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Search for Supernova Relic Neutrinos at KamLAND

S Obara

Frontier Research Institute for Interdisciplinary Sciences, Tohoku University, Sendai 980-8578, Japan

E-mail: `shuhei.obara.d4@tohoku.ac.jp`

S Ieki , K Ishidoshiro , T Mitsui, H Watanabe

Research Center for Neutrino Science, Tohoku University, Sendai 980-8578, Japan

M P Decowski

Nikhef and the University of Amsterdam, Science Park, Amsterdam, the Netherlands

and KamLAND collaboration

Abstract. We report a search for electron antineutrinos at KamLAND with an 8.3–30.8 MeV energy range via the inverse beta decay. In 6.72 kton-yr of KamLAND data, we found 18 neutrino candidates and no significant excess over estimated backgrounds. From data interpretation, with the assumption of some supernova relic neutrino spectrum predictions, we give upper flux limits of 60–110 $cm^{-2}\,s^{-1}$ (90% CL) in the analysis range and present a model-independent flux. These upper limits are the most stringent for 8–13 MeV region. We also improve on the upper probability limit of ^{8}B solar neutrinos converting into antineutrinos via the Resonant Spin Flavor Precession with the neutrino magnetic moment. Besides, we could set limits on the annihilation cross-section for light dark matter pairs to neutrino pairs.

1. Introduction

A core-collapse supernova explosion is the most dynamical neutrino emission process. In 1987, water-cherenkov and liquid-scintillator detectors observed supernova neutrinos from the Large Magellanic Cloud [1, 2, 3, 4, 5]. Diffused neutrinos from all the past supernovae is expected (supernova relic neutrino). Typically supernova relic neutrinos have order tens of MeV energy [6, 7, 8, 9]. There are a large number of reactor neutrinos and atmospheric neutrinos at that energy region as backgrounds; therefore, an energy range of 8–30 MeV is the golden region for searching supernova relic neutrinos for liquid-scintillator detectors.

Not only them but there are also other astrophysical neutrinos in that region. Solar ^{8}B neutrinos can be converted into electron antineutrinos via the combined processes of the Mikheyev-Smirnov-Wolfenstein effect and Resonant Spin Flavor Precession scenario [10]. MeV-scale dark-matter self-annihilation process might produce neutrino pairs [11].

2. Neutrino event search

We focused on electron antineutrinos ($\bar{\nu}_e$'s) via the inverse-beta decay reaction ($\bar{\nu}_e + p \rightarrow e^+ + n$) from 6.72 kton-yr of KamLAND data. The KamLAND detector locates at 1 km underground at Kamioka, Japan, and consists of a 3.2-kton water-cherenkov outer detector and a 1-kton liquid-scintillator inner detector. We used a 5.5 m radius spherical fiducial volume from the center of the KamLAND. Details of the KamLAND detector are described in [12]. An inner-balloon region is vetoed during the KamLAND-Zen periods, which is installed at the center of the KamLAND for neutrinoless double-beta decay search [13, 14]. The veto region is a 2.5-m-radius spherical volume centered in the detector and a 2.5-m-radius vertical cylindrical volume in the upper half of the detector.

Inverse-beta decay events are selected by the delayed-coincidence selection; the prompt signal is the scintillation photons from positron and annihilation gamma-rays, and the delayed signal is 2.2 MeV (4.9 MeV) gamma-ray from the thermalized neutron capture on a proton (carbon-12). Selection criteria for prompt energy (E_p), delayed energy (E_d), spatial correlation (ΔR), and timing difference (ΔT) are $7.5 < E_p < 30.0$ MeV, $1.8 < E_d < 2.6$ or $4.4 < E_d < 5.6$ MeV, $\Delta R <$160 cm, and $0.5 < \Delta T < 1000\,\mu$s, respectively. This corresponds to 8.3–30.8 MeV of neutrino energies. We found 18 final candidates with selecting single neutron-capture gamma-ray as the delayed event. Possible backgrounds are reactor $\bar{\nu}_e$, accidental coincidence, muon-induced spallation products, fast neutrons, atmospheric-neutrino charged-current (CC) interaction, and atmospheric-neutrino neutral-current (NC) interaction. The atmospheric NC interaction is the most challenging background in this energy region. We took into account the atmospheric-neutrino spectrum at Kamioka [15], the neutron binding energies in carbon for the P-shell (18.7 MeV) and the S-shell (41.7 MeV) configurations, the corresponding shell populations, and de-excitation models [16]. From this numerical calculation, we estimated the number of atmospheric NC backgrounds to be 20.6 ± 5.9 events. However, from the NEUT [17] simulation-based estimation, its number is $16.5^{+5.1}_{-4.5}$ events. In order to avoid depending on the estimation model, we treated the number of atmospheric NC backgrounds as a free parameter in the fitting of the data interpretation. Neutrino candidate profiles and details of background estimation are discussed in [18].

