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Low-energy astrophysics with KamLAND

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We present two results of a search for MeV-scale neutrino and anti-neutrino events correlated with gravitational wave events/candidates and large solar flares with KamLAND.
The KamLAND detector is a large-volume neutrino detector using liquid scintillator, which is located at 1 km underground under the top of Mt. Ikenoyama in Kamioka, Japan. KamLAND has multiple reaction channels to detect neutrinos. Electron antineutrino can be detected via inverse-beta decay with 1.8 MeV neutrino energy threshold. All flavors of neutrinos can be detected via neutrino-electron scattering without neutrino energy threshold. KamLAND has continued the neutrino observation since 2002 March.
We use the data set of 60 gravitational waves provided by the LIGO/Virgo collaboration during their second and third observing runs and search for coincident electron antineutrino events in KamLAND. We find no significant coincident signals within a ±500 s timing window from each gravitational wave and present 90% C.L. upper limits on the electron antineutrino fluence between 10^{8}–10^{13} cm^{-2} for neutrino energies of 1.8–111 MeV.
For a solar-flare neutrino search at KamLAND, we determine the timing window using the solar X-ray data set provided by the *GOES* satellite series from 2002 to 2019 and search for the excess of coincident event rate on the all-flavor neutrinos. We find no significant event rate excess in the flare time windows and get 90% C.L. upper limits on the fluence of neutrinos of all flavors (electron anti-neutrinos) between 10^{10}–10^{13} cm^{-2} (10^{8}–10^{13} cm^{-2}) for neutrino energies in the energy range of 0.4–35 MeV.

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1. The KamLAND experiment

1.1 KamLAND detector

The KamLAND detector is the largest liquid-scintillator-based anti-neutrino detector in operation since 2002, which is located about 1 km underground (2700 m water equivalent) under Mt. Ikenoyama in Kamioka, Japan. Rock above the detector reduces the muon flux produced as secondary particle of cosmic rays by five orders of magnitude.

KamLAND consists of a 10 m-radius × 20 m-height cylindrical tank (outer detector) and a 9 m-radius spherical stainless steel tank (inner detector). Neutrinos are detected by the inner detector (ID). The main volume of ID is 1 kt liquid scintillator and supported by a 6.5 m-radius nylon/EVOH balloon installed at the center of the ID. This nylon/EVOH balloon is called the outer balloon. The scintillation photons are counted by 1325 17-inch Photo Multiplier Tubes (PMTs) and 554 20-inch PMTs mounted on the inner surface of the spherical tank. Non-scintillating mineral oil is filled between the outer balloon and the spherical tank to suppress backgrounds from radioactive impurities in PMTs. The outer detector (OD) is a water-cherenkov detector using 3.2 kt pure water for shielding from external γ-ray backgrounds. An active muon counter is provided by 255 20-inch PMTs before a refurbishment in 2016 and 140 20-inch PMTs after the refurbishment [1]. The details of the KamLAND detector are summarized in [2].

Since August 2011, KamLAND has searched for the neutrinoless double-beta decay of ^{136}Xe using a nylon balloon (inner balloon) installed at the center of the detector, which is filled with xenon-loaded liquid scintillator [3]. The inner balloon radius was 1.5 m and the mass of xenon was about 400 kg in the first phase, which ran from August 2011 to September 2015, called KamLAND-Zen 400. In 2018 May, the KamLAND-Zen experiment was updated to KamLAND-Zen 800 using 1.9 m-radius inner balloon and the double amount of xenon for a higher sensitivity [4]. In these KamLAND-Zen periods, the region with xenon-loaded liquid scintillator was excluded from the target volume for the neutrino observation to suppress backgrounds from xenon nuclei, the inner balloon and supporting structure.

1.2 Neutrino detection in KamLAND

KamLAND has multiple neutrino-detection channels. We used the following two reaction channels; inverse-beta decay(IBD), $\bar{\nu}_e + p \rightarrow e^+ + n$, and neutrino-electron scattering(ES), $\nu + e^- \rightarrow \nu + e^-$ in this study.

