Study of the atmospheric neutrino background for Supernova Relic Neutrino search

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1. Introduction

Supernova Relic Neutrinos (SRNs)

Neutrinos from all past core-collapse supernovae (CCSNe) are accumulated to form an integrated flux, called **SRNs**. Detecting SRNs would provide valuable information about the explosion mechanism as well as the star formation history.

Super-Kamiokande (SK)

SK is a cylindrical water Cherenkov detector located 1,000m under the mountain and operated since 1996. It consists of the inner detector and the outer detector (for cosmic-ray muon veto), and its fiducial volume is 22.5 kton.

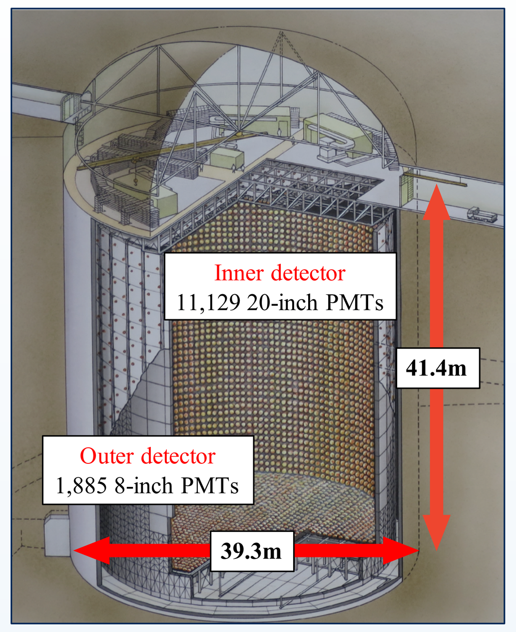

Figure 1 : SK detector

SRNs search in SK-IV

A search for SRNs using an SK-IV 2970.1-day data set was performed, but no significant excess over the background prediction was observed. Hence, an upper limit on the $\bar{\nu}_e$ flux was calculated. The obtained upper limits are the world's most stringent result while limits are a factor 3 to 30 above SRN flux model predictions (**see S. El Hedri Poster (Poster ID : 231)**).

SK-Gd

- SK has an upgrade plan to SK-Gd, which dissolves 0.2% gadolinium-sulfate ($Gd_2(SO_4)_3$) to enhance the sensitivity to the neutron signal (start in 2020).
- When Gd captures a neutron, Gd emits a few γ-rays whose energy sum is ~8 MeV.
- Neutron tagging efficiency : ~20% → ~50% (0.02% $Gd_2(SO_4)_3$) → **~80%** (0.2% $Gd_2(SO_4)_3$)

2. Signal & background in SK-Gd

- Inverse beta decay (IBD) of $\bar{\nu}_e$ ($\bar{\boldsymbol{\nu}}_e$ **+ p → e⁺ + n**) is searched.
- Prompt signal : **e⁺**
- Delayed signal : **Total ~8 MeV γ-rays** from neutron capture

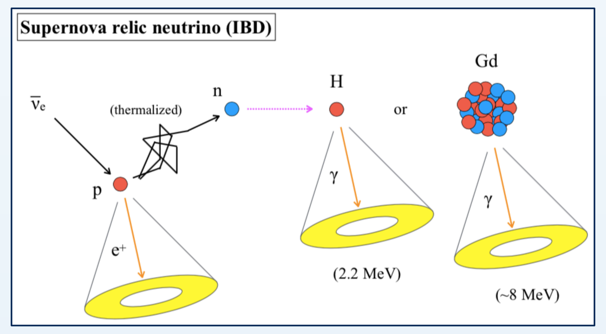

Figure 2 : $\bar{\nu}_e$'s IBD by SRNs

Atmospheric neutrino background

The MC production of atmospheric neutrino events are based on flux prediction by the HKKM2011 model and the neutrino interaction by NEUT ver. 5.3.6. This background is categorized into two.

Neutral-current quasielastic (NCQE) interactions

- Atmospheric neutrinos react with oxygen nuclei.
  → de-excitation γ-ray (+ n) (see Figure 3)
  ※ NCQE interactions are dominant < ~20 MeV.

