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# Reduction of Tl-208 background for Zr-96 neutrinoless double beta decay experiment using topological information of Cherenkov light

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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 $\beta$ 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 a 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.

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## 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 3rd 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 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. We have developed a method of the pulse shape discrimination to select PMT which receives Cherenkov light using $\chi^2$ 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]. In result, Cherenkov light still kept 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 left 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.

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

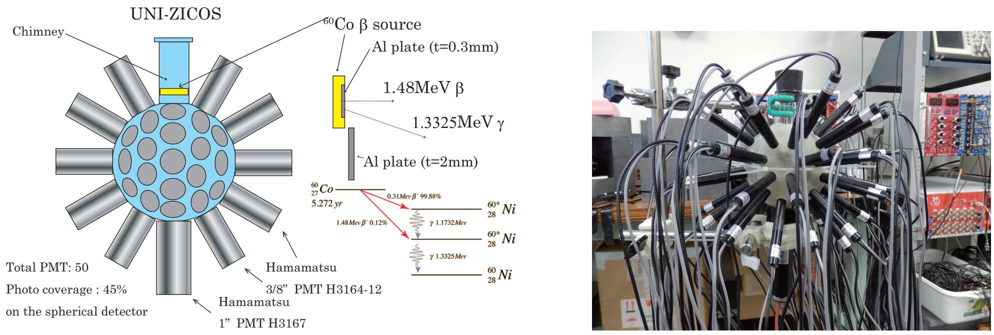


**Figure 1:** The conceptional design to measure the averaged angle from beta with maximum energy 1.48 MeV and 1.332 MeV gamma simultaneously using UNI-ZICOS detector. The detector has total 50 of Hamamatsu 3/8 inch H3164-12 photomultiplier on the hemispherical surface. At bottom, Hamamatsu 1-inch H3167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

energy in the window. Expected maximum energies after passing Al window are 0.3 MeV and 1.48 MeV, respectively. The right panel of Fig.1 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).

## 3. Definition of averaged angle

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

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

where $\theta_i$ 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 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. 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.

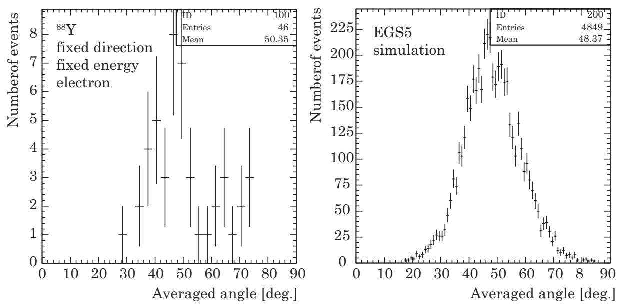


**Figure 2:** Left panel shows observed average angle for fixed energy and fixed direction electron produced by Compton scattering from $^{88}$Y. Right panel shows a simulated averaged angle. Both peaks are clustered around 50 degree.

The observed averaged angle for FEFD electrons is clustered around 50 degree as shown in left panel of Fig.2. 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.2. 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. Averaged angle for simultaneous beta and Compton electron

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.

The top left panel of Fig.3 shows the averaged angle which is obtained by $^{60}$Co beta source with 2mm Al plate (hatched) and without plate (cross), respectively. The averaged angle distribution after subtracting those data concerning 3.4 % attenuation of gamma has a peak at 58 degree as shown in top right panel of Fig.3. For the the simulation of simultaneous beta with $E$ $\leq$1.48 MeV

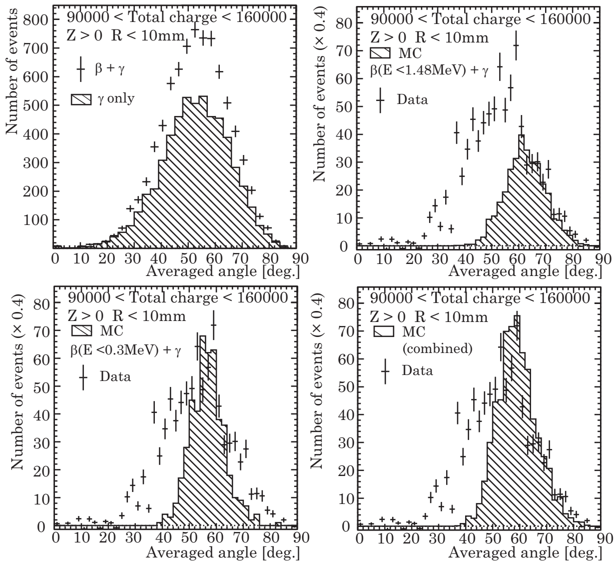


**Figure 3:** Left panel shows the averaged angle distribution for subtracted data and simulation of simultaneous beta with $E \leq 1.48$ MeV plus gamma. Middle panel shows same data but simulation of simultaneous beta with $E \leq 0.3$ MeV plus gamma. Right panel shows same data and combined those simulations. Note that the number of binning is different from other figures.

plus gamma, the averaged angle distribution has a peak around 60 degree as hatched shown in same figure. Considering tail distribution above 60 degree, the averaged angle ddistribution for data and simulation do not match so well as shown in top right panel of Fig.3.

In fact, 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 is illustrated in bottom left panel of Fig.3. 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 bottom right panel of Fig.3. However, for the 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.4 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.4 shows the averaged angle distribution of subtracting data (cross) and simulation of simultaneous beta with $E < 1.48$ MeV plus gamma (hatched). In this case, there are two peaks for data around 40 degree and 65 degree. If we overlay adequately the distribution of

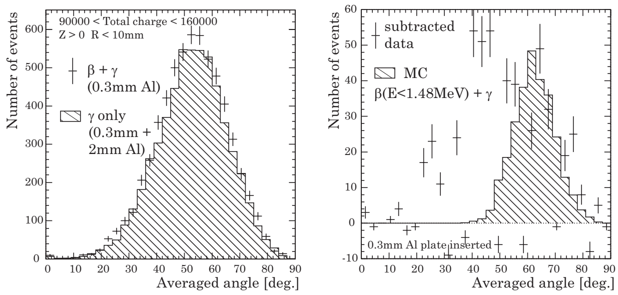


**Figure 4:** The left panel shows the averaged angle distribution for data with 0.3mm Al plate (cross) and with both 0.3mm and 2mm Al plates (shaded). The right panel shows subtracting data (cross) and simulation of simultaneous beta with $E$ <1.48 MeV plus gamma events (shaded).

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 do not consider the contribution for beta only events due to smaller scintillation photon yield than that of Compton edge as indicated by Monte Carlo simulation. Most of 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. 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 conclusion, 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 the Q-value of $^{96}$Zr neutrinoless double beta decay.

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