The detector has total 26 of Hamamatsu 3/8 inch H3164-12 photomultiplier on the hemispherical surface. The generated electron has 1.484 MeV monochromatic energy with fixed direction to the center of hemisphere due to detect Compton scattering gamma with 100 degree backward.

speed in vacuum, respectively. The 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, an ultimate background 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 contaminate to the energy region of interest. According to the simulation, there was a difference of hit pattern of Cherenkov lights between ^{208}Tl backgrounds and $0\nu\beta\beta$ signals, 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 [2]. Also, as we reported, the pulse shape of Cherenkov lights also has much faster rise time than that of scintillation [3]. Using CAEN V1751 FADC DES mode (2 GS/s), we have developed the pulse shape discrimination method whether Cherenkov lights are included in scintillation using χ^2 method in our previous paper[4]. In this paper, we have concluded that Cherenkov lights emitted by even 1 MeV electron may keep their topology.

In order to verify the topology of Cherenkov light for 1 MeV electron, we have to measure directly the averaged angle. We will report the recent result of direct measurement for averaged angle for Cherenkov light using HUNI-ZICOS detector.

2. Setup for the measurement

The conceptional design to measure the averaged angle is illustrated by the left side panel of Fig.1. Incident 1.836 MeV gamma emitted by ^{88}Y source interacts with an electron by Compton scattering, and the scattered gamma with scattering angle 100 degree should have 0.352 MeV. If we detect this gamma using La-GPS scintillator, then an electron with 1.484 MeV is generated with the unique direction as illustrated by the right side panel of Fig.1. Once the incident direction is set by 10 degree with respect to Y-axis on the X-Y plane, the generated electron goes along Y axis to the center of hemisphere surface.

In this time, we made new detector HUNI-ZICOS to measure the averaged angle of Cherenkov light emitted from 1.484 MeV electron. We used only half side of spherical surface for this measurement, because most of Cherenkov photon might emit forward to the initial direction of electron. Therefore, a custom made hemispherical flask was used for the container to fill Anisole which is solvent of our

Figure 2. Left side panel shows the custom made hemisphere flask. The diameter is 50 mm, and the plastic screw cap was prepared in order to avoid evaporate Anisole. Right side panel shows the truncated icosahedron PMT mounting jig which has holes at each vertex.

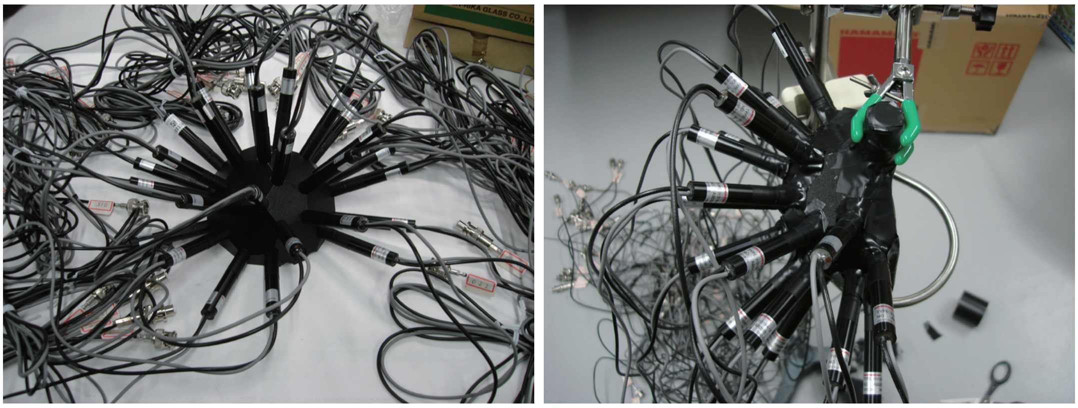

Figure 3. Left side panel shows the photograph when all PMT were mounted on the jig, and right side panel shows HUNI-ZICOS detector which consist of hemisphere flask adapted on the PMT mounting jig. In this time, we inserted UV cut filter between the flash and all PMTs in order to avoid the detection of scintillation from Anisole.

