PROCEEDINGS OF SCIENCE

Lower Energy Extension for Electron Anti-Neutrino Search in the Super-Kamiokande Experiment

Shota Izumiyama[a,*] **on behalf of the Super-Kamiokande collaboration**

[a] *Tokyo Institute of Technology, Oookayama 2-12-1, Meguro-ku, Tokyo, Japan*

E-mail: izumiyama@hep.phys.titech.ac.jp

The Super-Kamiokande-Gd (SK-Gd) experiment is one of the largest neutrino experiments sensitive to an energy region from a few MeV to TeV. It has a Gd-loaded water Cherenkov detector and the capability to identify delayed neutron signals associated with prompt interaction. We aim to observe Diffuse Supernova Neutrino Background which is collective neutrino flux from all supernovae in the universe, and search for electron anti-neutrinos via an inverse beta decay channel, $\bar{\nu}_e + p \to e^+ + n$. In addition, there is a $\bar{\nu}_e$ flux coming from reactors, which has not been observed yet in the SK, around the peak energy of DSNB flux, ~ 5 MeV. The latest result of the SK-Gd is conducted with an energy threshold of 7.5 MeV in kinetic energy. This energy threshold is determined by the trigger system. To extend the lower energy region, we are developing a new analysis method of $\bar{\nu}_e$. We expect a better understanding of background events in the DSNB search and the first reactor signal in the SK. I describe the new method and the result of a feasibility study using muon spallation events in this paper.

XVIII International Conference on Topics in Astroparticle and Underground Physics (TAUP2023)
28.08_01.09.2023
University of Vienna

*Speaker

© Copyright owned by the author(s) under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License (CC BY-NC-ND 4.0).

PoS(TAUP2023)183

1. Introduction

Diffuse Supernova Neutrino Background (DSNB) or supernova relic neutrino (SRN) is a collective neutrino flux from all supernovae in the universe and has not been observed yet. It consists of all neutrino flavors with the peak energy ~ 5 MeV. The Super-Kamiokande-Gd (SK-Gd) [1, 2] is a large water Cherenkov detector and one of the detectors having the highest sensitivity to the DSNB. We search for the electron anti-neutrinos $\bar{\nu}_e$ by an inverse beta decay (IBD) channel, $\bar{\nu}_e + p \rightarrow e^+ + n$, with neutron tagging technique [3]. In addition to the DSNB, reactors emit $\bar{\nu}_e$ in a region around a few MeV, which have not been observed in the SK yet. The conventional analysis of the DSNB uses a trigger of a long timing window to search for the neutron signal. However, its energy threshold is ~ 8 MeV and higher than the typical energy of reactor $\bar{\nu}_e$. We are developing an analysis method to decrease the energy threshold by focusing on a different trigger scheme. It opens the possibility of detection of reactor $\bar{\nu}_e$ signals. In this paper, I describe the method, the feasibility, and the prospects.

2. Method

We revisited the trigger scheme used for the DSNB analysis in this study. The trigger system in the SK is based on the number of hits in a 200 ns integration window (N_{200}) which corresponds to the total deposited energy in the detector. There are several trigger conditions according to N_{200}: for example, super low energy (SLE), and super high energy (SHE) triggers have the lowest and highest threshold of about 3 MeV (SLE), and 7 MeV (SHE) in visible energy respectively. The timing windows are $[-0.5, 1]$ μs for the SLE, and $[-5, 35]$ μs for the SHE trigger. To record weak delayed signals that are not sufficient to the trigger, the system issues an AFTer (AFT) trigger of a 500 μs timing window just after the SHE trigger. The neutron signal appears about 100 μs after the prompt e^+ signal. In the conventional analysis, we search the timing window of the SHE and AFT triggers for the neutron signal. Therefore, the analysis energy threshold of the DSNB is limited by 7.5 MeV in reconstructed $\bar{\nu}_e$ kinetic energy.