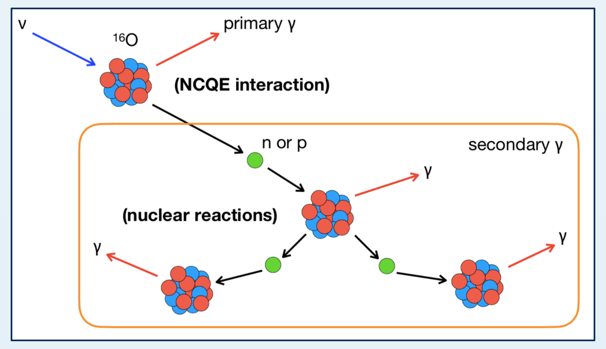

Figure 3 : NCQE interactions by atmospheric neutrinos

- The out-going nucleons, especially neutrons, further interact with oxygen nuclei, which produce γ-rays and additional neutrons in some cases.
  → NCQE events tend to have a reconstructed Cherenkov opening angle of > 42°
- The reconstructed Cherenkov angle for NCQE events is highly dependent on models of the neutrino interaction and the following neutron-oxygen (n-O) interaction.
  → The E_{rec} distributions for the reconstructed Cherenkov angle of MC does not reproduce that of data (see Figure 4).
- The model uncertainty affect the number of neutrons (neutron multiplicity).
  → The neutron multiplicity of MC does not agree with that of data [2].

Charged-current (CC) interactions

- Atmospheric neutrinos react with oxygen nuclei.
  → (invisible muon (< 120 MeV/c))
  → decay-e (+ n) (see Figure 5)
  ※ CC interactions are dominant > ~20 MeV.
- The Michel spectrum is well-known, hence the MC spectrum in some energy regions are fit by the observed spectrum in the same region.
- The number of events in data was much smaller than that in MC.

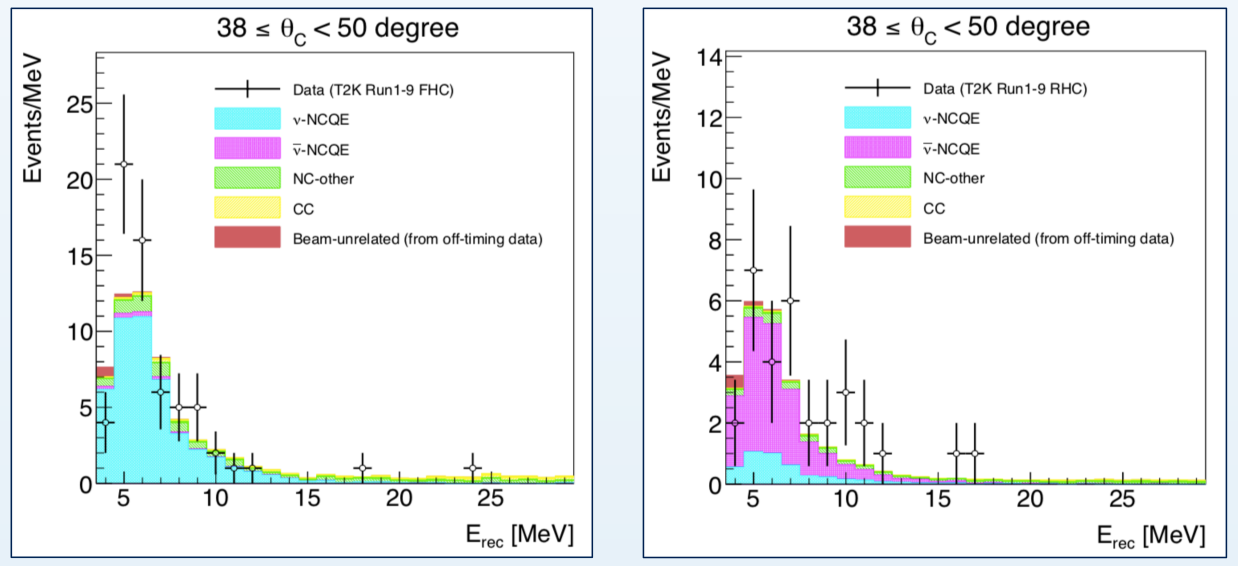

Figure 4 : The E_{rec} distributions for $\theta_C \in [38, 50]$ degrees [1] (left) T2K FHC(ν) mode (right) T2K RHC($\bar{\nu}$) mode

