研究論文

Performance of 2ν-ZICOS detector for two neutrino emission double beta decay using ^{96}Zr nuclei

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Abstract :

2ν-ZICOS experiment has been planned to measure the half-life of two neutrino emission double beta decay for ^{96}Zr nuclei. A newly designed 2ν-ZICOS detector will observe about 70 events of ^{96}Zr double beta decay using a special ETFE cubic bag, which will contain 720ml ZICOS liquid scintillator. The performance of 2ν-ZICOS detector such as the energy scale, the energy resolution, the vertex reconstruction, and the averaged angle, which is used for the reduction of beta decay events from ^{208}Tl, will be calibrated by using several radioactive gamma-ray sources. Here we will report some results of Monte Carlo simulation for those calibrations.

Key words : Neutrino emission double beta decay, Liquid scintillator, Energy scale, Energy resolution, Vertex reconstruction

1. 2ν-ZICOS detector

ZICOS is one of the future experiments for neutrinoless double beta decay. The target nuclei is ^{96}Zr and the Q-value is 3.35 MeV, therefore the radioactive backgrounds such as ^{214}Bi in Uranium series and ^{10}C, which is spallation product of energetic cosmic muons, could be removed by their lower energy.

The conceptional design of ZICOS detector is shown in the left panel of Fig. 1 .The detector consists of a spherical frame mounted by photomultipliers (PMTs), an inner balloon filled with 113 tonnes of liquid scintillator containing tetrakis(isopropyl acetoacetato)zirconium ($Zr(iPrac)_4$), and a buffer space for outside of the inner balloon filled with pure Anisole. Therefore it is almost similar structure as KamLAND-Zen detector. As reported by KamLAND-Zen-800 [1], non-negligible backgrounds were found around 3-4 MeV, and those were the decay products from ^{208}Tl which was not only adhere on the surface of inner balloon but also internal liquid scintillator. Fortunately, the Q-value of ^{136}Xe is 2.479 MeV so those backgrounds did not affect due to out of region of interest (ROI).

However, ^{208}Tl beta decay should be serious background for ZICOS experiment, because of the overlap with ROI for ^{96}Zr $0\nu\beta\beta$ events. In order to obtain half-life of order 10^{27} to 10^{28} years, we have to enrich ^{96}Zr to be 20-50%, and reduce 95% of ^{208}Tl

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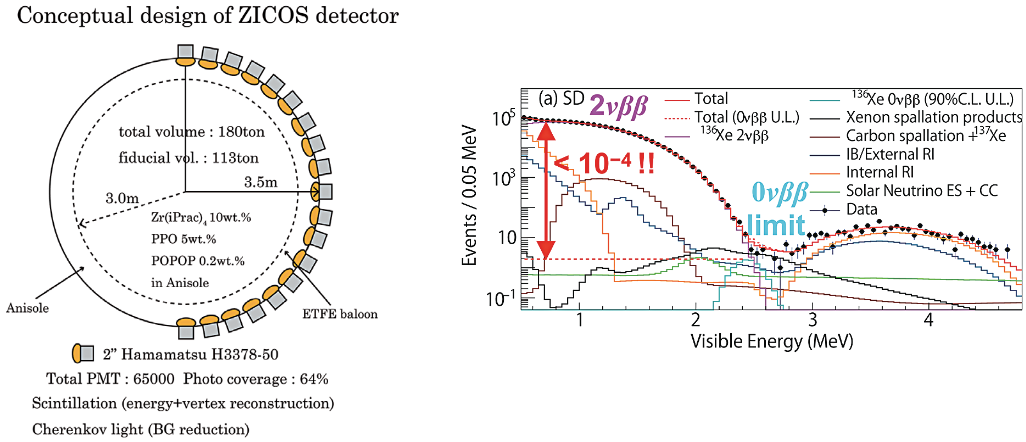

