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Directional measurement of anti-neutrinos

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Directional sensitive neutrino detectors contributed to astronomy and particle physics. The solar neutrino problem was firmly believed by the directional measurement of solar neutrinos, and the atmospheric neutrino oscillation was confirmed by the zenith angle distribution for two types of neutrinos. Recently, KamLAND showed the geo anti-neutrino detection realized by the event rate and energy spectra. It doesn't have the sensitivity of neutrino direction, so we can not distinguish the crust and mantle contribution. Lithium-loaded liquid scintillator has the potential to have the high sensitivity of coming anti-neutrino direction. Directional sensitive detectors will contribute to the better understanding of the earth interior using geo anti-neutrino flux information. Other motivations are the earlier determination of supernova direction and improvement of oscillation sensitivity for reactor anti-neutrinos.

1. DIRECTIONAL MEASUREMENT

The water Cherenkov detectors have a good angular resolution in the electron scattering (ES) reaction $\nu + e \rightarrow \nu + e$ owing to the forward scattering. Actually, Kamiokande and Super-Kamiokande showed the directional measurement for solar neutrinos, and finally they confirmed the solar neutrino deficit. On the other hand, low energy anti-neutrinos are detected by the charged current (CC) reaction $\bar{\nu}_e + p \rightarrow n + e^+$ (inverse beta decay reaction). This is tagged by the delayed coincidence based on the prompt positron signal and delayed neutron capture signal. Although the positron is emitted almost isotropically, the forward recoil neutron retains the information of the coming neutrino direction. The neutrino source direction can be measured by the unit vector $\hat{r}_{ne^+}$ having its origin at the delayed neutron capture vertex and pointing to the prompt positron vertex.

The CHOOZ experiment was the first to succeed in pointing to the source direction with reactor anti-neutrinos [1]. The liquid scintillator contained gadolinium, which has large neutron capture cross section. It produces high energy capture gamma-rays ($\sim$ 8 MeV) by (n, γ) reaction. But they obscure the neutron capture point and weaken the directional sensitivity. This problem can be solved if the liquid scintillator is loaded with boron or lithium, whose neutron capture signals are made by (n, α) reaction,

$$n +^{10}\mathrm{B} \rightarrow^{7}\mathrm{Li}^* + \alpha \ (\mathrm{BR} = 94\%,\ Q = 2.3\ \mathrm{MeV})$$

$$^{7}\mathrm{Li}^* \rightarrow^{7}\mathrm{Li} + \gamma \ (E_\gamma = 0.48\ \mathrm{MeV})$$

$$n +^{10}\mathrm{B} \rightarrow^{7}\mathrm{Li} + \alpha \ (\mathrm{BR} = 6\%,\ Q = 2.8\ \mathrm{MeV})$$

or

$$n +^{6}\mathrm{Li} \rightarrow^{3}\mathrm{H} + \alpha \ (Q = 4.8\ \mathrm{MeV}).$$

Table 1
Natural abundance and thermal neutron capture cross section for ^{6}Li and ^{10}B, which produce alpha particle by (n, α) reaction.

	natural abundance	cross section (barns)
^{6}Li	0.075	9.4×10^2
^{10}B	0.199	3.8×10^3

The natural abundance and thermal neutron capture cross section for ^{6}Li and ^{10}B are shown in Table 1. The neutron thermalizing and capture process are simulated by Geant4 [2], and the angular distribution of anti-neutrino events are shown in Figure 1. The ^{6}Li loaded liquid scintillator has the best sensitivity and the higher

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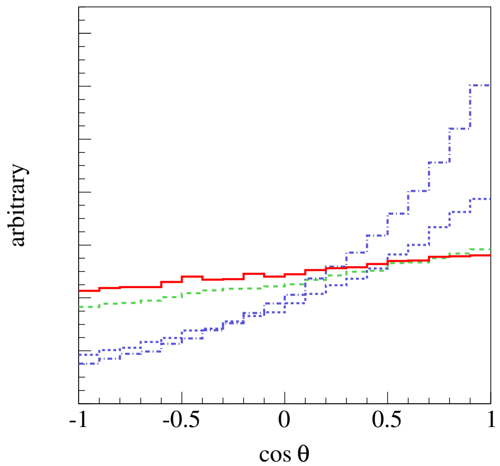

Figure 1. Angular distribution between the neutrino source direction and $\hat{r}_{ne^+}$ having its origin at the delayed neutron capture vertex and pointing to the neutrino interaction point. These lines show KamLAND (solid line), ^{10}B loaded (dashed line : 1.0 wt%), ^{6}Li loaded (dotted line : 0.15 wt%, dot-dashed line : 1.5 wt%) liquid scintillator.

concentration of ^{6}Li will give the better angular resolution. The later simulations are given by the liquid scintillator loaded with ^{6}Li by 1.5 wt%.

2. PHYSICS TARGET

2.1. Geo neutrinos

Recently, the KamLAND experiment published the first observation of geologically produced antineutrinos [3]. The geo neutrino study is very important for the understanding of planet dynamics and formation mechanism. The Bulk Silicate Earth (BSE) model predicts 16 TW radiogenic power from ^{238}U and ^{232}Th decay. According to the BSE model, the radiogenic contribution is approximately half of the measured heat dissipation rate from the earth. It is difficult to estimate the radiogenic heat contribution from the mantle, because the deeper part of the earth is unreachable. So the separation of the geo neutrino flux from crust and mantle contribution is necessary.

