研究論文

Demonstration of Tl-208 background reduction using a topological information of Cherenkov light for Zr-96 Neutrinoless Double Beta Decay experiment

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Abstract

The topological information (averaged angle) of Cherenkov light was measured by UNI-ZICOS detector. We have retuned the pulse shape discrimination for a selection of the photomultiplier which receives Cherenkov light for Hamamatsu H3164-12, and have developed a method of the vertex reconstruction. An averaged angle for fixed energy fixed direction electron generated by Compton scattering from ^{88}Y was used for the validity checking of the selection of PMT, and the obtained peak was found around 50 degree which was reproduced by Monte Carlo simulation. A pseudo background events of simultaneous beta and Compton electron scattered by gamma from the decay of ^{208}Tl was simulated by ^{60}Co source. Obtained data indicated that the averaged angle of simultaneous beta with $E \leq 1.48$ MeV plus gamma events should have a peak around 60 degree, and the value is different from 48 degree for an usual electron. In conclusion, the averaged angle will be able to use as reduction method for ^{208}Tl beta decay backgrounds even though they have an energy around 3.35 MeV which is Q-value of ^{96}Zr neutrinoless double beta decay.

Key words : Neutrinoless Double Beta Decay, Liquid Scintillator, Cherenkov Light, Topological Information, Tl-208 decay background

1. Background reduction using a topological information of Cherenkov light

For the measurement of ^{96}Zr neutrinoless double beta decay, natural U/Th series produce some backgrounds. Especially ^{208}Tl beta decay is one of most serious background, because of their energy deposits in the detector. The Q-value of ^{96}Zr neutrinoless double beta decay is 3.35 MeV, and this value is 3 rd highest energy of target nuclei. On the other hands, the maximum energy of beta decay from ^{208}Tl is 1.796 MeV (49%), and the emitted gamma has a 2.6145 MeV (99.2%). A large enough volume of the detector such as KamLAND-Zen may observe all these products, and therefore total energy could be around 3.35 MeV[1].

Two electrons emitted by $0\nu\beta\beta$ have an unique vertex, on the other hands, a beta and the Compton scattering electron from the decay of ^{208}Tl should

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have different vertex. Therefore the photomultiplier (PMT) hit pattern of Cherenkov light could be different. According to Monte Carlo simulation, 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 in Ref.[3], the pulse shape of Cherenkov light has also much faster rise time than that of Scintillation. Using CAEN V1751 FADC DES mode (2 GS/s), we have developed method of the pulse shape discrimination to select PMT which receives Cherenkov light using χ^2 method[4]. In that paper, we have obtained that Cherenkov light emitted by even O(1) MeV electron might keep their topology.

In order to verify the topology of Cherenkov light for O(1) MeV electron, we measured directly the averaged angle of the fixed energy and fixed direction (FEFD) electron generated by Compton scattering from ^{88}Y using HUNI-ZICOS detector[5]. Observed averaged angle was clustered around 40 degree, and the simulation reproduced this result well. Usually the averaged angle is equal to the Cherenkov angle, therefore the angle should be 48 degree in case of Anisole. This mismatch was due to both unique position of hitted PMT and the vertex to be assumed at the center of PMT jig, because no Scintillation was observed in this measurement. In fact, we succeeded that Cherenkov lights still keep their topology even though 1.484 MeV electron.

In this paper, we would like to measure an averaged angle for simultaneous beta and Compton electron scattered by gamma occurred in the detector such as ^{208}Tl decay, and would like to confirm that the averaged angle for those events should be different from the value for an usual electron.

2. Setup for the measurement

The conceptional design to measure the averaged angle is illustrated by the left panel of Fig.1. We made new detector UNI-ZICOS to measure the averaged angle of Cherenkov light for simultaneous beta and Compton electron scattered by gamma to demonstrate ^{208}Tl backgrounds. The detector contained ZICOS Liquid Scintillator (10 wt.% of Zr(iPrac)$_4$, 5 wt.% of PPO, and 0.2 wt.% of POPOP in Anisole) in the flask. Total 50 3/8 inch PMT Hamamatsu H3164-12 were mounted at all apexes of the truncated icosahedron jig except top and bottom regular pentagon, which has a hole at center for the Chimney and for Hamamatsu 1-inch PMT H3167 which used for DAQ trigger, respectively.