Figure 1. The left side panel shows the conceptional design of ZICOS detector. The inner detector is located in a pure water tank which is shield for external radiation, and has huge number of fast timing photomultipliers such as Hamamatsu H3378-50 with 64% photo coverage. The inner balloon will be filled with a liquid scintillator which contains 10 wt.% of $Zr(iPrac)_4$, 5 wt.% of PPO and 0.1 wt.% of POPOP. The outside of inner balloon will be filled with a pure Anisole in order to reduce background events from the balloon. The right side panel shows the recent results from KamLAND-Zen-800 ^{136}Xe $0\nu\beta\beta$ observation [1].

background as observed in KamLAND-Zen. For that purpose, we have developed the averaged angle which is topological information of Cherenkov lights as discussed in our previous papers [2][3][4][5][6], even though ^{208}Tl decay may still remain on the surface of inner balloon.

^{96}Zr is also a candidate nuclei of $2\nu\beta\beta$. The half-life was measured by NEMO-3 experiment using the tracking drift chamber. Using 9.4 g of ^{96}Zr and 1221 days observation corresponding to 0.031 kgy, the obtained half-life was $T^{2\nu}_{1/2} = [2.35 \pm 0.14(stat.) \pm 0.16(sys.)] \times 10^{19}$ years [7] They observed 429.2 ± 26.2 events with a 7.5% efficiency. Using this result, about 200 events for $2\nu\beta\beta$ using 1 g of ^{96}Zr will be observed, if the detector efficiency reaches at 100%.

As described above, 200 events of $2\nu\beta\beta$ will be observed using an order of 1 g for ^{96}Zr nuclei. For the purpose, we have prepared 2ν-ZICOS detector as shown in the left side panel of Fig. 2 . This detector uses 16cm diameter round bottom flask using an pure quartz (GE214), which is shown in right panel of Fig. 2 , and 20 low-background fast rise-time 2inch PMT Hamamatsu H3378-50, which will be used not only for both the energy scale and the vertex reconstruction with scintillation but for the background event reduction with the pulse shape discrimination of Cherenkov lights, are mounted at the surface of the regular icosahedron with 8cm radius of inscribed sphere. A 0.73 little of liquid scintillator loaded 73 g of $Zr(iPrac)_4$, which contained about 0.3 g of ^{96}Zr, will be filled inside of inner ETFE bag (9cm cubic). The expected number of signals for 2 neutrino double beta decay is about 70 events per year among about 1 million backgrounds.

Thus 2ν-ZICOS detector will observed $2\nu\beta\beta$ events using both their energies and vertexes, and will remove the beta decay events form ^{208}Tl, which might contaminate the flask, with the emission of famous 2.615 MeV gamma-ray using a topological informationof Cherenkov lights. Therefore the performance of 2ν-ZICOS detector such as the energy scale, the energy resolution, the vertex reconstruction, and the averaged angle which is topological information of Cherenkov lights are very important, and those will be calibrated by using several radioactive gamma-ray sources. This paper will report some results of Monte Carlo simulation for those calibrations.