liquid scintillator for the convenience observation of Cherenkov light. Also the photomultiplier (PMT) should be mounted around this hemispherical surface. We prepared 26 PMTs (3/8 inch Hamamatsu H3164-12) for this purpose, which have 400K sensitivity for photocathod, Line focus 8 dynode, 1.0×10^6 gain, 0.5 nsec for time transit spread, and 0.8 nsec for rise time. In order to mount these PMTs on the surface of hemisphere flask, we also prepared special jig which has 26 holes at each vertex of the truncated icosahedron. This jig was produced by 3D printer using Nylon resin. Figure 2 shows the photograph of the custom made hemispherical flask and the truncated icosahedron PMT mounting jig.

All PMTs were inserted into each hole of the mounting jig. The jig was painted by black, however it was not light shield. Therefore we had to cover the detector entirely using by the black sheet during the data taking. The left side panel of Fig.3 shows the photographs for just PMT mounting on the jig. The right side photograph shows that HUNI-ZICOS was detector located on the flask clip and the chimney was pinched by another clamp from the stand. When the PMT mounting jig and the hemisphere flask were joined, we inserted UV cut filter SC-37 produced by Fuji film Corporation in order to remove scintillation light (~ 300 nm) from Anisole for the detection only Cherenkov light, since PMT H3164-12 has small but non negligible sensitivity for the wave length. Scintillation light emits uniformly,

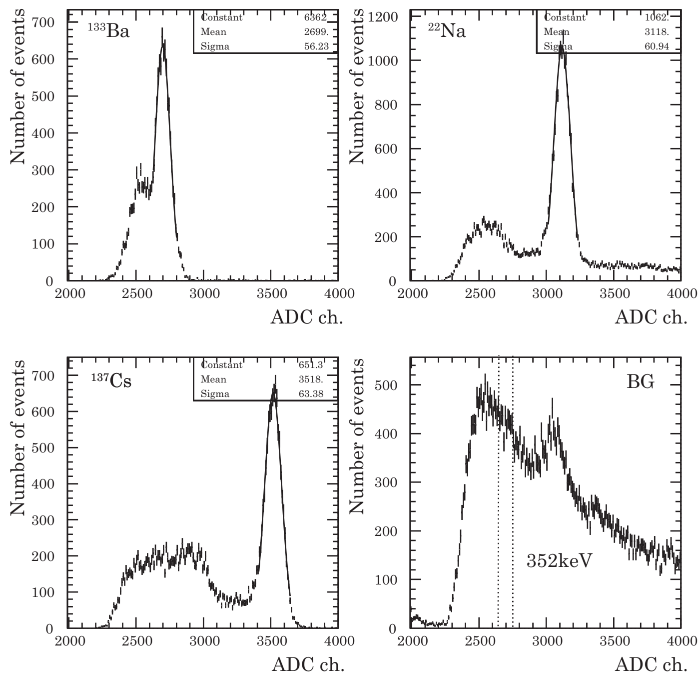

Figure 4. Calibration of La-GPS scintillation detector. Used calibration gamma sources were ^{133}Ba (356 keV), ^{22}Na (511 keV), ^{137}Cs (662 keV), and ^{60}Co (1.173 MeV and 1.332 MeV), respectively. Bottom right panel shows the background spectrum of La-GPS scintillator. We have set the threshold around 280 keV.

so the value of averaged angle should be different from Cherenkov light.

The signal cables of each PMT of HUNI-ZICOS detector were connected to CAEN V1742 FADC (32 Channel 12bit 5 GS/s Switched Capacitor Digitizer) and HV cable was connected to HV A7030 24ch board mounted in the mainframe SV5527LC to apply 1250 V for all PMTs. The signal cable from La-GPS scintillation detector was connected to LeCroy 1182 ADC with 200 nsec delay due to make a gate signal.

