Study of Ocean Bottom Detector for observation of geo-neutrino from the mantle

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Abstract. Observation of anti-neutrinos emitted from radioactive isotopes inside Earth(geo-neutrinos) brings direct information on the Earth's chemical composition and its heat balance, which strongly relate to the Earth's dynamics. To date, two experiments (KamLAND and Borexino) have measured geo-neutrinos and constrained the range of acceptable models for the Earth's chemical composition, but distinguishing the mantle flux by land-based detectors is challenging as the crust signal is about 70% of the total anti-neutrino flux. Given the oceanic crust is thinner and has lower concentration of radioactive elements than continental crust, geo-neutrino detector in the ocean, Ocean Bottom Detector (OBD), makes it sensitive to geo-neutrinos originating from the Earth's mantle. Our working group was jointly constructed from interdisciplinary communities in Japan which include particle physics, geoscience, and ocean engineering. We have started to work on technological developments of OBD. We are now developing a 20 kg prototype liquid scintillator detector. This detector will undergo operation deployment tests at 1 km depth seafloor in 2022.

1. Introduction

1.1. Geo-neutrino observation

Since the first observation by Cowan and Reines, improvements in the accuracy of observations have revealed many properties of neutrinos. Due to their high transparency, neutrinos are now used as a tool to understand astronomical objects, such as Earth. Electron anti-neutrinos from natural radioactive decays of Earth's ^{238}U, ^{232}Th and ^{40}K are called as geo-neutrinos. In current observation, geo-neutrinos from ^{238}U and ^{232}Th decay chains are being measured with liquid scintillator (LS) detectors via inverse-β decay reaction ($\bar{\nu}_e + p \rightarrow e^+ + n$). Unfortunately, we need new techniques for observation of ^{40}K geo-neutrinos since its energy is below the reaction threshold, 1.8 MeV.

Geo-neutirno flux can be translated to the amount of ^{238}U and ^{232}Th which drive the Earth's heat engine. Geo-neutrino observation is the only way to directory measure the amount of the radiogenic heat sources.

To date, experimental measurements of geo-neutrino's global flux has constrainted the range of acceptable models for the Earth's composition, but distinguishing the mantle flux by current detectors, which are all locate on the crust, is challenging, as the crust model has large uncertainty and the crust contribution is about 70 % of the total flux. Therefore, as the next step, a detector which can directly observe radiogenic heat in the mantle is required. We conceive that our detector, Ocean Bottom Detector is very suitable for that.

1.2. Why mantle geo-neutrino?

Observation of mantle geo-neutrinos is expected to reveal mantle structure. Although it has been observed by seismic waves, mantle structure is still mysterious such as mantle convection. Observations of mantle geo-neutrinos can be used to test various models of mantle structure. By observing mantle geo-neutrinos, it is possible to estimate the amount of internal fuel too. Since the transfer of heat from the mantle to the crust is responsible for the geomagnetic field and plate tectonics, the determination of the heat balance is essential for understanding the dynamics of the Earth.

2. OBD : Ocean Bottom Detector

Oceanic crust is thinner and has less U and Th than continental crust, so OBD can detect mantle signal clearly (Figure 1). In addition, OBD has other unique advantages, such as the ability to avoid non-separatable background, reactor neutrinos, by maintaining the distance from the reactors, and the ability to be deployed in multiple locations across the sea.

In 2005, University of Hawaii and Makai Ocean Engineering [1] began to work on an anti-neutrino detector to be placed in the deep ocean, "Hanohano". Technological developments and detailed detector design were reported in [2]. The idea became popular and was expected to be realized, but funding for the project never materialized. In 2019, collaboration research was started by Tohoku University (KamLAND team) and JAMSTEC (Japan Agency for Marine-Earth Science and Technology). We brought together scientists from physics, engineering and geoscience with a shared goal of the understanding the Earth's interior.

Currently, we are developing 20-kg prototype LS (Liquid Scintillator)-detector and aim world's first measurement in the sea with LS detector. In 2022, this detector will be installed at JAMSTEC's Hatsushima Observatory, which is located 1 km depth in the ocean. We are planning to take data several months and check the equipment works properly.

