Directional Measurement of Anti-Neutrinos with KamLAND

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I show possibility of directional measurement of electron anti-neutrinos with liquid scintillator detector. Relative vertex position of prompt positron and delayed neutron events is useful to extract directional information of anti-neutrinos. In order to minimize diffusion of thermal neutron and capture signal, development of new liquid scintillator containing an isotope which goes to (n,α) interaction with large cross section is needed. Also, development of an imaging device to obtain high vertex resolution is necessary. The key issue in the development is the optics with large depth of field and appropriate aperture. In addition, the photo-sensor should have one-photo-electron sensitivity and position information.

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1. Introduction

KamLAND is the anti-neutrino detector located at 1,000-m underground at Kamioka in Japan. It detects electron anti-neutrinos through inverse-beta decay in 1-kton Liquid Scintillator (LS) with 1,879 Photo Multiplier Tubes (PMTs). This reaction gives two signals with an interval of 200 μ sec. This coincidence allows almost background-free measurement.

In addition, these two signals have the potential of directional measurement of anti-neutrino. The key for the directional measurement is the development of the imaging system. In this paper, I give the possibility of directional measurement in a possible future plan of KamLAND.

2. Physics Motivation

KamLAND experiment has shown precise measurement of anti-neutrinos from the Earth's interior ("geo anti-neutrino") and nuclear reactors ("reactor anti-neutrino"). As described below, more precise study of geo- and reactor-neutrinos will be possible with the information of incident anti-neutrino direction.

2.1 Geo anti-neutrino

In the measurement of the geo anti-neutrino, the directional information enables us to measure the radiogenic heat source distribution inside the Earth, and to give another method to separate geo anti-neutrino from reactor one, on top of the energy spectral analysis being performed currently.

2.2 Reactor anti-neutrino

In the reactor anti-neutrino measurement, the directional measurement gives improvement of oscillation analysis because if we can distinguish the source reactor, the distance to it is specified. The directional sensitive neutrino detector may also be used for reactor monitoring.

2.3 Supernova anti-neutrino

The detector with directional measurement capability will be able to locate a supernova to inform the network of neutrino detectors as a supernova early warning.

Furthermore, the directional measurement can provide an additional tool to reduce the background and to distinguish various sources of anti-neutrinos. And thus, this technique, if developed successfully, will provide further advantage of large liquid scintillator detectors.

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3. Directional Measurement Principle

In KamLAND, electron anti-neutrinos are detected through the inverse-beta decay:

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

This reaction gives two signals: a prompt positron and a delayed neutron capture. These two signals provide us the chance to perform a direction measurement, because their positional information holds the directional information of incident anti-neutrino.

The prompt positron deposits the kinetic energy, and then emits two gammas by the annihilation with an electron. The position of this prompt signal is close to the incident anti-neutrino vertex position. The relation between neutron and positron angles (Figure1) is decided only by kinematics (Figure2). The notable point is that a neutron is always emitted forward direction with respect to the incident anti-neutrino momentum vector. Therefore, the direction of the incident anti-neutrino can be inferred if the neutron direction is measured [1].

However, the directional measurement is difficult with the present KamLAND. Because the information of the neutron direction is lost due to the thermal diffusion and long interaction length of 2.2-MeV gamma ray from neutron capture on proton. Another reason is that the position resolution of PMTs is not enough. So we need to develop the new detection system for the directional measurement.

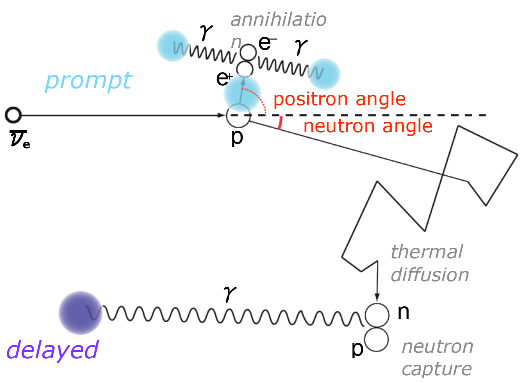


Figure1. Electron anti-neutrino detection by inverse-beta decay.