The directional sensitivity with the lithium-loaded liquid scintillator is evaluated by the simulation. Positron vertex is calculated from the weighted average of energy deposit point and the reasonable vertex resolution, 5.0 cm/$\sqrt{E(\mathrm{MeV})}$. As shown in Figure 2, The slope of angular distribution gives the information about the mantle contribution. As shown in Figure 3, the crust and mantle contribution are estimated using the angular distribution. That provides us a measurement of U and Th distribution and total mass in the earth. In this simulation, the total radiogenic heat from U and Th is measured to be 18±6 TW.

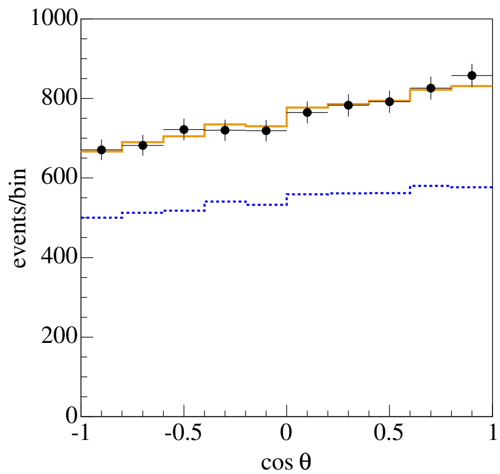

Figure 2. Nadir angle distribution of geo antineutrinos assuming 50 kton Li-loaded liquid scintillator (1.5 wt%) and 5 year data-set. The dot line and solid line show the crust and crust + mantle contribution.

2.2. Supernova neutrinos

The supernova is considered as the explosion in the final stage of the stellar evolution, so called 'supernova explosion'. In the core-collapse supernova, zillions of neutrinos are emitted during a supernova explosion. The neutrino signal is faster than other electromagnetic signals. Therefore, if the supernova neutrinos give the direction of a supernova explosion, other astronomical observations of its early stage can be achieved.

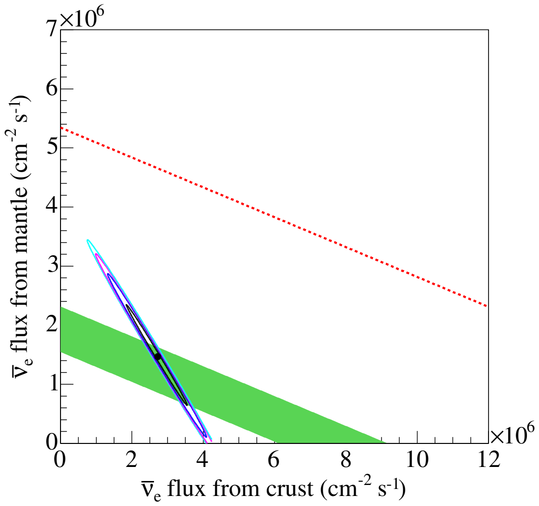

Figure 3. Geo neutrino flux measurement with the directional sensitive detector assuming no background. The solid lines show the allowed region of 68.27%, 95%, 99%, and 99.73% C.L., and the shaded region and dot line show the BSE model (16 TW) and fully radiogenic (44 TW) predictions.

For the pointing of supernova explosions, I defined the following estimator,

$$\vec{p} = \frac{1}{N} \sum_i \hat{r}_{ne^+}.$$

Assuming Galactic supernovae at 10 kpc, the 50 kton detector with lithium-loaded liquid scintillator can determine the supernova direction within a circle of radius 2.7° using the dominant anti-neutrino CC reaction. Although Super-Kamiokande has the high angular resolution with Cherenkov light, it can measure it only in accuracy of 9.2° [4], because the ES reaction gives minor contribution.

2.3. Reactor neutrinos

The KamLAND experiment showed the precise measurement of neutrino oscillation parameters [5] using 1 kton liquid scintillator. The long baseline between the reactors and the detector, typically 180 km, enable KamLAND to search for the oscillation solution of solar neutrino problem using reactor anti-neutrinos. The directional measurement will improve the neutrino oscillation sensitivity because we can know the neutrino flight distance by the source reactor pointing. In the simulation, using the directional event selection, the largest Kashiwazaki reactor contributes up to $\sim$ 50% of all reactors.

3. FURTHER IMPROVEMENT

For the further improvement of directional sensitivity, we need to develop the detector. The prompt positron event makes annihilation γ-rays, and the energy deposit points spread by their gamma-ray contribution. If they are separated from the positron contribution, the diffusion effect can be suppressed. That will be achieved by the segmentation of detector or optical discrimination of energy deposit point by high resolution imaging devices (e.g. CCD camera). In addition, the requirement for detector vertex resolution is within a few centimeters, so we also need to develop the liquid scintillator to get a high light output and a short time constant.

4. CONCLUSION

There are many motivations for the directional measurement of anti-neutrinos. The directional measurement of geo neutrinos will reveal the U and Th distribution and total mass in the earth. That will contribute to the verification of the BSE model. Other motivations are the earlier determination of the supernova direction and reactor neutrino oscillation study. For these purposes, we can choose a detector with a high directional sensitivity using the lithium-loaded liquid scintillator.

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