ZICOS - A new project for neutrinoless double beta decay using Zirconium complex in organic liquid scintillator

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Abstract. A liquid scintillator containing ^{96}Zr has been developed for ZICOS experiment. We will use 180 tons of liquid scintillator with 64 % photo coverage of 20 inch photomultiplier. In order to reach the sensitivity $T^{0\nu}_{1/2} \geq 10^{27}$ years, we have to achieve 50 % enrichment of ^{96}Zr and reduce 95 % of ^{208}Tl decay backgrounds. Using Monte Carlo simulation, we could reduce 93 % of ^{208}Tl background with 78 % efficiency for $0\nu\beta\beta$ signal using difference of Cherenkov hit pattern. For the separation of Cherenkov and scintillation signals, we measured the timing pulse shape of Zr loaded liquid scintillator using FADC digitizer, and we found an inconsistent pulse shape at the rising time with the template of scintillation. Also the event rate with an inconsistent pulse shape seems to have a directionality.

1. ZICOS experiment

We have proposed a new experiment for neutrinoless double beta decay ($0\nu\beta\beta$) search using nucleus ^{96}Zr [1]. A ^{96}Zr has third highest Q-value (3.35 MeV) among possible $0\nu\beta\beta$ isotopes, therefore, in general, some radioactive backgrounds such as ^{214}Bi in Uranium series and ^{10}C, which is spallation product of the energetic cosmic muon, could be avoidable due to their lower energy.

We will use total 180 tons of liquid scintillator containing 10 wt.% concentration of a tetrakis (isopropyl acetoacetato) zirconium (Zr(iPrac)$_4$), which corresponds to 72 kg (45 kg in fiducial volume) of ^{96}Zr assuming 2.6 % natural abundance, inside of the balloon. The inner balloon (3.5 m in radius) is located in the spherical detector (4.0 m in radius) which has 64 % of photo coverage of 20 inch photomultiplier (PMT) as shown in Fig.1. The outside of the inner balloon will be filled with pure water which has almost same density as Anisole. This is very important for reducing backgrounds due to ^{208}Tl decay which may adhere to the surface of inner balloon as described later. The energy resolution is expected to 2.6 % at 3.35 MeV[2].

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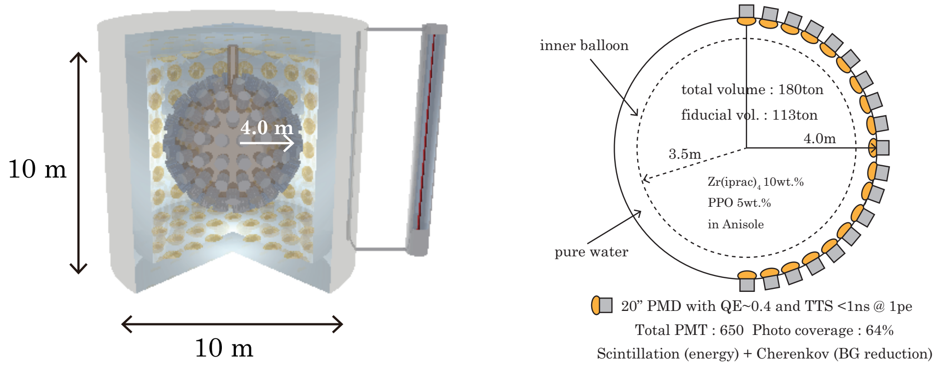

Figure 1. The left panel shows the global design of the ZICOS detector. The inner balloon will be filled with a liquid scintillator which contains 10 wt.% of $Zr(iPrac)_4$. The right panel shows the conceptual design of inner detector.

2. Background reduction using Cherenkov light

In order to reach the sensitivity $T^{0\nu}_{1/2} \geq 10^{27}$ years, which corresponds to $m_\nu \sim 0.01$eV, we have to achieve 50 % enrichment of ^{96}Zr and reduce the radioactive backgrounds significantly. According to recent results form KamLAND-Zen[3], there found backgrounds around 3.35 MeV, and they were events of ^{208}Tl decay which occurred on the surface of balloon. In the case of KamLAND-Zen, they also used a liquid scintillator at outside of the balloon, therefore they succeeded to reduce ^{208}Tl backgrounds at 2.5MeV (Q-value of ^{136}Xe) even though whose vertexes remain within their fiducial volume due to measure all energies from ^{208}Tl decay (Q-value is 4.99 MeV).