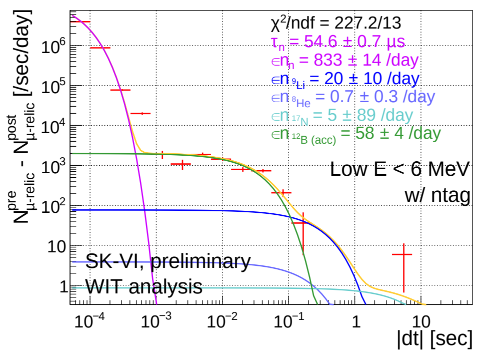
In parallel to the trigger and data acquisition (DAQ) system of the SHE and SLE, we have a complementary DAQ system called Wideband Intelligent Trigger (WIT) [4]. This applies online reconstruction and triggers according to the reconstructed quality. The WIT has a capability of 2.5 MeV kinetic energy threshold, which covers energy from Gd-capture signal of a neutron. In contrast to the SHE+AFT triggers, the WIT trigger timing window is 1.3 μs as short as the SLE trigger. We utilize this low energy threshold in the IBD analysis.

The algorithm developed to search for lower energy IBD events consists of three steps: (1) Construct an event cluster that is close in timing within 500 μs among the WIT-triggered events. The earliest events in the cluster is "prompt" event and successor events are "delayed" events. (2) Apply event reduction according to event qualities and so on. (3) Identify if the delayed events are neutron or not according to event criteria. These criteria are based on the conventional analysis, and the criteria used in Section 3 are tentative and still being developed.

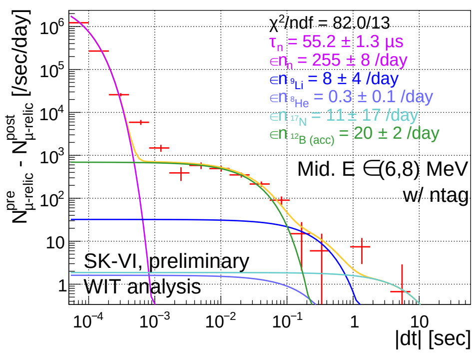
3. Feasibility Study with Spallation Events

We have confirmed the feasibility of the developed algorithm with real data using muon spallation events. Cosmic muons arrive at the SK detector with ~ 2 Hz. Energetic muon can break up

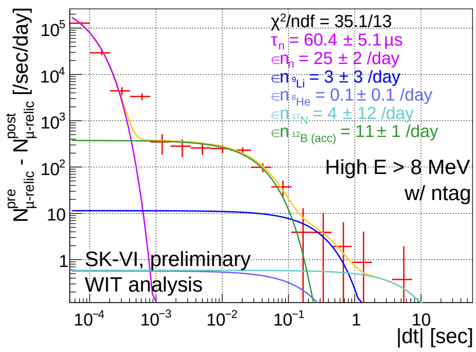
PoS(TAUP2023)183



(a) Lowest energy bin: $E_{\text{rec}} \in [2.75, 6]$ MeV.



(b) Middle energy bin: $E_{\text{rec}} \in [6, 8]$ MeV.



(c) Highest energy bin: $E_{\text{rec}} > 8$ MeV.

Figure 1: Timing distribution of spallation-like events with exponential fittings.

oxygen nuclei and generate radioactive isotopes. Some isotopes, for example, ^{9}Li, decay into $\beta + \mathrm{n}$ which are observed as IBD-like signals. In addition, when two beta decay isotopes accidentally coincide with each other, such events also behave as an IBD-like signal. In other words, we can use those IBD-like events as dummy events to study the IBD signal of $\bar{\nu}_e$.