We used ^{60}Co isotope for beta and gamma source. The decay scheme of ^{60}Co is also illustrated in the middle panel of Fig,1. A 99.9 % of beta has a maximum energy 0.318 MeV, and two gammas with 1.173 and 1.332 MeV are emitted. On the other hands, a 0.12 % of beta has a maximum energy 1.491 MeV, and only 1.332 MeV gamma is emitted. The energy threshold to emit Cherenkov light in Anisole is 0.18 MeV, so both betas have enough energy to emit Cherenkov photon.

The right top panel of Fig.1 shows the beta source prepared by Japan Radioisotope Association (JRIA), and the right bottom panel shows a holder of the beta source. Four Teflon threads supports the holder from top of the Chimney with a rubber stopper. According to the description from JRIA, the beta source has thin Aluminum (Al) window (5mg/cm^2 which corresponds to 0.0185mm thickness), and therefore all betas should deposit their energy in thewindow. Expected maximum energies after passing Al window are 0.3 MeV and 1.48 MeV,respectively.

The left panel of Fig.2 shows the photograph of UNI-ZICOS detector. All signal cables from H3164-12 PMT were connected to two CAEN V1742 FADCs (32 Channel 12 bit 5 GS/s Switched Capacitor Digitizer) as shown in the right panel of Fig.2. Due to limitation of data transfer speed, the trigger rate should be less than 5 Hz. In case of 2.5 Hz, the data size was 1.2 GByte per 10 minutes.

Most observed events should be Compton electron

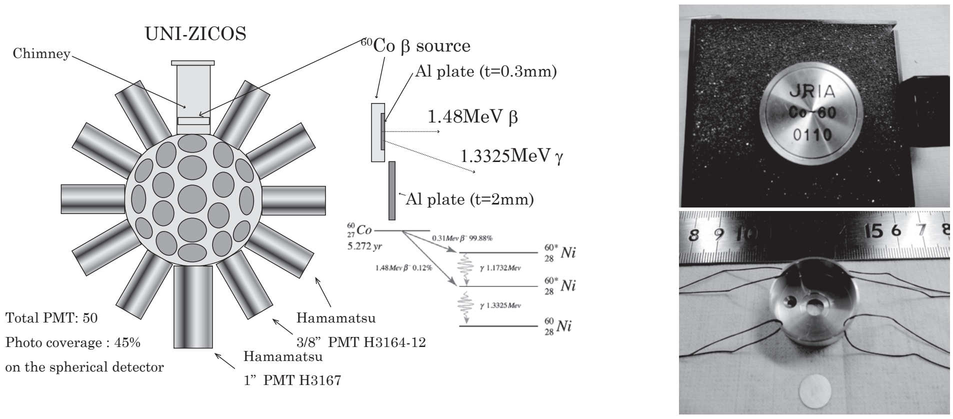

Figure 1. The conceptional design to measure the averaged angle from beta with maximum energy 1.48 MeV and 1.332 MeV gamma simultaneously using UNI-ZICOS detector. The detector has total 50 of Hamamatsu 3/8 inch H3164-12 photomultiplier on the hemispherica surface. At bottom, Hamamatsu 1-inch H3167 PMT is used for a trigger.

Figure 2. Photographs of UNI-ZICOS detector and CAEN V1742 digitizer.

scattered by gamma, because small fraction of beta can reach at the surface of liquid scintillator due to small acceptance of the chimney. Therefore we took two dataset whether Al plate with 2mm thickness was inserted just below ^{60}Co source or not. This means that 2mm Al plate terminates all betas completely.