On the other hands, ZICOS detector will use pure water instead of liquid scintillator at outside of the balloon, therefore almost half of ^{208}Tl backgrounds observed in KamLAND-Zen should be reduced by missing the energy. However, another half still exist inside of balloon. In order to remove those backgrounds, we have been developed techniques which use Cherenkov light for discrimination of signal and background[2]. Basically ^{208}Tl decays into the exited state of ^{208}Pb with emission of beta, and the transition to ground state with the emission of several gammas including 2.6145 MeV gamma after the beta decay. Therefore some electrons emitted by Compton scattering are able to emit Cherenkov lights from different positions, while the electrons from $0\nu\beta\beta$ also emit Cherenkov lights but from same position. This difference could be used for the reduction of ^{208}Tl events.

In fact, the Monte Carlo simulation with EGS5, which simulates ^{208}Tl beta decay (E_{max} = 1.7963 MeV) and two gammas (E_γ = 2.6145 MeV and 0.5832 MeV), indicates that 95 % of ^{208}Tl events, whose averaged position of vertexes exist within fiducial volume, could be reduced by the distance of each electrons as shown in left panel of Fig.2. Instead of the vertex reconstruction using Cherenkov light, we could consider the difference of PMT hit pattern between signals and backgrounds as shown in middle panel of Fig.2. Once we use the vertex position obtained by scintillation light, then we can define an averaged direction as $\hat{d} \equiv \sum_{i=1}^{nhit} \vec{d}_i$, where $\vec{d}_i$ is unit vector to i-th PMT from the vertex, and *nhit* is the number of PMT hit which received Cherenkov lights larger than 1 pe. Using the averaged direction, we can also define an averaged angle as $\hat{\theta} \equiv \frac{1}{nhit} \sum_{i=1}^{nhit} \theta_i$, where θ_i is an angle between the averaged direction ($\hat{d}$) and the vector $\vec{d}_i$. If we set the averaged angle 48 degree as a cut point, we can reduce 93 % of ^{208}Tl events even though we keep 78 % of $0\nu\beta\beta$ events as shown in right panel of Fig.2.

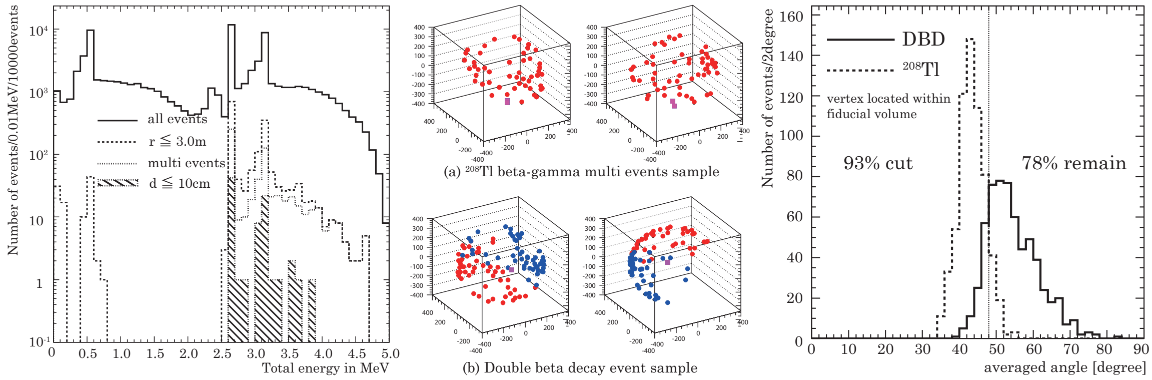

Figure 2. The left panel shows the reduction step of ^{208}Tl events using Monte Carlo simulation. The middle panel shows PMT hit pattern for typical (a) ^{208}Tl and (b) $0\nu\beta\beta$ in case of vertex located within the fiducial volume. The right panel shows that the averaged angle distribution for each case.