IBD is sensitive only to electron anti-neutrino ($\bar{\nu}_e$) with energy more than 1.8 MeV. But it is a strong advantage of this channel that the cross section is roughly 10 times larger than that of ES. In addition, this channel can suppress the background by a delayed-coincidence method. The positron's kinetic energy and the two γ-rays from annihilation with electron are observed as one event called prompt event. The incident neutrino energy, E_ν, can be reconstructed from $E_\nu \simeq E_\mathrm{p} + T_n + 0.8$ MeV, where E_p is the observed energy of the prompt signal and T_n is the kinetic energy of neutron. With half-life about 207 μs, the neutron is captured by proton (carbon) and emits 2.2(4.9) MeV γ-ray, which is called delayed event. Taking time-space correlation between these two events, we can observe electron anti-neutrino in almost background-free condition.

ES channel cannot take advantage of the background suppression with delayed-coincidence and cannot provide the incident neutrino energy. However, this channel is sensitive to all flavors of neutrinos, though the cross section depends on the flavor of neutrino.

2. Search for gravitational wave neutrinos

Gravitational-wave experiment LIGO/Virgo collaboration founds a lot of burst events. They reported the event profiles in the second observing run (LIGO-O2) [5], the first half of the third observing run (LIGO-O3) [6], and the latest online alert on their public website [7]. From the gravitational wave source, thermal neutrino emission is theoretically predicted with the energy of a few tens MeV [8–10]. The follow-up searches for neutrinos have been performed by IceCube, Super-K, Borexino, and other various detectors [11–13]. KamLAND also reported the results for the first three gravitational wave events [14]. In this analysis, we searched $\bar{\nu}_e$s associated with gravitational waves found in LIGO-O2 and -O3. A list of gravitational waves in LIGO-O2 and -O3 are taken from the published article [5] and their online gravitational wave candidate event database (GraceDB) [7], respectively. Taking into account some retraction of candidates in the GraceDB and the running status of the KamLAND detector at the timing of the gravitational wave event, we chose 60 gravitational waves summarized in Ref. [15].

We focused on $\bar{\nu}_e$ via the IBD channel in KamLAND with $0.9 < E_\mathrm{p} < 100\,\mathrm{MeV}$ corresponding to $1.8 < E_\nu < 111\,\mathrm{MeV}$. For the IBD selection, the energy of delayed event (E_d) should be $1.8 < E_\mathrm{d} < 2.6\,\mathrm{MeV}$ or $4.4 < E_\mathrm{d} < 5.6\,\mathrm{MeV}$. The spatial distance ($\Delta R$) and time difference ($\Delta T$) between the prompt and the delayed event are selected with $\Delta T < 200\,\mathrm{cm}$ and $0.5 < \Delta T < 1000\,\mu\mathrm{s}$, respectively. Besides, a likelihood-based signal selection was applied for rejecting radioactivity-oriented background contamination. Muon and related spallation products are vetoed as standard KamLAND analysis [16]. Fiducial volume is restricted within a 6 m radius sphere from the center of the KamLAND, corresponding to $(5.98 \pm 0.13) \times 10^{31}$ of the number of target protons. For the KamLAND-Zen 400 and 800 phases, the delayed events in a 2.5 m radius sphere from the center or a 2.5 m cylindrical radius of the upper hemisphere are rejected to suppress the inner-balloon-related background contamination. In this analysis, a KamLAND dataset corresponding to LIGO-O3 is in the KamLAND-Zen 800 phase and excludes the inner-balloon volume. The neutrino detection efficiency for the LIGO-O2 and -O3 datasets are $\sim 93\%$ and $\sim 77\%$, respectively.