In this analysis, I evaluated time differences between muon and IBD-like events (relic candidates). I searched for the IBD-like events in WIT low energy events (total energy $E_{\text{rec}} \in [2.75, 100]$ MeV) and defined time difference $\mathrm{dt} := t_\mu - t_{\text{IBD}}$. Since the sampled events are dominated by non-correlated events with muons, I extracted spallation events by subtracting "pre" and "post" samples: pre-samples are a WIT event and a muon event pairs of $\mathrm{dt} < 0$ s, post-samples are the pairs of $\mathrm{dt} > 0$ s. Only pre-samples include spallation events, and post-samples consist of the non-correlated events. Therefore, the subtracted dt distribution shows the distribution of spallation events.

The extracted spallation events are shown in Figure 1. These events are extracted from data taken in January 2022. I defined $N^{\text{pre (post)}}_{\mu\text{- relic}}(|\mathrm{dt}|)$:

$$N^{\text{pre (post)}}_{\mu\text{- relic}}(|\mathrm{dt}|) := \frac{(\text{number of pre (post) pairs at } |\mathrm{dt}| \text{ bin})}{(\text{bin width [sec]}) \times (\text{live time [day]})}. \tag{1}$$

After that, I fit the distribution of $N^{\text{pre}}_{\mu\text{- relic}} - N^{\text{post}}_{\mu\text{- relic}}$ with combined exponential functions:

$$f(\mathrm{dt}) := \sum_{i \in \{\text{isotopes}\}} p_i/\tau_i \exp(-\mathrm{dt}/\tau_i), \tag{2}$$

PoS(TAUP2023)183

where p_i means production yield and τ_i is decay time constant of isotope i. In this analysis, I consider ^{9}Li, ^{8}He, and ^{17}N for $\beta + \mathrm{n}$ decay candidates, neutron pair, and accidental ^{12}B pair. τ_i are fixed with value shown in reference [5] except for the neutron pair. Except for $|\mathrm{dt}| < 1$ ms region where neutron pairs are dominant, fitting works well, and the exponential curves of β decays appear cleary. The clear signal below 6 MeV shows that the new analysis strategy using low-energy triggers other than the conventional SHE trigger works well for the IBD event search.

4. Conclusion and Prospect

We are developing a new analysis method to search for $\bar{\nu}_e$ signals below the conventional analysis threshold of 7.5 MeV. Higher energy deposit from neutron capture by Gd enables us to record delayed neutron signals by themselves without the SHE and AFT triggers. In this paper, we confirmed the feasibility of the new method with spallation events. We continue further developments and searches for $\bar{\nu}_e$ signals around 5 MeV region where reactor $\bar{\nu}_e$ events are expected. In addition, we expect a better understanding of spallation events using a lower energy spectrum to constrain the effect on the DSNB search.

Acknowledgments

We gratefully acknowledge cooperation of the Kamioka Mining and Smelting Company. The Super-Kamiokande experiment was built and has been operated with funding from the Japanese Ministry of Education, Science, Sports and Culture, and the U.S. Department of Energy. This work was partially supported by JSPS KAKENHI Grant Number JP23KJ0890, and JST, the establishment of university fellowships towards the creation of science technology innovation, Grant Number JP-MJFS2112.

References

[1] Super-Kamiokande collaboration, *The Super-Kamiokande detector*, *Nucl. Instrum. Meth. A* **501** (2003) 418.

[2] Super-Kamiokande collaboration, *First gadolinium loading to Super-Kamiokande*, *Nucl. Instrum. Meth. A* **1027** (2022) 166248 [2109.00360].

[3] Super-Kamiokande collaboration, *Search for Astrophysical Electron Antineutrinos in Super-Kamiokande with 0.01% Gadolinium-loaded Water*, *Astrophys. J. Lett.* **951** (2023) L27 [2305.05135].

[4] Super-Kamiokande collaboration, *The new Wide-band Solar Neutrino Trigger for Super-Kamiokande*, *Phys. Procedia* **61** (2015) 666.

[5] S.W. Li and J.F. Beacom, *First calculation of cosmic-ray muon spallation backgrounds for MeV astrophysical neutrino signals in Super-Kamiokande*, *Phys. Rev. C* **89** (2014) 045801 [1402.4687].

PoS(TAUP2023)183