3. Separation of Cherenkov and Scintillation

Since it is important to measure the energy as precise as possible using scintillation light for the discrimination of signal and backgrounds, we have to distinguish PMT whether received Cherenkov light or not. The separation of Cherenkov and scintillation signals is realized by the difference of emission mechanism. Cherenkov radiation is generated by the vibration of molecular polarity due to the electron-magnetic interaction, so that the time spread corresponds to passing time of the electron (a few 100 pico seconds). On the other hands, the scintillation is a fluorescence from the transition of orbital electron between exited state and lower state, therefore the timing spread with a few tenth of nano seconds in case of an organic liquid scintillator. Such difference of spectral shape at the rising time due to Cherenkov lights emitted from cosmic muon was really observed in Linear Alkyl Benzene [4].

We had tried to measure such timing using CAEN FADC V1721 digitizer. In order to compare the spectral shape, we made a template for scintillation light. For the measurement of scintillation, we collimated ^{60}Co source using lead block, and entered gammas at far edge of the vial in parallel direction with respect to the PMT surface in order to avoid incident of Cherenkov light. The template of scintillation was made by following steps. At first, we accumulated pulses around the Compton edge. Then we got both Mean and RMS using FADC count distribution for each timing bin. At this time, we conventionally fixed the peak position at 60 ns for all pulses. Actually there were two types for the shape of template, which was fast timing and delayed timing due to the resolution of FADC (2 ns). However we showed here only the shape which has better chi square in order to avoid the confusion. The crosses shown in Fig.3 and Fig.4 show the template of scintillation obtained by Anisole and Zr loaded liquid scintillator, respectively. Both templates have about 7 ns for the decay time.

Next we measured the timing spectral shape of Anisole. In this time, gammas from ^{60}Co source were also collimated by lead block, and scattered gammas which had 150 degree of the scattering angle with respect to the incident gamma were detected by NaI scintillator. Therefore the scattering electrons generated inside Anisole have both an unique direction (4.45 degree for scattering angle) and energy (1.02 MeV). The PMT was located at 90 degree, which is an angle between the incident gamma and the PMT surface, because the PMT is easy to receive

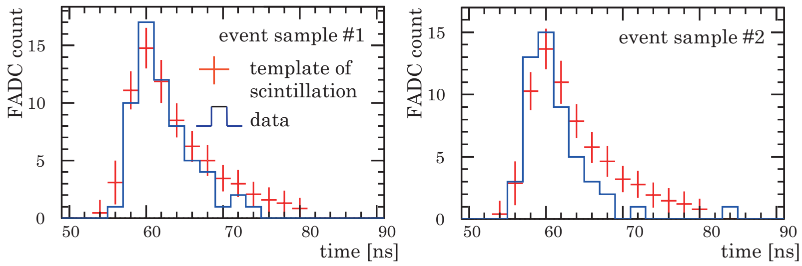

Figure 3. Observed timing pulse shape in Anisole. The left panel of shape is consistent with template of scintillation, however typical shape is similar to right panel.

Cherenkov lights. Figure 3 shows typical timing pulse shape observed in Anisole. Most of events had the shape of the right panel of Fig.3. This shape is not agree with the template of scintillation, and it has faster both rising and decay time. Backgrounds such as Cherenkov occurred in the vial glass or the PMT surface had same shape but smaller charge than above events. Same shape was also observed in pure water. Recently we observed same shape in Anisole even though using the UV cut filter (product of FUJIFILM Corporation: SC-37), which cuts off the light shorter than 400 nm, and no scintillation event shown in left panel of Fig.3 was observed, because the peak of wavelength for scintillation is 300 nm. Therefore we assume that an observed shape in Anisole shown in right panel of Fig.3 mainly consist of Cherenkov light.

At last, we measured the timing pulse shape for Zr loaded liquid scintillator. Figure 4 shows typical pulse shape mainly observed in the liquid scintillator. The left panel of Fig.4 is consistent with the shape of scintillation, and about 70 % of events look like this shape. The middle panel of Fig.4 has statistically inconsistent rising time shape with the template. If the difference of