3. Vertex reconstruction

Using same technique to provide a template of the charge ratio (*Qtime/Qtotal*) as shown in our previous paper Ref.[4], we retuned χ^2 method of the pulse shape discrimination for PMT H3164-12 using HUNI-ZICOS detector. Using this χ^2, we can select PMT which receives Cherenkov light even though in the liquid scintillator. An averaged angle is the topological information of Cherenkov lights, and the definition is represented as following formula;

$$\text{averaged angle} = \sum_{\mathrm{i=1}}^{\mathrm{Nhit}} \theta_{\mathrm{i}}/\mathrm{Nhit} \qquad (1)$$

where θ_i is an opening angle between an averaged direction and unit vector from the vertex to i-th PMT position, and Nhit is the number of PMT which receives Cherenkov light. An averaged direction is also obtained by adding all unit vectors. According to the definition of the averaged angle, we have to obtain the vertex position using an information of the scintillation. The detector size is so small that the arrival timing of each PMT can not be used for obtaining the vertex. In spite of the timing, we use a photon yield of each PMT for the vertex reconstruction. Assuming the vertex as a point at the center of the detector, the scintillation photon

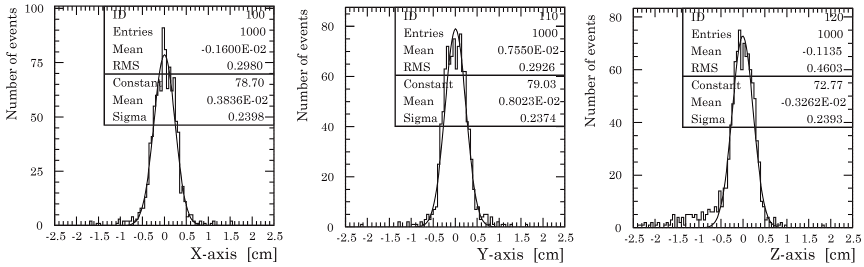

Figure 3. The vertex reconstruction was done by using simulation.

yield detected by each PMT should be same, since all PMTs are mounted on a spherical surface.

Even if the vertex is not at the center of the detector, we can correct each photon yield by the distance between the vertex and PMT position. Most probable vertex position could be reconstructed by assuming that all PMTs should have same effective photon yield which is corrected by the distance between PMT position and the vertex. Figure 3 shows 3 dimensional differences between the reconstructed vertex and generated position using Monte Carlo simulation. Here we define that X-axis and Y-axis are on the horizontal plane and Z-axis is set to a vertical direction to the plane. The origin is set at the center of flask, and the positive direction of Z is set to the Chimney. Obtained vertexes are clustered around generated positions, and the sigma is almost 0.24 cm for every dimension.

4. Averaged angle for fixed energy fixed direction electron

Before taking data for a measurement of the averaged angle of simultaneous beta and Compton electron events, we have to take same kind of data for the averaged angle using fixed energy fixed direction (FEFD) electron generated by Compton scattering from ^{88}Y as reported in Ref.[5]. Since the vertex position is able to calculate using by the method described in previous section, an actual averaged angle should be obtained. If the selection of PMT which receives Cherenkov light is correct, then the averaged angle predicted by Monte Carlo simulation show same distribution as data.

Here we have to say about a poor statistics of data. During this measurement, we had a big earthquake in March 2022. We have lost 5 PMT for UNI-ZICOS and some DAQ components were broken. It took more one month to recover the system, therefore the time of measurement was limited. Even though such missing PMTs, it should be small effect for the measurement of an averaged angle, because of their scattered positions.

The observed averaged angle for FEFD electrons is clustered around 50 degree as shown in left panel of Fig.4. As reported in Ref.[5], the averaged angle was clustered around 40 degree. This was due to both an unique position of PMT which receives Cherenkov light and the vertex position assumed to be at the center of truncated icosahedron photomultiplier jig. In this time, the vertex is reconstructed by using scintillation photon yield for each PMT, therefore the peak value should be different. Both peak position of averaged angle for data and Monte Carlo simulation are clustered around 50 degree as shown in Fig.4. It is easily understood that the averaged angle is almost same as Cherenkov angle. In case of Anisole, Cherenkov angle is 48 degree. From this result, our selection of PMT using the pulse shape discrimination is correctly working.