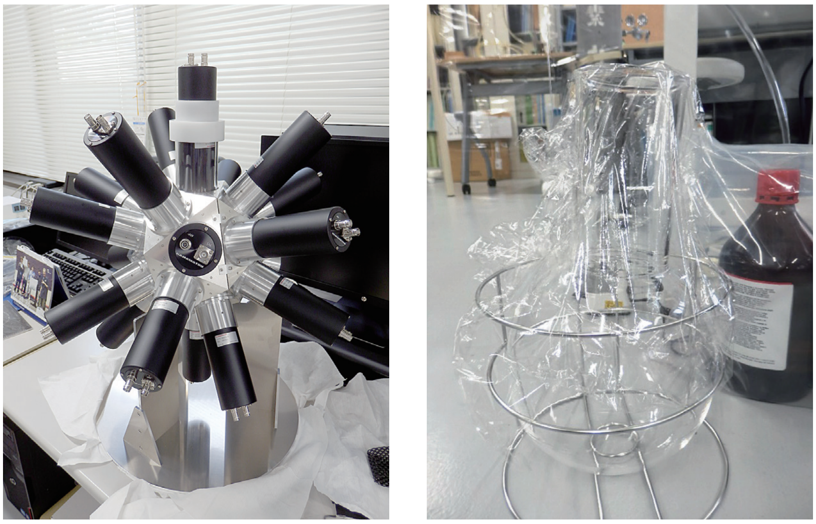

Figure 2. The left side panel shows the picture of 2ν-ZICOS detector. Total 20 Hamamatsu H3378-50 PMTs are mounted at the surface of regular icosahedron with 8cm radius of inscribed sphere. The PMTs receive not only scintillation lights but also Cherenkov lights. The right side panel shows a ultra-pure quartz round bottom flask.

2. Energy scale and resolution

The energy scale will be performed by using gamma-ray sources from outside of 2ν-ZICOS detector. We have radioactive sources for ^{137}Cs(662 keV), ^{60}Co(1.173 MeV, 1.332 MeV), ^{22}Na(1.275 MeV, 0.511 MeV), and ^{88}Y(0.898 MeV(93.7%), 1.836 MeV(99.2%)). The simulation was executed in case of the source position (+30cm, 0cm, 0cm) and the electron scattered by induced gamma-ray was tracked by an entire region of the detector. Therefore Cherenkov photon was also generated by whole region even for inside or outside of inner ETFE bag, however the scintillation photon was only generated by inside the ETFE bag.

Figure 3 shows the detected photon yield distribution of scattered electron for each radioactive source from the simulation using scintillation only. Most of reaction should be Compton scattering, so that no peak due to photo-electric effect was found. Figure 4 shows also the correlation between energy deposited in the scintillator and detected total photon for each radio-active sources. There is a clear linearity between the observed scintillation yield and the deposited energy inside of ETFE bag, therefore we will be able to use the total photon yield as a scale of the electron energy.

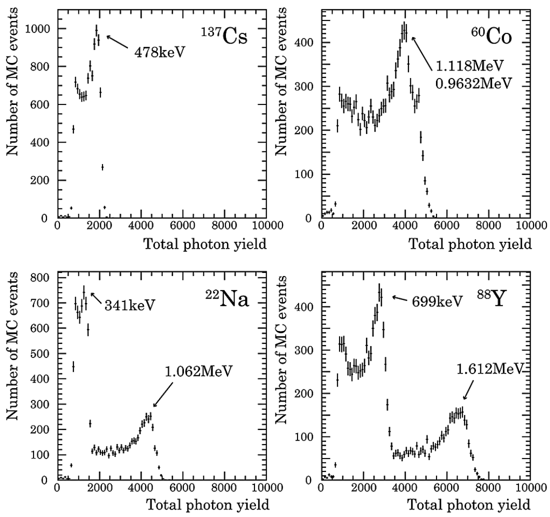

Figure 3. From left top panel to right bottom panes show the detected photon yield for radioactive gamma-ray sources for ^{137}Cs(662 keV), ^{60}Co(1.173 MeV, 1.332 MeV), ^{22}Na(1.275 MeV, 0.511 MeV), and ^{88}Y(0.898 MeV(93.7%), 1.836 MeV(99.2%)). The energies indicated in each panel correspond to the energy of Compton edge.