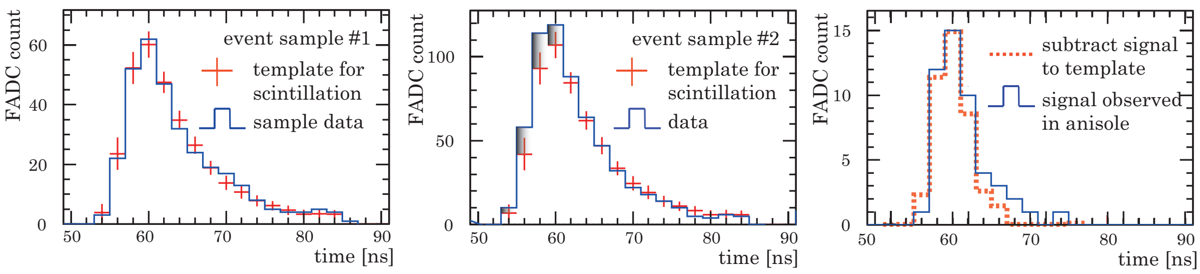

Figure 4. Typical timing pulse shape observed in Zr loaded liquid scintillator. The left panel of shape is consistent with template of scintillation, however, the middle panel differ from the template at the rising time. The template shape was overlaid by fitting at decay tail.

shape at the rising time is caused by Cherenkov lights, we could extract the spectrum using subtraction of data and template. The dashed line in the right panel of Fig.4 shows subtracted shape which corresponds to the shaded region in middle panel, and the typical pulse shape observed in Anisole as shown in Fig.3 is overlaid as a solid line with adjusting the peak position. Those shapes look consistent with each other. This means that the inconsistent shape at rising time might be caused by Cherenkov lights.

In order to estimate statistically this inconsistency, we could define an accumulated sigma (ACS) which is a summation of sigma between data and template at first 3 bins of the rising time. Figure 5 shows the ACS distribution in case of 90 degree and 10 degree, which is the angle between incident gamma and the PMT surface, respectively. Latter case means that the PMT might not be easy to receive Cherenkov lights. In the left panel of Fig.5, there is peak around

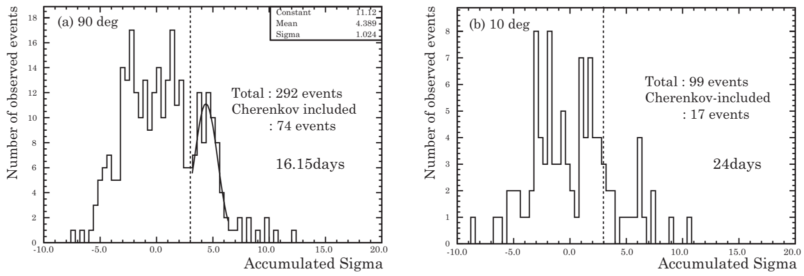

Figure 5. The accumulated sigma (ACS) distribution for (a) 90 degree and (b) 10 degree, which is the angle between incident gamma and the PMT surface.

4.4 on the ACS. Looking at event by event, those events have actually inconsistent pulse shape at the rising time with the template of scintillation.

If we assume that the event which has greater ACS value than 3.0 possibly include Cherenkov lights at the rising time, then the event rate with ACS ≥ 3.0 is 4.6 events per day for 90 degree and 0.7 events per day for 10 degree, respectively. The significance is almost 6 sigma. Same situation was also observed in case of Anisole. There were 5 events for 90 degree and 1 event for 10 degree for the event shown in right panel of Fig.3 with 7days measurement.

Therefore, Cherenkov lights emitted by 1 MeV electron seems to have a directionality even though such a low energy electron could be multiply scattered. However, the event rate of only scintillation received in Zr loaded liquid scintillator also seems to have a directionality. We will have to check this using statistically sufficient data.

4. Conclusion

A conceptual design for ZICOS experiment with 180 tons of liquid scintillator loaded 10 wt.% $Zr(iPrac)_4$ was presented. The energy resolution is expected by 2.6 % at 3.35 MeV assuming 64 % photo coverage using 20 inch PMT. In order to reach the sensitivity of $T^{0\nu}_{1/2} \geq 10^{27}$ years, we have to achieve 50 % enrichment of ^{96}Zr and reduce 95 % of ^{208}Tl backgrounds.

We tried to demonstrate the method for ^{208}Tl background reduction using Cherenkov hit pattern, and got 93 % reduction with 78 % signal efficiency. For the separation of Cherenkov and scintillation signals, we measured a timing pulse shape using FADC digitizer, and found the difference at the rising time. The pulse shape discrimination using the accumulated sigma was also demonstrated. To confirm observed directionality, we need more statistics and detailed analysis.

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