3. Calibration of La-GPS Scintillator

The gate trigger signal to V1742 FADC for data acquisition (DAQ) was generated by La-GPS scintillator, when it detected Compton scattered gamma from HUNI-ZICOS detector. However, there should be backgrounds inside or outside of La-GPS detector, even if the detector was located inside of Pb shield. Therefore, we took data in case of not only Compton scattered gammas but also backgrounds. In the analysis steps, we extracted signals, which means Compton scattering gammas, from huge backgrounds using FADC data as described in Analysis section. However, in order to suppress backgrounds which detected by La-GPS detector, we had to set the threshold to take data as higher as we can. Scattered gammas should have their energy of 325 keV, therefore, we should set the threshold as adequate channel considering the energy resolution. In this point of view, we have took calibration data for La-GPS detector as shown in Fig.4 at the end of every data taking.

Here we used ^{133}Ba (356 keV), ^{137}Cs (662 keV), and ^{22}Na (511 keV) for gamma sources. Each position of photo electric peak was obtained by the Gaussian fitting, then scale factor of an energy as a function of ADC count was calculated. The right side bottom panel in Fig.4 shows that the energy spectrum of backgrounds obtained La-GPS scintillation detector which was located in 5 cm Pb shield. According to the scale factor, we have set the trigger threshold around 280 keV. Dashed line represents the $\pm 1\sigma$ region of scattering gamma selection which we will

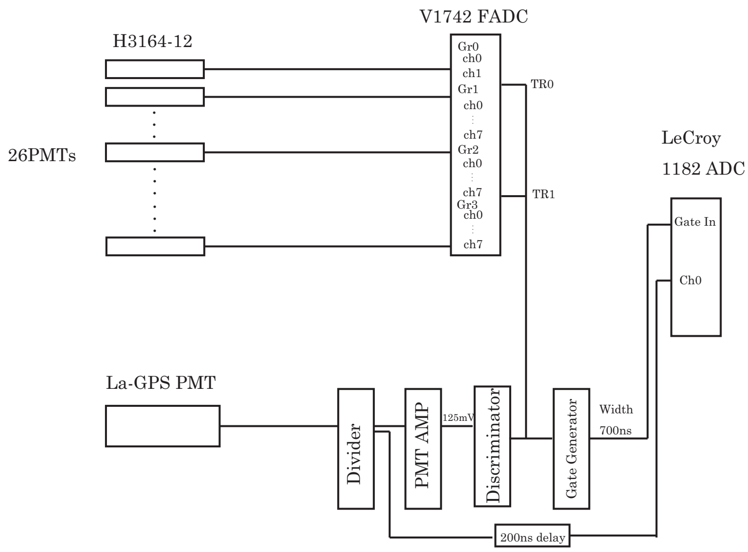

Figure 5. DAQ trigger logic is illustrated. Global trigger was generated by the signal from La-GPS scintillator, and it was sent to both LeCroy 1182 ADC which was converted the La-GPS PMT signal and CAEN V1742 FADC which is connected to 26 H3164-12 PMTs from HUNIZICOS detector. The trigger signal was inputted to TR0 and TR1 connectors which generates Fast (Low Latency) Local Trigger common to couples of groups.

discuss in the analysis section.

4. Data taking

As we explained in previous section, the data from V1742 FADC was acquired by global trigger generated by La-GPS scintillation detector. DAQ trigger logic is illustrated in Fig.5. V1742 FADC has TR0 and TR1 channel to take data as a fast (low latency) trigger. It makes high resolution timing to digitizing up to 50 psec. So we used these channels for input signal from the discriminator of La-GPS signals. Same signal was sent to the gate generator which generates external trigger gate (width 700 nsec) to 1182 ADC. Due to take a time of the gate generator, the original analog signal of La-GPS scintillator was delayed by 200 nsec.

We have two VME systems for DAQ environment. One is connected to Sun Ultra5 (Solaris 7) via SBS (Bit3) Model 618, and another is connected to Linux (CentOS 6) via CAEN V3718 (A2818). Both controllers connect between VME bus and PCI bus, respectively. The LeCroy 1182 ADC was mounted on Bit3 VME board, and the CAEN V1742 FADC on another VME, since the DAQ was controlled by individual data taking program. Therefore we had to merge those data event by event after the taking data using trigger timing.

All 26 channels of FADC data was taken for all events. The V1742 FADC has a local memory to store the data, so we took FADC data once every 1 second. On the other hands, 1182 ADC data was acquired by LAM bit on which means that the signal conversion was completed by the external trigger. According to dead time caused by the conversion, 1182 ADC data might be lost in spite of V1742 FADC data alive. Therefore we recorded system time when data was taken by each computer.