5. Detector response using gamma ray

Next we have measured the energy spectrum of several gamma sources. In this measurement, we used both PMT H3167 which was mounted at the bottom of UNI-ZICOS detector and No4 H3164-12

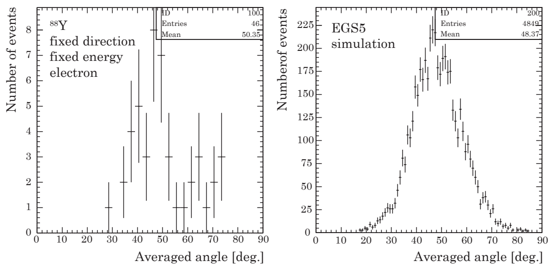

Figure 4. The left panel shows observed average angle for fixed energy and fixed direction electron produced by Compton scattering from ^{88}Y. The right panel shows a simulated averaged angle. Both peaks are clustered around 50 degree.

which was mounted on the first row (total 5 H3164-12 PMTs were mounted on first row) for DAQ trigger in order to detect an incident beta efficiently. Coincidence method was also used for rejecting accidental backgrounds such as an electrical noise.

Figure 5 shows observed total charge distribution for 1.484 MeV FEFD electron from ^{88}Y, Compton scattering for several gamma sources (^{137}Cs, ^{60}Co, ^{22}Na, and ^{88}Y), and Monte Carlo simulation of ^{60}Co. The charge was obtained by summing FADC counts, and it corresponds to the light yield of PMT. Actually the simulation represents the photon yield. Total charge was also obtained by summing all charges of hitted PMT. Total charge distribution of FEFD electron has a peak around 94,610 counts as shown in top left panel of Fig.5. Considering all positions of Compton edge for each RI, the energy scale of UNI-ZICOS detector has a good linearity as 65 counts/keV. Also total photon yield distribution for Monte Carlo simulation of ^{60}Co indicated in case of both only gamma (solid cross), simultaneous beta with maximum energy 1.48 MeV ($E \leq 1.48$MeV) plus gamma (dashed cross), and only beta with $E \leq 1.48$ MeV (dotted cross). However the number of beta events is not actual one, there should exist a difference around the Compton edge of 1.332 MeV gamma. Also only beta events should not contribute if we selected data around the Compton edge.

6. Data selection for simultaneous beta and Compton electron scattered by gamma

Finally we measured the averaged angle for simultaneous beta and Compton electron scattered by gamma from ^{60}Co source. The source was inserted into the Chimney of UNI-ZICOS detector,therefore beta with maximum energy 0.3 MeV could be detected by liquid scintillator. However, as described in setup section, most of observed events were only Compton electron, so the event rate should be much smaller than the radioactivity 100 kBq of ^{60}Co source. In fact, we have tuned the trigger threshold as trigger rate to be less than 5 Hz as described in setup session.

Top two panels of Fig.6 show the total charge distribution for ^{60}Co beta source in case of both no 2mm Al plate (cross) and inserting the plate (hatched) in case of total charge > 90,000, because we use only data around the Compton edge. Again the 2mm Al plate completely terminates all betas. Top left panel shows higher region of total charge, and there is clear peak around 450,000 which is generated by cosmic muons. The peak position is so quite same between them that the PMT gain was stable in those data taking. Top right panel shows total charge distribution around the Compton edge. There seems to be difference between Al plate on and off. The excess is caused by simultaneous beta and Compton electron scattered by gamma event. We call herefrom this event as simultaneous beta plus gamma. Middle and Bottom panels of Fig.6 show Z and R= $\sqrt{x^2+y^2}$ distribution for Monte Carlo simulation and data, respectively. According these results, we have to select events with $Z > 0$ cm and $R < 10$ cm for the analysis of an averaged angle using simultaneous beta with maximum energy 1.48 MeV plus gamma.