An energy resolution will be not so easy to demonstrate experimentally. The fixed energy fixed direction (FEFD) electron explained by Ref.[10] will be one of the option to get energy resolution using 1.836 MeV gamma-ray from ^{88}Y. Using illustrated setup in left panel of Fig. 5 , an electron with a monochromatic

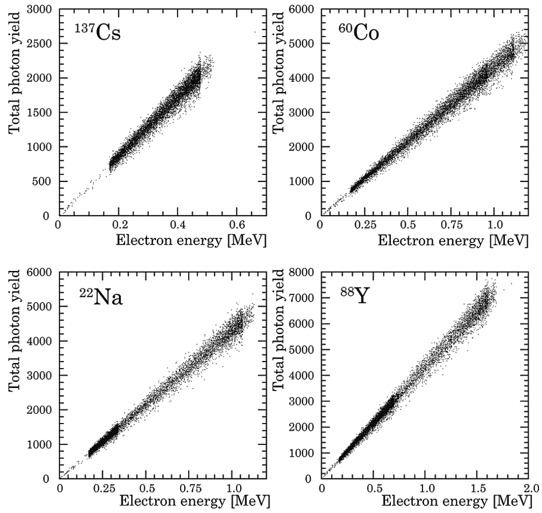

Figure 4.　From left top panel to right bottom panes show the correlation between detected total photon yield and the energy deposited in the scintillator for each radioactive isotopes. Clear linearity was found.

energy of 1.484 MeV will be obtained. The simulated total photon yield for this setup is illustrated in the right panel of Fig. 5 . The energy resolution seems to be almost 1% for 49% photo coverage of 2ν-ZICOS detector, however it is quite better than one we estimated before as described in Ref.[8]. This simulation did not consider the experimental condition such as noise or scintillation fluctuation. We will have to check actual energy resolution carefully.

3. Vertex reconstruction and resolution

A method of the vertex reconstruction has been developed for UNI-ZICOS detector as described in Ref.[10], however there was no clear explanation of the method in the paper.

The scintillation photon emits uniformly at the track position of charged particle. In the simulation, the charged particle (electron) was tracked at each adequate step, and corresponding numbers of photon were generated with uniform direction. Each photon was also tracked until PMT counts the photon if the photon goes into the photo cathode area. In this time, total amount of photon corresponding energy could be tuned by 10000 photon/MeV for scintillation and 100 photon/MeV for Cherenkov light, but we did not take into account the photoelectric efficient of the PMT cathode.

Using detected number of photon (DNP_i) for i-th hitted PMT, we calculated the corrected number of photon (CNP) as following equation;

$$\mathrm{CNP}_i = \mathrm{DNP}_i \times (\frac{r}{d_i})^2 \frac{1}{\cos\theta_i} \qquad (1)$$

where d_i and r show the distance between i-th hitted PMT and possible vertex position and the radius of the detector, respectively. θ_i is the opening angle between the direction of photon and the direction to i-th hitted PMT from center. After this calculation, we summed total number of corrected photon for all hitted PMTs, and obtained averaged value for total corrected photon (AveQ) as following;

$$\mathrm{AveQ} \;=\; \frac{1}{Nhit}\sum_{i=1}^{Nhit}\mathrm{CNP}_i \qquad (2)$$

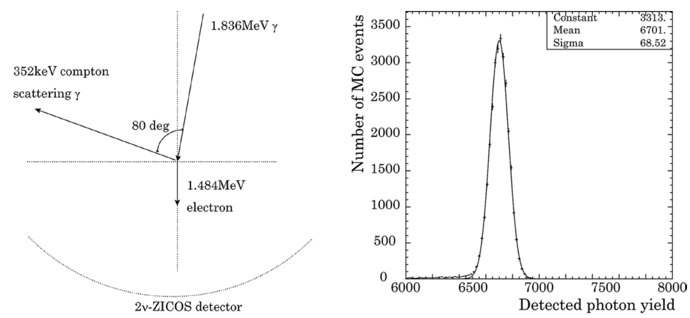

Figure 5.　The left panel shows a setup to obtain an electron with fixed energy 1.484MeV and fixed direction by Compton scattering from ^{88}Y gamma-ray. The right panel shows a simulated total photon yield for this events. The energy resolution seems to be almost 1%, but we did not consider experimental condition such as noise or scintillation fluctuation.

where *Nhit* is number of hitted PMT. Then we took the variance (VAR),
the standard deviation (STD), and the resolution (RES) as following steps.