The data taking was continued during 2 or 3 days for 1 run, however, the FADC data was divided by 20 minutes for 1 sub run, because of limitation of data size (2 GB yte per 1 file for FORTRAN analysis program). It depended on the trigger rate of La-GPS scintillator, however, the typical data size became about 350 GByte for 1 run. Such huge data were stored in another Linux computer with huge disk space or NAS system.

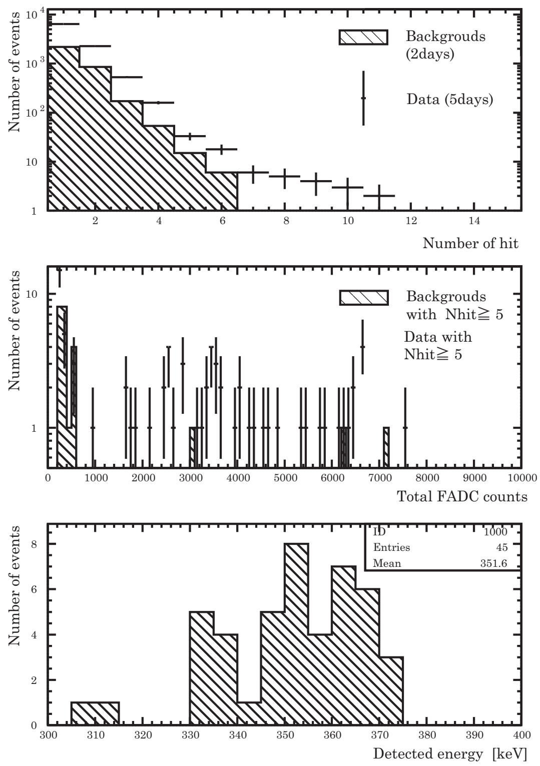

Figure 6. First event selection was done by Nhit cut as shown in top of panel. Most of backgrounds were clustered below 5 hit. Next selection was using by total FADC count. The middle panel shows the total FADC count distribution for data and backgrounds, and most of backgrounds were clustered blow 1000. After those event selections, remaining events shows that the energy distribution of the La-GPS signal was clustered around 352 keV as shown in the bottom panel.

5. Analysis

After data taking, we merged FADC data and ADC data using event record time stamped by those computers. FADC data was taken once every 1 second, so we had to select them within plus 1 second when the 1187 ADC detected 352keV gamma candidate.

Collected FADC events were analyzed by following step. First step is the number of hitted PMT (Nhit) cut. We took sum of FADC count between FADC time 50 and 80 nsec, which the peak was adjusted at 60 nsec for all channels and all events. The FADC count for each timing has been subtracted by baseline which is calculated by 40 timing (1 timing corresponds to 0.25 nsec) from first data. Then we count number of hitted PMT if the sum of FADC count exceed threshold. This threshold depends on each channels. We took those values carefully using background (no ^{88}Y source) run. Then next step was the calculation of total FADC count cut. After total FADC count cut, then we calculated the averaged angle assuming the vertex position was at the center of the truncated icosahedron PMT mounting jig (not the center of flat surface of the hemisphere flask).

The top panel of Fig.6 shows that Nhit distribution. According to this figure, most of FADC had a null hit because of accidental trigger due to backgrounds of La-GPS scintillation detector. Here we have plotted in the case of ^{88}Y source and no source. Despite of different data taking period, the event selection for (1) Nhit≥ 5 was applied by collecting on source event. The middle panel of Fig.6 shows total FADC count distribution for selected event by Nhit≥ 5. Clearly we could select on source event for (2) total FADC count greater than 1000 with a few backgrounds. After these selection, the energy distribution of La-GPS scintillation detector was illustrated by the bottom