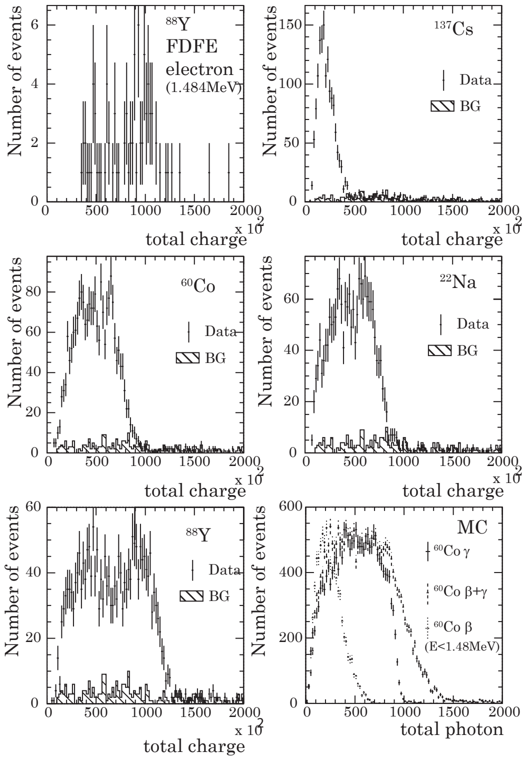

Figure 5. The top left panel shows the total charge distribution of fixed energy and and fixed direction electron generated by Compton scattering from ^{88}Y. From top right to bottom left panels show the total charge distribution of Compton scattering for several gamma sources. The bottom right panel shows total charge distribution for Monte Carlo simulation in case of only gamma (solid cross), simultaneous beta with maximum energy 1.48 MeV plus gamma (dashed cross) and beta only (dotted cross).

7. Averaged angle for simultaneous beta and Compton electron

Using data selection described above section, we took data using ^{60}Co beta source located in the Chimney of UNI-ZICOS detector. The left panel of Fig.7 shows the averaged angle which is obtained by ^{60}Co beta source with 2mm Al plate (hatched) and without plate (cross), respectively. The right panel shows the averaged angle distribution obtained by subtracting those data. Considering 2mm thickness of the plate, gammas should be absorbed about 3.4 % in the plate.

The averaged angle distribution after subtracting those data might have a peak at 58 degree. For the the simulation of simultaneous beta with $E \leq 1.48$ MeV plus gamma, the averaged angle distribution has a peak around 60 degree. Those peaks looks agree well, however, considering tail distribution above 60 degree, the distribution of data and simulation do not match so well as shown in left panel of Fig.8.

According to the bottom right panel of Fig.5 and the top right panel of Fig.6, most excess events observed by simultaneous beta plus gamma should not be caused by beta with $E \leq 1.48$ MeV, but $E \leq 0.3$ MeV. Then the averaged angle distribution for simulation of simultaneous beta with $E \leq 0.3$ MeV plus gamma shows the middle panel of Fig.8. Actually the energy of this beta is much smaller than the energy of Compton edge, so the contribution of Cherenkov light of this beta for the calculation of averaged angle should be weak. Therefore, the peak position of averaged angle of gamma only event and simultaneous beta with $E \leq 0.3$ MeV plus gamma is almost same.

If we assume to observe both beta with $E \leq 0.3$ MeV and with $E \leq 1.48$ MeV, the combined distribution for both simulations looks reproduce observed data as shown in right panel of Fig.8. However, for the