$$\mathrm{VAR} = \frac{1}{Nhit}\sum_{i=1}^{Nhit}(\mathrm{CNP}_i - \mathrm{AveQ})^2 \quad (3)$$

$$\mathrm{STD} = \sqrt{\mathrm{VAR}} \quad (4)$$

$$\mathrm{RES} = \frac{\mathrm{STD}}{\mathrm{AveQ}} \quad (5)$$

Above calculation should be performed on huge grid as a possible vertex position in whole detector region. Exactly speaking, we divided the detector into 0.1cm step for 3 dimension. We could obtain most possible vertex position with most smallest resolution. Top panels of Fig. 6 shows the difference between obtained vertex position and generated position, and bottom panels show obtained vertex distribution for ^{137}Cs gamma-ray from 137Cs. Obtained vertex positions were well reconstructed with 0.3cm resolution in any direction even a few hundred keV electron.

Actual performance of the vertex reconstruction should be demonstrated by an experimental method. We will use ^{137}Cs radio-active source 516 type made by Japan Radioisotope Association for this purpose. The package of this source and the location were shown in the left panel of Fig. 7 . The source will be located at the center of 2ν-ZICOS detector. Unfortunately JRIA did not recommend to use this source for an unnatural environment such as inside of liquid scintillator, therefore we will cover this source using vacuum-sealed nylon bag. The Teflon thread will also be used for hanging this bag.

The right panel of Fig. 7 shows the vertex distribution for gamma-ray from ^{137}Cs vertex calibration whether considering the shadow effect due to ^{137}Cs source package or not in case of larger total photon yield. The intensity of ^{137}Cs is 100kBq, so we

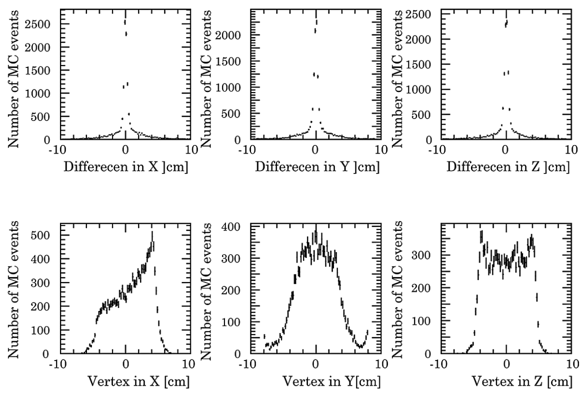

Figure 6. Top panels show the difference between reconstructed vertex and generated position in each axis in case of ^{137}Cs 662 keV gamma-ray. Bottom panels show the reconstructed vertex position in each axis.

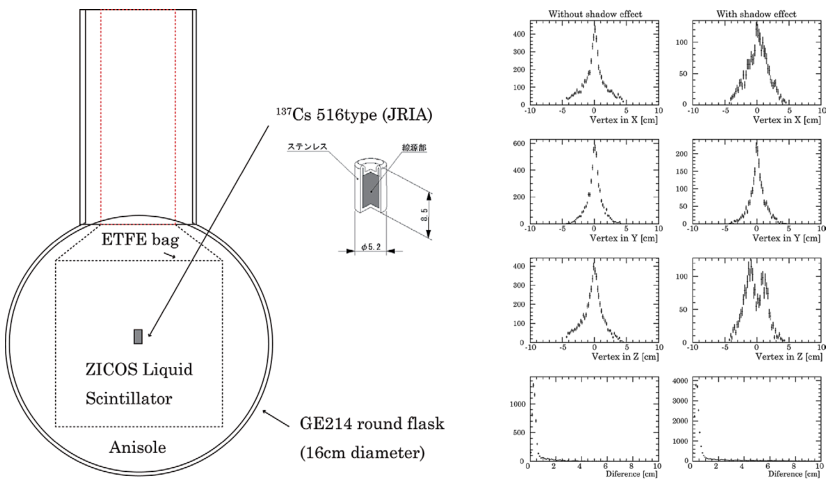

Figure 7. Left panel shows a ^{137}Cs radioactive source 516 type (JRIA) we be located at the center of 2ν-ZICOS detector. Right panels show the vertex distributions for 3-dimension and difference between vertex position and generated position with/without shadow effect.