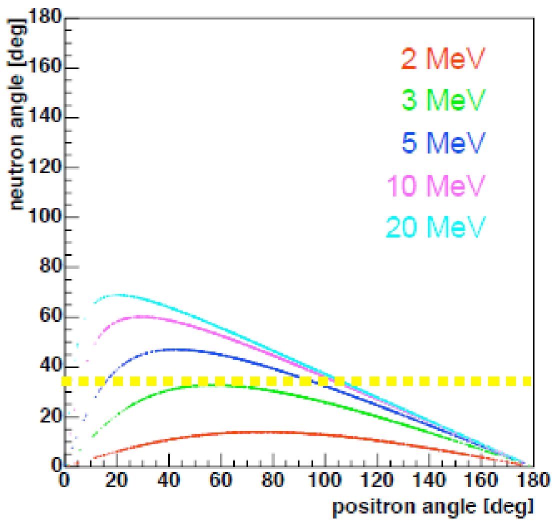


Figure2. Neutron direction as a function of positron direction for each fixed incident anti-neutrino energy.

4. Three Developments for New Detector

If the delayed neutron is detected without much diffusion, the neutron direction can be measured from the relative position of two signals. To change the delayed signal process for such a reaction, new liquid scintillator development is necessary. And to detect the position of signals, one effective means is imaging. The imaging system consists of optics to make an image and position sensitive photo-sensor to read it.

4.1 Liquid Scintillator

To minimize the thermal diffusion, the liquid scintillator should have large neutron-capture cross section. And (n,α) reaction is preferable to avoid further dissipation of neutron capture. The most promising candidate is ^{6}Li-loaded liquid scintillator[2].

4.2 Photo-Sensor

Photo-Sensor should have position sensitivity to detect a reaction as an image. It should have high quantum efficiency to get as many photons as possible. And the ability of continuous read-out is required to detect two signals with short time interval.

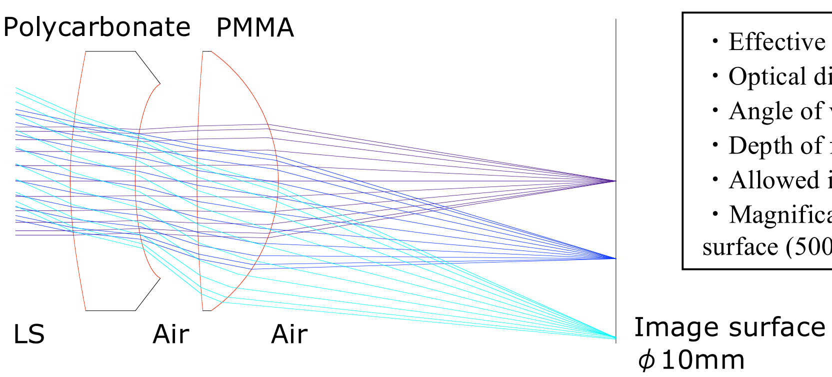
4.3 Optics

The requirement for optics is having large depth of field, high light collection efficiency and small aberration.

Specific requirements in KamLAND are as follows.

- Object range: 2,500~15,500 mm
- Angle of view: ~90 deg.
- Position resolution: ~10 mm

The distance from optics to the object is short (2.5m) despite the long range of object (13m). To give first priority to the depth of field, one idea is using pan-focus[1] optics with short effective focal length and small optical diameter (effective aperture), and providing a photo-sensor for each optics ("optics-sensor unit"). But in this idea the acceptance of individual unit is quite small. So we need large number of optics-sensor units to get enough photo-coverage and accordingly each optics should be simple structure and low cost. *Figure3* is an example.



- Effective focal length: 10.4 mm
- Optical diameter: 3.4 mm
- Angle of view: 50 deg.
- Depth of field: 2,500 mm ~∞
- Allowed image blur: ~0.01 mm
- Magnification at the best focused surface (5000 mm): -0.00231

Figure3. An example of pan-focus optics.

[1] Optical technique to keep all objects between a particular and infinite distances in focus.

This example can indeed cover all object range. But it needs too large number (~10^7) of optics-sensor units to get enough photo-coverage. So we need study of other approach to satisfy requirements and more R&D for optics.

References

[1] M. Batygov, *On the Possibility of Directional Analysis for Geo-neutrinos*, *Earth,Moon and Planets(2006)99:183-192*

[2] I. Shimizu, *Directional Measurement of Anti-Neutrinos,*NOW,Lecco,sep14,2006