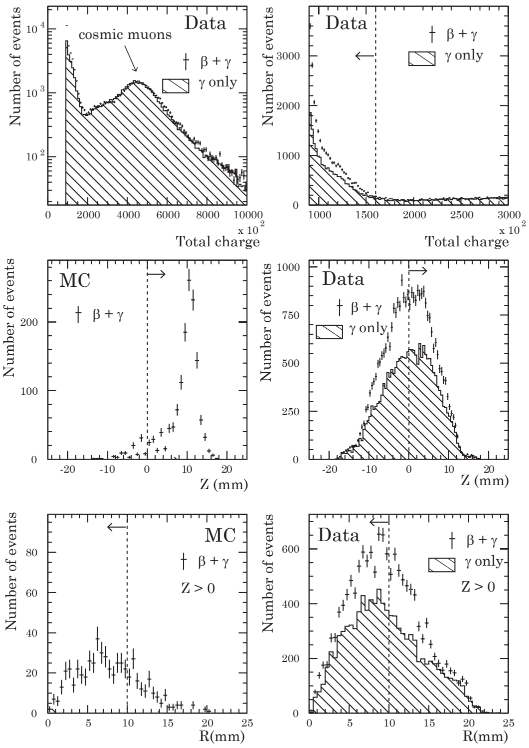

Figure 6. Top two panels show the total charge distribution in case of without Al plate (cross) and with plate (hatched). The top left panel shows higher region, and the peak around 450,000 is produced by cosmic muons, and they are consistent. The top left indicate for lower region. Middle panels shows vertex distribution in Z axis. The middle left panel shows case of simulation for simultaneous beta with $E \leq 1.48$ MeV and gamma and right panel shows data with and without Al plate in case of 90, 000 < total charge < 160, 000. The bottom panels show also the vertex distribution in Radius for simulation and data but both vertex cut $Z > 0$ mm was applied. For data, the total charge cut was also applied.

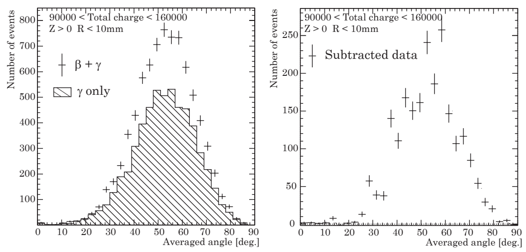

Figure 7. The left panel shows the averaged angle distribution for data with 2mm Al plate (hatched) and without plate (cross). The right panel shows the averaged angle distribution obtained by subtracting those data with the attenuation correction of gamma in the plate.

distribution below 50 degree, the simulation does not reproduce the data.

In order to confirm above assumption, we inserted 0.3mm Al plate to terminate beta with $E \leq 0.3$ MeV. The left panel of Fig.9 shows the averaged angle distribution of data with 0.3 mm Al plate (cross) and with both 0.3 mm and 2 mm plate (hatched). Former case indicates that only beta with $E < 1.48$ MeV (a few hundred keV energy should deposit in 0.3 mm Al plate) might exist in Compton edge events. On the other hands, latter case indicates that only Compton edge events exist. Subtracting those data with considering attenuation in 2mm Al plate, the residual averaged angle distribution should be caused by simultaneous beta with $E < 1.48$MeV plus gamma.

The right panel of Fig.9 shows the averaged angle distribution of subtracting data (cross) and simulation of simultaneous beta with $E < 1.48$ MeV plus gamma

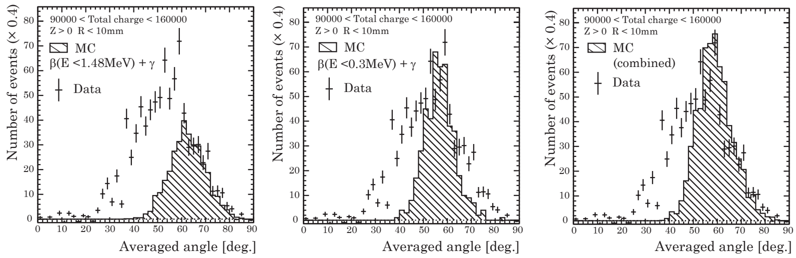

Figure 8. The left panel shows the averaged angle distribution for subtracted data and simulation of simultaneous beta with $E \leq 1.48$ MeV plus gamma. The middle panel shows same data but simulation of simultaneous beta with $E \leq 0.3$ MeV plus gamma. The right panel shows same data and combined those simulations. Note that the number of binning is different from other figures.