will not be able to take all data due to high trigger rate. Therefore, we will set the trigger threshold around order of 100Hz. There should be difference for the vertex distribution between shadow effect and no effect. Therefore, we will have to check an actual performance of vertex reconstruction using above setup.

4. Averaged angle

Once the vertex position was reconstructed, next we have to select PMTs which receive Cherenkov lights for the calculation of an averaged angle. Using similar technique described in Ref.[9], we have developed the pulse shape discrimination for CAEN V1742 digitizer and PMT H3378-50. We have selected samples with only scintillation and with both scintillation and Cherenkov light. Figure 8 shows pulse shape of t=43ns, 46ns, 48ns, and 50ns, and the pulse height sequence for those samples. Timing t=60ns corresponds to peak of the pulse shape. The pulse height of Cherenkov light increased obviously faster than that of scintillation, therefore we could define same kind of χ^2 in order to discriminate the pulse shape whether Cherenkov light included or not as described in Ref.[9].

Using same kind of χ^2 methods as described in Ref.[9], we will be able to select PMTs which receive Cherenkov lights. After this selection, we will be also able to obtain the averaged angle for the background events reduction such as ^{208}Tl beta decay. An averaged angle includes the topological information of Cherenkov lights, and the definition is represented as following formula;

$$\text{averaged angle} = \frac{1}{Nhit}\sum_{i=1}^{Nhit}\theta_i \qquad (6)$$

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. In the simulation, we identified the PMTs so easy that we could calculate the averaged angle using those PMT information.

Figure 9 shows simulated averaged angle distribution for gamma-ray from ^{137}Cs, ^{60}Co, ^{22}Na, and ^{88}Y with same setup as section of energy scale. Except ^{137}Cs, there was a peak around 50 degree for above 1 MeV. These distributions will be also demonstrated by actual calibration.

For the performance of background event reduction using this averaged angle, we simulated events of $2\nu\beta\beta$ of ^{96}Zr and ^{208}Tl beta decay. Figure 10 shows an averaged angle distribution for $2\nu\beta\beta$ of ^{96}Zr and ^{208}Tl beta decay. The peak position were seen at 60 and 70 degree, respectively. The separation ability seems to be weaker than what we expected in Ref.[5] because of dominated 2.615 MeV gamma-ray for ^{208}Tl