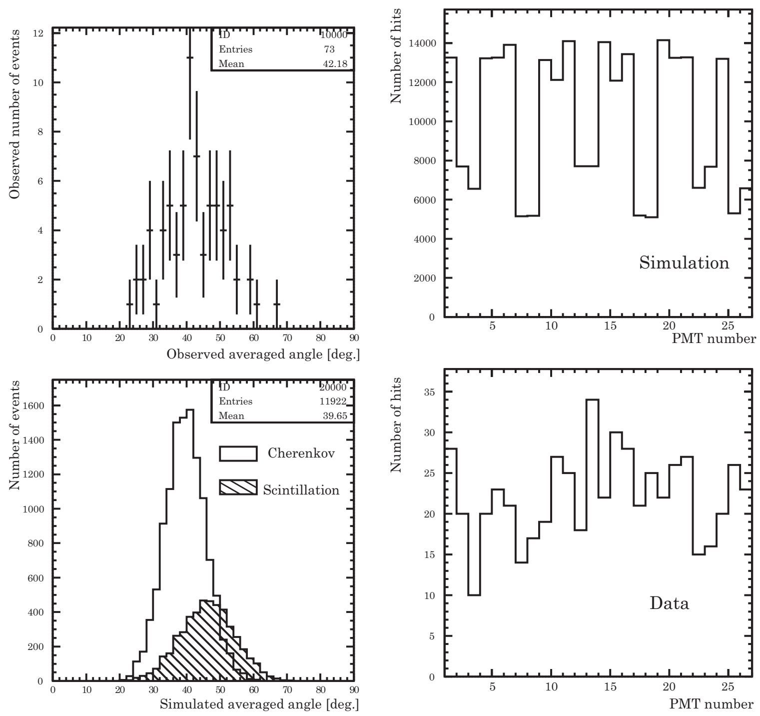

Figure 7. Lest side two panels show the averaged angle distribution. Top panel shows the data after event selection. The peak was seen around 40 degree. Bottom pane shows the simulation for both Cherenkov and scintillation. Cherenkov light (solid line) agree with the data, on the other hands, scintillation (shaded region) indicates the peak around 49 degree. This is consistent with the average value of angle between the direction of electron and the vector from the center of jig and each PMT, which is actually 52 degree. Right panels show the hitmap for simulation (top panel) and data(bottom panel). There is similar structure of PMTs whether open to receive Cherenkov photon or not, since the generated electron has a fixed direction to the center of hemisphere surface.

panel of Fig.6. As you can see, most of selected events clustered around 352 keV. Therefore, we succeeded to extract event of Compton scattering gamma. Then we could investigate the averaged angle for these events.

6 . Result and Discussion

After the event selection, we calculated the averaged angle for each events. The definition of the averaged angle was explained by our previous paper [2], but current definition was slightly different. In this time, the vertex position of each event was not the center of light yield for hitted PMT, because we did not use liquid scintillator for this measurement. Therefore we assumed the vertex was at the center of truncated icosahedron PMT mounting jig, where Compton scattering was occurred and the scattered gamma was detected through Pb block slit, even though the range of 1.484 MeV electron is about 7mm in Anisole. This assumption might affect the value of averaged angle, however, there might be no issue for the verification of averaged angle from simulation used by same definition.

The left side top panel of Fig.7 shows the averaged angle distribution for selected events by (1) and (2). Total data taking period is 8.5 days. The observed averaged angle was clustered around 40 degree. It was not Cherenkov angle 47 degree calculated by 1.484 MeV electron as we indicated by previous paper [2]. This might be caused by the difference of definition of the averaged angle as described above or the difference of PMT position. Even those reasons, the simulation could gave us answer to the verification. The left side bottom panel of Fig.7 shows the averaged angle distribution of simulation for Cherenkov light (line) and scintillation light (shaded region), respectively. Again the averaged angle was clustered around 40 degree in case of Cherenkov light. On the other hands, the averaged angle of scintillation was clustered around 49 degree. This was due to uniform emission of scintillation and PMT position of HUNI-ZICOS detector.