3. Data interpretation

We fitted the obtained data and estimated backgrounds searching for supernova relic neutrinos, assuming the Nakazato model [8, 9] with normal mass ordering as the energy spectrum shape. Figure 1 shows the fit result in the two free parameter space between the number of supernova relic neutrino signals and the number of atmospheric NC backgrounds. The best fit parameter represents 0-event neutrino signals and 7.5-event atmospheric NC backgrounds which is 2σ (1σ) consistent with the numerical (simulation) estimation. Energy spectra and radial distributions as the best fit results are shown in Figure 2. We tested this fitting with some theoretical predictions, but all cases showed 0 neutrino signal as the best fit result. Therefore, we provided upper flux limits with 90% confidence level (CL) on the Kaplinghat+00 [6], Horiuchi+06 [7], Nakazato+15(max NH), and Nakazato+15(min, IH) models [8, 9], as to be 74.5, 61.6, 108, and 105 $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, respectively. We also gave the model-independent upper flux limits on electron antineutrinos (Figure 3). Our result shows the most stringent upper flux limits in the neutrino energy range of 8–13 MeV.

In addition, we also tested the solar ^{8}B neutrino conversion process and provided the most stringent upper limits on the conversion probability as $P_{\nu_e \rightarrow \bar{\nu}_e} < 3.5 \times 10^{-5}$ (90% CL). Dark-matter self-annihilation cross section is also constrained as $\langle \sigma_A \mathbf{v} \rangle < (1\text{–}11) \times 10^{-24}\,\mathrm{cm}^{-3}\mathrm{s}^{-1}$ (90% CL) below 14 MeV of dark-matter mass region. Details of the above analyses and results are summarized in [18].

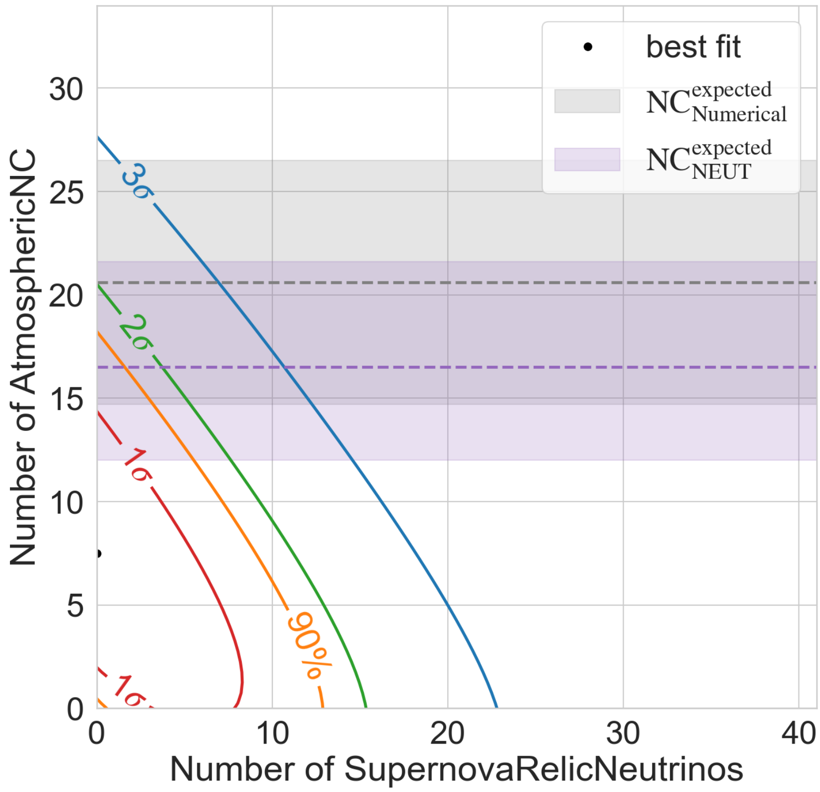
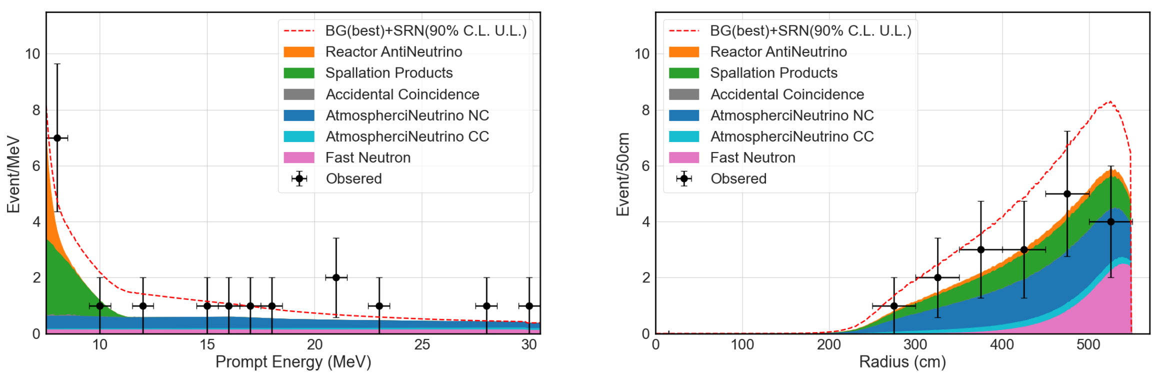