The neutrino event timing window was set as ±500 s from each gravitational wave [17]. Using offtime from the gravitational waves, IBD-like events un-correlated with the gravitational waves are estimated to be 4.08×10^{-3} and 4.27×10^{-3} for gravitational wave events found in LIGO-O2 and -O3 periods, respectively. After the data interpretation, we found no $\bar{\nu}_e$ signals in that timing window and give an upper limit on the fluence with the Feldman-Cousins method [18] for each gravitational wave, assuming the monochromatic neutrino energy. Figure 1 shows the $\bar{\nu}_e$ fluence upper limits with 90% confidence level (C.L.) for each gravitational wave event found by LIGO-O2 and -O3.

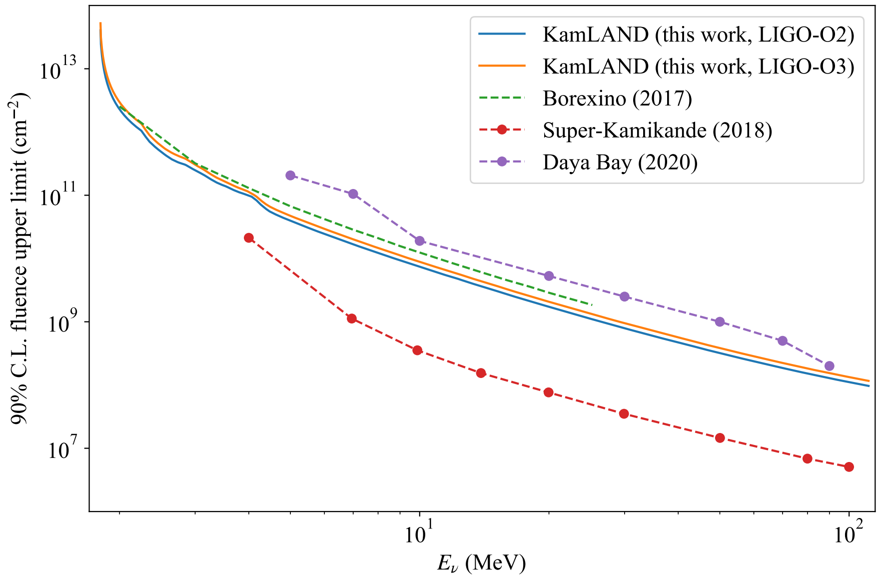

Figure 1: Upper limits on the $\bar{\nu}_e$ fluence with 90% C.L. Figure is reproduced from Ref. [15].

3. Search for solar flare neutrino

Solar flares are the largest explosive events in the solar system, which is described as reconnection of magnetic field and acceleration of charged particles. Observations of electromagnetic signals have contributed to the understanding of these burst phenomena [19]. Neutrinos are expected to be emitted from decays of charged pion as secondary particle of the initially-accelerated protons. Because solar flare neutrino spectrum depends on the profile of initially-accelerated charged particles, the observation of solar flare neutrino plays a key role in the understanding of particle acceleration mechanism in solar flare.

Some studies were developed to construct solar flare neutrino emission model [20–22]. An estimation from [22] predicts 398 – 770 cm^{-2} neutrino fluence per flare at Earth in 10 – 100 MeV, which corresponds to $O(10^{-9})$ electron scatterings in KamLAND. For current neutrino detectors, it is hardly feasible to detect neutrino from a single flare. Thus, it is important to search for statistical excess using a number of flares.

The Homestake experiment reported an event excess possibly correlated to a large solar flare in 1991 [23], though subsequent studies by KAMIOKANDE II [24], LSD [25] and SNO [26] found no event excess related to solar flares. In 2019, Borexino performed a coincidence analysis of neutrino event candidates with solar flares selected from *the Geostationary Operational Environmental Satellites (GOES)* database and excluded the allowed parameter space for the solar flare neutrino fluence [27].