- The reason for much smaller values than the MC is that the neutron model may be inappropriate and this is consistent with the neutron multiplicity results from T2K where the number of tagged neutrons in data is much lower than that in MC [2].
- The difference between data and MC for CC events could also be due to a difference in the production of de-excitation γ-rays.

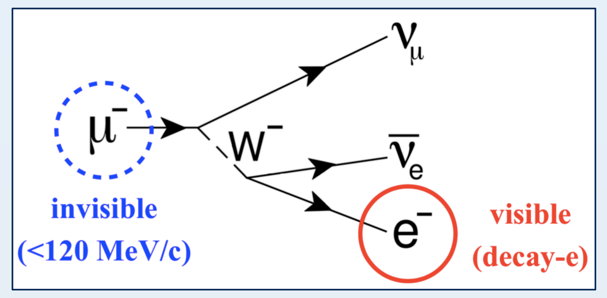

Figure 5 : Invisible muon and decay-e

Other background

Muon spallation : Cosmic-ray muons (~2 Hz in SK) break up oxygen nuclei in water and radioactive isotopes are produced, some of which decay into "e + n". Especially, **⁹Li** is the most likely background. Even if the final state is not a "e + n" combination, when "e" or γ-ray forms a coincidental pair with a neutron, this becomes a background to the SRNs search.

Reactor neutrinos : $\bar{\nu}_e$ is emitted from reactor plants.

3. Result

- From figure 6, some SRN flux models can be tested after 5-10 years of operation in SK-Gd. The reach after the 10-year operation is comparable or a bit worse compared to the other models.
- The sensitivity can be improved by reducing error and background like NCQE, CC, etc., especially construction of precise neutron model is important to reduce these uncertainties.

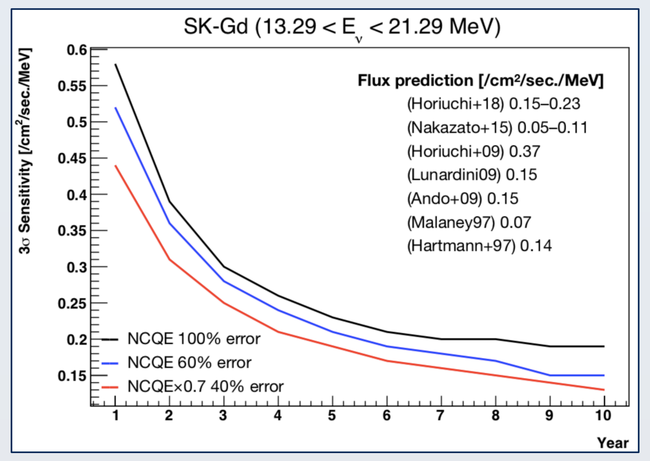

Figure 6 : The 3σ sensitivity

4. Summary

- Detecting SRNs would enable us to study the supernova mechanism as well as the star formation history; however, they have never been discovered even in the most sensitive searches at SK.
- SK has an upgrade plan to SK-Gd to enhance the sensitivity to SRNs, and some SRN flux models can be tested after 5-10 years of operation in SK-Gd.

Future

- We will construct new n-O interaction model by using other experimental data.
  → The new n-O interaction model will be loaded into SK detector Monte Carlo simulation (MC).
- We will search SRNs using the SK-Gd data and MC with new n-O interaction model.

Reference : Y. Ashida. Ph.D Thesis, Kyoto University, 2020.
[1] K. Abe et al., Phys. Rev. D 100, 112009 (2019) [2] R. Akutsu. Ph.D Thesis, The University of Tokyo, 2019.

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