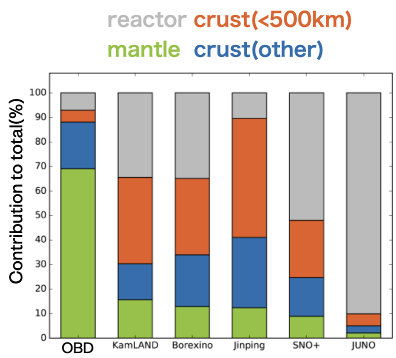


Figure 1: Contribution to total expected anti-neutrino flux.The figure was modified by Šrámek, O.[3]

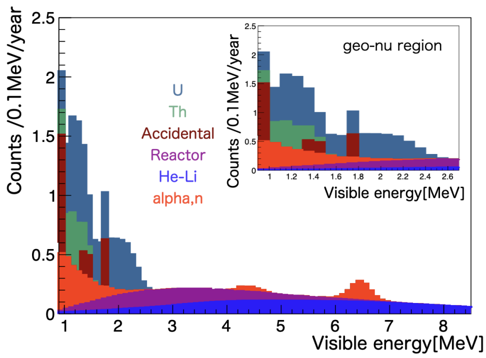


Figure 2: Expected energy spectrum of 1.5 kt OBD estimated by Geant4 simulation.

The LS is designed to be contained in a acrylic vessel (12 m width, 14 m height) surrounded by 3 m thick buffer oil area. The outermost layer is stainless tank which has ~3000 PMT. The radioactive contamination (e.g. ^{238}U, ^{232}Th and ^{40}K) is assumed to be in the detector components, such as LS, cylindrical acrylic vessel, and PMT shields. Cosmic ray produces spallation background. Figure 2 shows the expected energy spectrum of 1.5 kt OBD estimated by Geant4 simulation. Accidental and (α, n) backgrounds are estimated by Geant4 simulation. He-Li background is scaled from KamLAND data. Geo-neutrino and reactor neutrino spectra are given by [4]. The sensitivity of mantle geo-neutrino is estimated to be 3.5 σ for 3-year measurement.

3. Detector Development

In order to shield the cosmic rays by seawater, OBD should be installed at a depth of 2-5 km. It is necessary to develop a detector that can operate well in this low temperature and high pressure environment (20-50 MPa and 4 °C).

3.1. PMT shield

To prevent damage and implosion of PMTs, we install protection shield around each PMT. Off course, PMT shield must be strong, and also low-radioactive to reduce accidental-background.

We consider glass and acrylic as material candidates. They have some advantages and disadvantages. Glass is usually used in high-pressure experiments and marine engineering. But it contains about two orders of magnitude more radioactive materials than our target. Quartz glass is low-radioactive but expensive. On the other hands, acrylic is reasonable and low-radioactivity. But acrylic is not usually used for marine engineering and experiments. Now we are developing PMT shield in both materials.

3.1.1. Glass shield We are working with the company OKAMOTO GLASS. To reduce radioactive material, we select the adequate material with them. And the contamination in the manufacturing process is serious, so we apply platinum coating on the surface of manufacturing pot. Table 1 summarises amount of radioactivity in the glass.

Table 1: Amount of radioactive material

	^{238}U	^{232}Th	^{40}K
w/o coating	2.8×10^{-8}	3.4×10^{-8}	1.6×10^{-8}
w/ coating	1.4×10^{-8}	$< 5.0 \times 10^{-9}$	3.4×10^{-9}
target value	1×10^{-8}	1×10^{-8}	1×10^{-8}

This result is enough for large buffer detector. But to make buffer smaller, more low-background glass is needed.

3.1.2. Acrylic shield We did pressure resistance test with following 4 test balls which have different thicknesses and types of connection. A:10 mm & insertion, B:15 mm & insertion, C:10 mm & screw, D:15 mm & screw. We applied up to 40 MPa of pressure using JAMSTEC's pressure test equipment. In first-time test, ball-A burst and ball-C was leaked at 21 MPa. And we did second test with surviving balls, B and D, but ball-D was burst after 20 min. under 40 MPa and ball-B was leaked (Figure 3).