As described in previous section, a 1.484.MeV electron was generated with the fixed direction to the center of hemisphere surface. In this case, the PMTs which received Cherenkov lights was decided by Cherenkov ring. Using these PMTs, the calculated averaged angle value are 40 degree assuming vertex to be the center of PMT mounting jig. It is not 47 degree which has been obtained by old simulation with other PMT position. The value of angle itself is not essence for the topology of Cherenkov light. In order to confirm topology of Cherenkov light, the hitmap should be checked. The right side top panel of Fig.7 shows the hitmap of simulation for Cherenkov light. As you can see, PMT #2, #3, #7, #8, #12, #13, #17, #18, #22, #23, #25 and #26 have lower number of hit. This non flat structure is actually due to the topology of Cherenkov lights. Looking at the right side bottom panel of Fig.7, almost same non flat structure can be seen in case of real data except small detailed difference.

Simulation has complete asymmetric hit pattern due to fixed direction, however, the real data shows some tendencies due to the difference of event direction because of finite size of Pb block slit or La-GPS crystal. On the other hands, scintillation should emit uniformly, therefore all PMT equally receive scintillation and the hitmap has a complete flat structure. The angles between the direction of electron and each PMT from the center of PMT mounting jig are averaged and obtained by 52 degree. The shaded distribution in left bottom panel of Fig.7 corresponds to this angle. Slight difference might be caused by difference of number of hit (simulation was selected 5 to 10 hit).

In conclusion, we succeed to obtain the averaged angle for Cherenkov light emitted from 1.484 MeV electron with fixed direction, and it is 40 degree in case of HUNI-ZICOS PMT geometry and assuming vertex at the center of PMT mounting jig. Obtained hitmap seems to have same non flat structure as that of simulation due to topology of Cherenkov light. This is an evidence that Cherenkov lights emitted from 1.484 MeV electron should really have their topology and we can use the averaged angle for the reduction of ^{208}Tl backgrounds.

7. Conclusion

The topological information of Cherenkov light from low energy electron was measured by HUNIZICOS detector. The 1.484 MeV electron with the direction to the center of hemispherical surface of the detector was generated by Compton back scattering with 100 degree from ^{88}Y 1.836 MeV gamma. The observed averaged angle of Cherenkov light emitted from this electron was clustered around 40 degree assuming the vertex to be at the center of PMT mounting jig. It was not Cherenkov opening angle around 47 degree as obtained by old simulation and the vertex to be at the center of light yield for hitted PMT. According to the HUNI-ZICOS simulation, the averaged angle of Cherenkov light was also clustered around 40 degree. On the other hands, the simulated averaged angle of scintillation was clustered around 49 degree, which is almost consistent with the averaged angle value between the direction to center of surface and each photomultiplier from the center of PMT mounting jig. The observed hitmap seemed to have same non flat structure as that of simulation due to Cherenkov ring. This is an evidence that Cherenkov lights emitted from 1.484 MeV electron should really have their topology. Therefore, we concluded that we will be able to reduce ^{208}Tl background using the averaged angle for ^{96}Zr neutrinoless double beta decay search.

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HUN-ZICOS 検出器を用いたチェレンコフ光の位相幾何学情報の直接観測

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要　旨

HUNI-ZICOS 検出器を用いて低エネルギー電子が放出するチェレンコフ光の位相幾何学情報の直接観測を行った。単一方向・単色エネルギーを持つ電子を用いてチェレンコフ光の平均角を観測したところ、光電子増倍管を設置する切頂20面体の治具の中心をバーテックスと仮定すると、40度に事象が集中していた。また、シミュレーションによると、チェレンコフ光の平均角は同様に40度に集中していた。これに対して、シンチレーション光の平均角は49度に集中していた。これは、切頂20面体の中心から半球の中心方向と、各光電子増倍管との間の角度の平均値と一致している。また、観測された光電子増倍管のヒットマップはチェレンコフ光リングにより一定の構造にはなっておらず、シミュレーションのヒットマップの構造とも合致している。これらの事実は、低エネルギー電子から放射されたチェレンコフ光は位相幾何学情報を維持していることの証拠である。つまり、平均角を用いればニュートリノを放出しない二重ベータ崩壊事象の探索で問題となる^{208}Tl の背景事象を除去できると結論づけた。

Key words：ニュートリノを放出しない二重ベータ崩壊、液体シンチレータ、
チェレンコフ光、波形分別法、位相幾何学情報

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