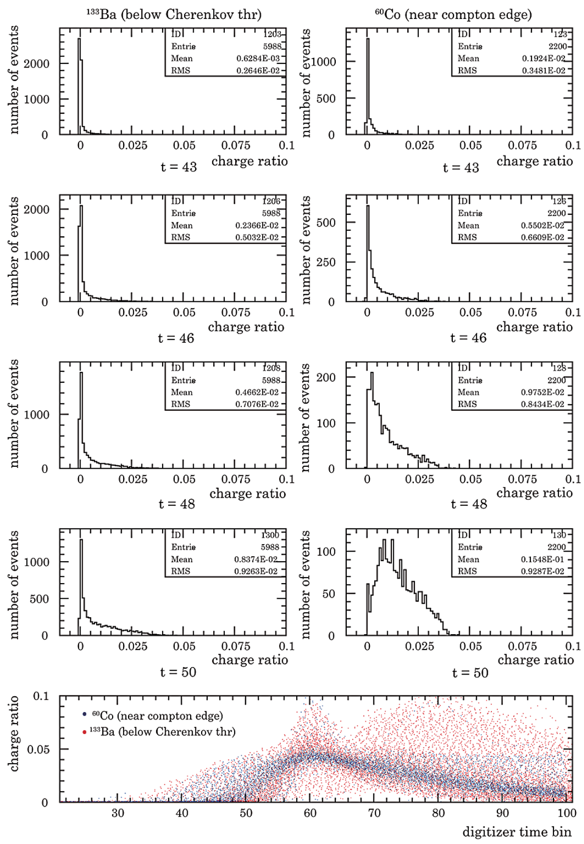

Figure 8. Top 8 panels shows the pulse height distribution of t=43ns, 46ns, 48ns, and 50ns for samples with only scintillation and with both scintillation and Cherenkov. Timing t=60ns corresponds to peak of the pulse shape. Bottom panel shows the pulse height sequence for those samples. Blue and red correspond to whether Cherenkov photon involved or not, respectively.

beta decay. In other words, most of beta electron did not come in the liquid scintillator due to gap between round bottom flask and the ETFE cubic bag. If the cut point will be set at 60 degree, 51% of ^{208}Tl origin events could be removed with 89% of $2\nu\beta\beta$ efficiency.

5. Radiation shield

In the last, we considered an effect of the environmental gamma-ray. In order to avoid this, we have to build the radiation shield using lead blocks. We need to know how much amount of gamma-ray exist passing through the shield, therefore the background event rate was directly measured by using large CsI crystal detector. The left panels of Fig. 11 show the background event rate measured at outside and inside of 10 cm lead radiation shield, and subtracted event rate. Clear backgrounds such ^{214}Bi and ^{208}Tl for U/Th series, and ^{40}K were seen. For instance, the number of events of ^{208}Tl (2.615 MeV gamma-ray) for outside of the lead shield is 2,500 events/day. The linear absorption coefficient of lead at 2.6 MeV is 0.43 cm^{-1}, therefore the transmittance of this gamma-ray for 10 cm lead is 0.0073. The remaining ^{208}Tl gamma-ray is 18 events per day which corresponds to 6,500 events per year. Assuming the detection efficiency of CsI detector to be 20%, about 33,000 events per year could be entered for 2.615 MeV gamma-ray in case of 50 cm^3 CsI detector. 2ν-ZICOS detector has 730 cm^3 scintillator, and the detection efficiency is assumed to be almost 10%, therefore the ^{208}Tl 2.615 MeV gamma-ray will be detected about 47,000 events per year. This is huge number compared to 70 events of $2\nu\beta\beta$ for 2ν-ZICOS detector.

If we use 20 cm thickness instead of 10 cm for the lead shield, the transmittance of 2.615 MeV gamma-

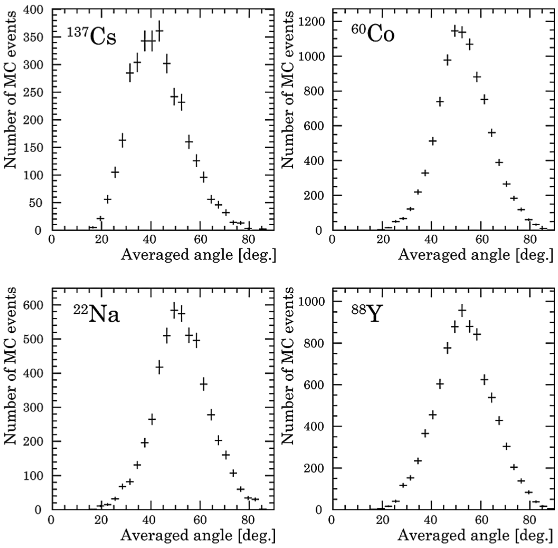

Figure 9. A simulated averaged angle distribution for gamma-ray from ^{137}Cs, ^{60}Co, ^{22}Na, and ^{88}Y with same setup as section of energy scale. Except ^{137}Cs, there was a peak around 50 degree for above 1 MeV.