(a) broken ball-A (b) broken ball-D

Figure 3: Broken balls in pressure test

We found out that test balls have a problem with connection part of two hemispheres. We are now developing new design and will do pressure resistance test again soon.

3.2. Liquid Scintillator

The deep sea environment is not a common experimental environment for LS due to its low temperature and high pressure. We plan to use LAB (Linear Alkyl Benzene) based LS because of its low flashing point. LS consists of LAB and PPO (2,5-diphenyloxazole) as a fluor. We started to check low temperature effect of LS in the unpressurized state. LS became cloudy at 4 °C because of water contamination. We found that N_2 purges out water contamination and LS keeps it transparent (Figure 4).

(a) w/o N2 purge (b) w/ N2 purge

Figure 4: LAB LS transparency check. After leaving the bottles at 2-4 °C for a few hours, the transparency was checked in the case of with and without N_2 purge.

The temperature and PPO amount dependencies of light yield were investigated with the experimental equipment (Figure 5). This equipment was designed to measure LS light yield under controlled low temperature of 4±1 °C by the chiller. LS was filled in an airtight container which has view port at the bottom. In the experiment, due to the large background, the energy of electrons emitted by Compton scattering γ-ray from the ^{137}Cs source was observed in the LS by a 2-inch PMT (photomultiplier tub), and the events were recorded only when the back-scattered γ-rays were observed by the another PMT with NaI. Figure 7 shows ADC distributions of both PMTs. In Figure 7(b), a red histogram shows selected events and its fitted result is used for comparison of the light yield in Figure 6. Figure 6 shows that the light yield is increased when its temperature is lowered from 20°C to 4°C for any PPO concentration. Furthermore, the light yield is almost saturated when more than 3 g/L of PPO is dissolved in LS. We conclude that LAB LS with 3 g/L PPO is appropriate recipe for OBD.

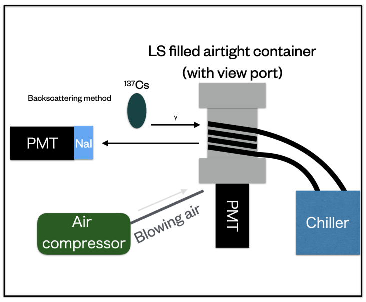


Figure 5: experimental equipment

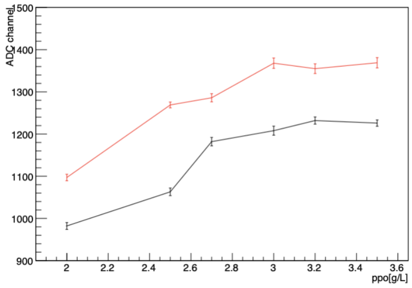
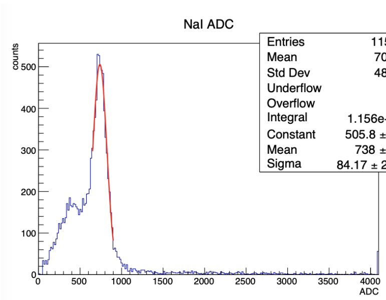
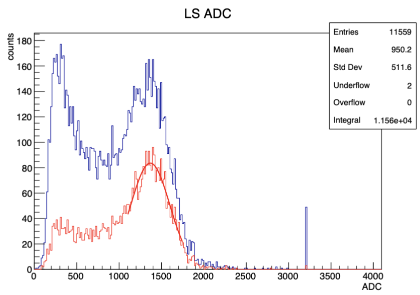


Figure 6: LS light yield plot red:4°C black:20°C



(a) ADC of NaI



(b) ADC of LAB-LS,
blue: raw data, red: data of back-scattering events

Figure 7: Result sample of 4°C LS (PPO 3g/L)

4. Summary and Future Prospect

OBD project broadens our perspective and works across the disciplinary boundaries of particle physics, geoscience, and ocean engineering. The kt scale detector will be a breakthrough in neutrino geoscience. The development of technology to operate detectors in the deep sea environment has begun. Our working group plans to install 20-kg LS detector into 1 km seafloor in 2022.

Acknowledgement

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