In this analysis, we searched neutrinos correlated with solar flares in assumption that the luminosity of solar flare neutrino is proportional to the soft X-ray luminosity as in Ref. [27]. From the *GOES* flare database, we chose 614 X- or M- class flares in our analysis period, from 2002 March to 2019 September, considering the KamLAND operation status. The time windows for flare neutrino search were determined using the derivative of the soft X-ray light curve based on

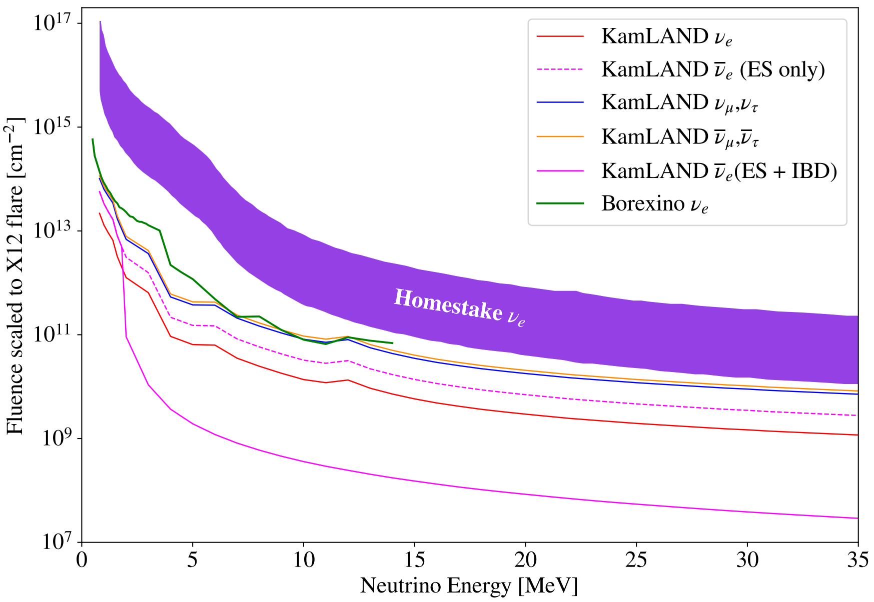

Figure 2: Fluence upper limits with 90% C.L. scaled to the Homestake flare intensity. Figure is reproduced from Ref. [29]

the method proposed in Ref. [28]. The average length of the 614 time windows is 1028 s and the cumulative flare intensity is 303×10^{-4} W/m^2.

As for neutrino event selection, we used both IBD and ES in this analysis. The selection of IBD was the same as described in the previous section. For ES event selection, all single events remaining after muon-spallation-related event veto [3], ^{238}U decay series veto [16] and KamLAND-Zen volume cut(described above) are ES candidates. Assuming monochromatic solar flare neutrino spectrum, the analysis volume and the lower energy threshold to count the ES candidates were optimized for each assumed neutrino energy [29]. To take a coincidence analysis, the number of background events in each flare time window was estimated using offtime windows of each flare time window.

After a χ^2 study with respect to the number of neutrino reactions (IBD/ES) by flare, we found no statistical excess related to solar flare and got 90% C.L. upper limits on the neutrino fluence from solar flares for each neutrino flavors and each neutrino energies. Figure 2 shows the fluence upper limits scaled to the Homestake flare intensity. This analysis provided a limit on unsearched parameter space for solar flare neutrino fluence.

4. Summary

KamLAND is a large-volume (anti-)neutrino detector which is sensitive to MeV-scale neutrinos.

We found no $\bar{\nu}_e$ events in KamLAND associated with the gravitational waves detected by the second and third LIGO/Virgo observing runs. The upper limits on the $\bar{\nu}_e$ fluence with 90% CL are given for neutrino energies in the energy range of 1.8–111 MeV.

Another analysis on solar flare neutrino in KamLAND was done and no statistical excess related to solar flares were found. KamLAND set the strongest limits on fluences of solar flare neutrinos in energy range of 0.4 – 35 MeV.

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