Figure 1. Fit result between two free parameter spaces: number of supernova relic neutrino signals and number of atmospheric-neutrino NC backgrounds. The black dot represents the best fit point of the two free parameters as 0 and 7.5 events, respectively. The red, orange, green, and blue lines are confidence intervals. The horizontal gray band is the expected number of atmospheric neutrino NC backgrounds from the numerical calculation, and the purple band is from the NEUT simulation.



(a) Energy (b) Radius

Figure 2. Best fit result and 90% CL upper limit of supernova relic neutrinos in energy spectrum(a) and radial distribution(b). Filled stacked spectra are the best fit backgrounds, and red dashed line corresponds to the upper limit with 90% CL.

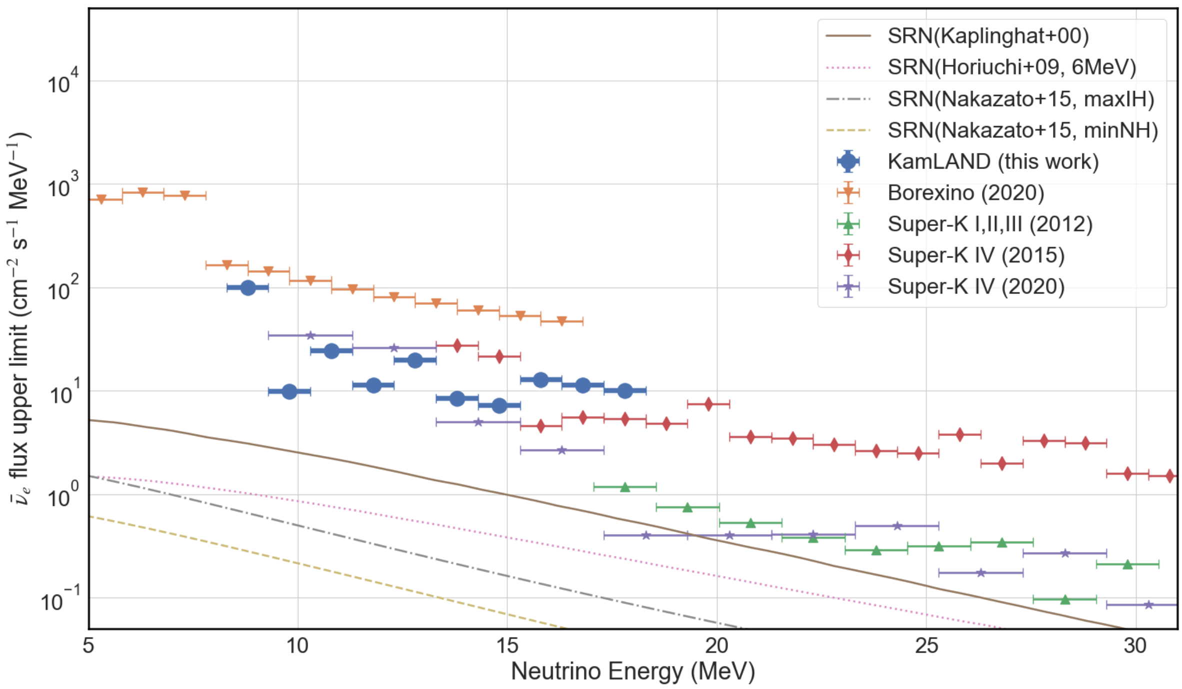


Figure 3. Upper limits on model-independent electron-antineutrino flux. Blue dots are this work. Other color dots show the results from Borexino [19], Super-K I,II,III [20], Super-K IV [21], and Super-K IV [22]. Figure is reproduced from [18].

4. Summary

We searched for astrophysical electron antineutrinos at KamLAND with 6.72 kton-yr exposure. No significant signals are found over our background model. We set flux upper limits on some supernova relic neutrinos and model-independent neutrinos.

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