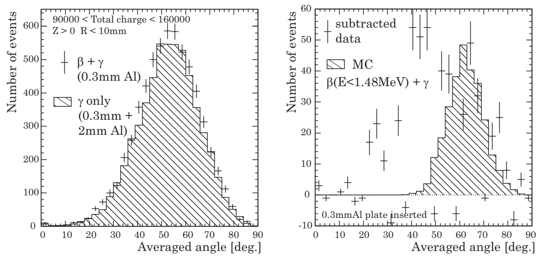

Figure 9. The left panel shows the averaged angle distribution for data with 0.3mm Al plate (cross) and with both 0.3mm and 2mm Al plates (shaded). The right panel shows subtracting data (cross) and simulation of simultaneous beta with E <1.48 MeV plus gamma events (shaded).

(shaded). In this case, there are two peaks for data around 40 degree and 65 degree. If we overlay adequately the distribution of the simulation on data, the distribution looks agree with higher peak of subtracted data. Again the simulation does not reproduce the observed distribution below 50 degree.

In this analysis, we did not consider the contribution for beta only events due to smaller scintillation photon yield than that of Compton edge as shown in the bottom right panel of Fig.6. Betas deposit their energy at near surface of the liquid scintillator, therefore the acceptance of PMT should be smaller than that of inner events. However, the simulation do not take into account the reflection at the boundary of surface of our liquid scintillator. Actual scintillation photon yield of data could be larger than that of simulation due to such reflection. In this point of view, the averaged angle distribution below 50 degree may come from beta only events, however we can not recognize the source.

In results, the averaged angle of simultaneous beta plus gamma should have a peak around 60 degree, and it is different from 48 degree for usual electron. This means that the averaged angle of simultaneous beta and Compton electron scattered by gamma from ^{208}Tl decay should be different from other physics events, so we will be able to use this technique to reduce backgrounds from ^{208}Tl beta decay which will be appeared around 3.35 MeV which is Q-value of ^{96}Zr neutrinoless double beta decay.

8. Conclusion

In order to measure the averaged angle using UNI-ZICOS detector, we have returned the pulse shape discrimination for selection of PMT which receives Cherenkov lights, and have developed a method of the vertex reconstruction. Using new these methods, we took data for FEFD events from ^{88}Y and the averaged angle distribution had a peak around 50 degree, and the simulation also reproduced. This is easily understood that the averaged angle is almost same as Cherenkov angle (48 degree). This indicated that the selection method seems to be working well.

The averaged angle of Cherenkov light from simultaneous beta plus gamma using ^{60}Co beta source was measured. Obtained data indicated that the averaged angle of simultaneous beta with $E \leq$ 1.48 MeV plus gamma should have a peak around 60 degree, and the value is different from 48 degree for an usual electron.

In conclusion, the averaged angle will be able to use as background reduction method for ^{208}Tl beta decay even though they have an energy around 3.35 MeV which is Q-value of ^{96}Zr neutrinoless double beta decay.

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Zr-96によるニュートリノを放出しない二重ベータ崩壊実験のための チェレンコフ光の位相幾何学情報を用いたTl-208背景事象除去の実証

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要　旨

チェレンコフ光の位相幾何学情報（平均角）をUNI-ZICOS検出器で測定した。まず、浜松ホトニクス社のH3164-12光電子増倍管を用いてチェレンコフ光を受光した光電子増倍管を選択するためにパルス形状弁別の方法を再調整し、事象のバーテックスの再構成の方法を開発した。これらを用いて、^{88}Yからのコンプトン散乱により一定エネルギーで一定方向に生成される電子の平均角度を測定したところ、得られた平均角のピーク位置は約50度であり、モンテカルロシミュレーションでも、ほぼ再現した。更に、ベータ電子とコンプトン電子を同時に観測する^{208}Tlの疑似背景事象を^{60}Co線源を用いて再現したところ、1.48MeVの最大エネルギーを持つベータ線とガンマ線によるコンプトン電子が同時に発生した事象の平均角は60度であり、通常の電子事象の48度とは異っていた。結論として、^{96}Zrニュートリを放出しない二重ベータ崩壊を観測する際に約3.35MeV付近に観測される^{208}Tl崩壊の背景事象を除去する手法として、平均角が使用できることがわかった。

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、位相幾何学情報、Tl-208背景事象

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