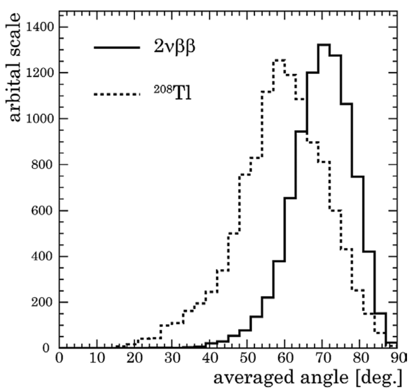

Figure 10. An averaged angle distribution for $2\nu\beta\beta$ of ^{96}Zr and ^{208}Tl beta decay.

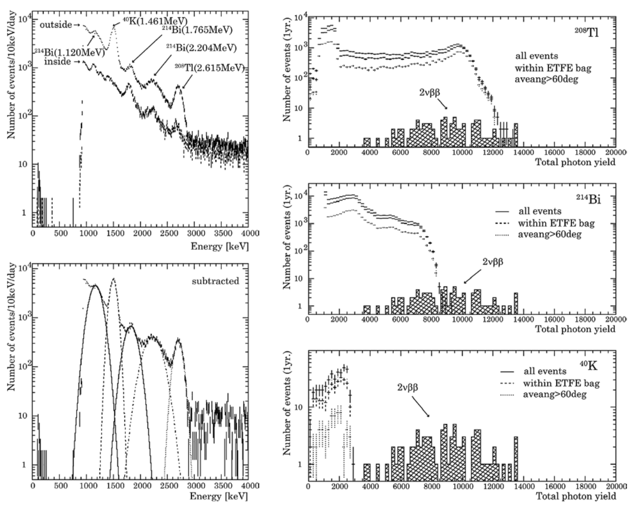

Figure 11. The left panel shows environmental gamma-ray measured by large CsI crystal detector at outside and inside of 10cm lead radiation shield. Clear backgrounds such as ^{214}Bi and ^{208}Tl for U/Th series, and ^{40}K are found. The right panel shows simulated background events from those backgrounds contained in the GE214 ultra-pure quartz used by the round bottom flask.

ray is 3.3×10^{-5}. 2ν-ZICOS detector will detect about 200 events per year for ^{208}Tl 2.615 MeV gamma-ray using same estimation as above. Therefore the signal to noise ratio will be almost 0.4.

6. Conclusion

In conclusion, some detector performances such as the energy scale, the energy resolution, the vertex reconstruction, and the averaged angle obtained by the simulation are consistent with what we expected, however the thickness of lead block for the radiation shield seems to be insufficient. As described in Ref. [11], the background events from ^{208}Tl in an ultra-pure quartz GE214 will be observed as shown in right panel of Fig.11, and it might be 2 order of magnitude larger than $2\nu\beta\beta$ events. Therefore, in this time, we will use 15 cm thickness of the lead block, because of the limit of a number of lead blocks which we will be able to borrow in Kamioka mine.

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Zr-96 原子核を用いたニュートリノの放出を伴う二重ベータ崩壊の観測のための 2ν-ZICOS 検出器の性能

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要旨

2ν-ZICOS実験は、^{96}Zr 原子核を用いて2つのニュートリノを放出する二重ベータ崩壊の半減期を観測する実験である。新たにデザインされた2ν-ZICOS 検出器は、720mLのETFE立方体バックを使用して70事象の^{96}Zrの二重ベータ崩壊を観測する計画である。2ν-ZICOS 検出器のエネルギースケール、エネルギー分解能、事象発生位置の再構成、背景事象の除去に使用される平均角といった性能の評価を、いくつかの種類のガンマ線源を用いてキャリブレーションをしなければいけない。本論文では、これらのキャリブレーションについてモンテカルロシミュレーションの結果を報告する。

Key Words : ニュートリノの放出を伴う二重ベータ崩壊，液体シンチレータ，エネルギースケール，エネルギー分解能，事象発生位置の再構成

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