First result of a search for astrophysical electron antineutrino in SK-Gd experiment

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Abstract

Since 2020, Super-Kamiokande (SK) detector has been updated by loading gadolinium (Gd) as a new experimental phase, 'SK-Gd.' In the SK-Gd experiment, event selection with delayed coincidence using neutron capture signal, such as inverse beta decay of electron antineutrinos, is improved thanks to high cross-section and high energy gamma-ray emission of thermal neutron capture on Gd.

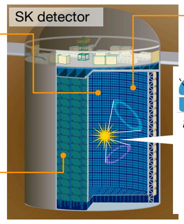
In July 2022, the observation with 0.01% of Gd mass concentration was completed, and currently, an updated phase with 0.03% mass concentration is in operation. We report the first result of a search for astrophysical electron antineutrinos flux for the energy range of O(10) MeV in SK-Gd with a 22.5×552 kton×day exposure at 0.01% Gd mass concentration. Finally, the future prospect for the DSNB search in SK-Gd is discussed.

1. Introduction

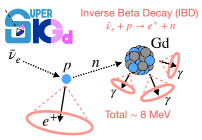
SK-Gd experiment

New experimental phase of Super-Kamiokande (SK) with enhanced neutron detection

SK-Gd detector [1]
- 50 ktons of ultra-pure water with Gd sulfate
- 1000 m overburden from Mt. Ikenoyama, Gifu, Japan

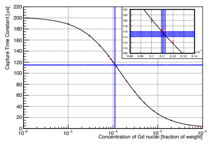


Inner Detector (ID)
- 22.5 kt of Fiducial Volume (FV)
- 11,126 50-inch PMTs



Outer Detector (OD)
- 1,885 8-inch PMTs
- Veto cosmic-ray muon

SK-VI [2]: 0.01w% mass concentration
- Operated from Sep. 2020 to Jun. 2022
- ~50% of neutrons are captured on Gd
- Time constant: ~ 115 μs

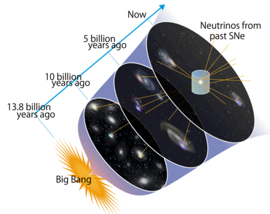


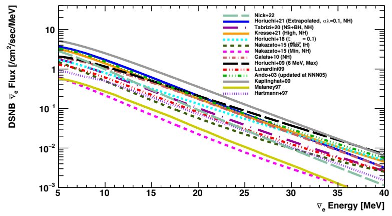
Astrophysical Electron Antineutrinos

MeV scale $\bar{\nu}_e$ is emitted from astrophysical phenomena
Supernova, Low-energy DM, Solar antineutrinos…

Diffuse Supernova Neutrino Background (DSNB)
- Integrated flux of neutrinos emitted from past all Supernovae (SNe).
- SRN flux includes star evolution information :

$$\Phi_{SRN} \propto \int [\text{SN rate}] \otimes \begin{bmatrix}\nu \text{ emission} \\ \text{from SN}\end{bmatrix} \otimes [\text{Red shift}]$$





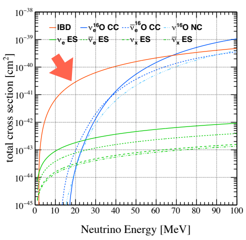
One order spreading among modern flux predictions

Detecting DSNB allows us to investigate
NOT ONLY ν emission from SN
BUT ALSO history of star formation

2. Signal and Background

Signal Events

For MeV scale $\bar{\nu}_e$, IBD interaction has largest cross section with water target



Target signal: positron (e+) + neutron (n)

$$\bar{\nu}_e + p \to e^+ + n$$

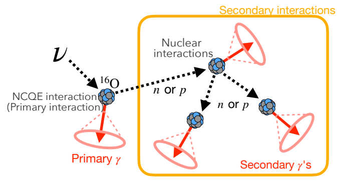
Prompt positron event
- Energy range: 8 – 30 MeV for recon. total energy
- Veto cosmic-ray muon

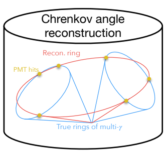
Delayed neutron event
- Search from extended 535 μs window
- Search method follows to Ref. [3] → Energy thr. change to **3.5 MeV**
- Neutron detection efficiency : 35.6%

Delayed coincidence enables to drastically reduce background without neutrons

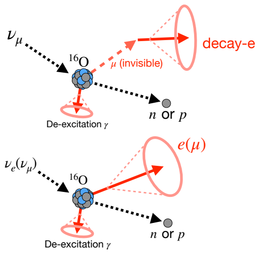
Background Events

Atm. NC Quasi-Elastic (NCQE)



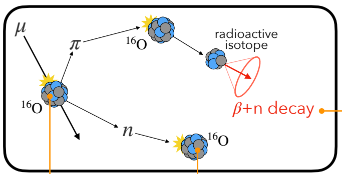


Atm. other interactions

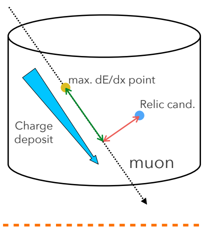


- Multiple-gamma rays : Reduce using opening angle of recon. ring θC.
- Muons, pions : Reduce using PMT charge pattern, opening angle θC.
- Electrons : Estimate from Michel spectrum of decay-e.

Cosmic-ray muon spallation induced isotopes decay



Isotope decay with n
- Mainly consist of ^{9}Li decay
- Likelihood using time, space, charge correlation with muon
- Optimize to reduce O(1)% for spallation event

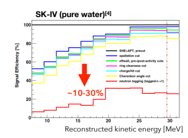


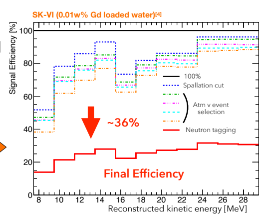
Hadronic shower
- Detect "neutron cloud"
- Remove using time and space correlation b/w cloud and muon

Multiple isotopes decay
- Detect multiple isotopes decay → Cause multiple low-energy event
- Remove using time and space correlation

Signal Efficiency

✓ Signal efficiency was improved due to Gd capture signal



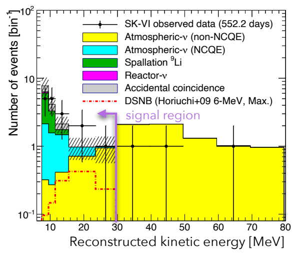


3. Search Result

Energy Spectrum

✓ 16 events are found in 552.2 d data
✓ Expected background are estimated
✓ p-Value is calculated

E_{rec} (MeV)	Observed	Expected	p-value
7.5–9.5	5	7.73 ± 2.54	0.798
9.5–11.5	5	4.14 ± 1.23	0.398
11.5–15.5	3	2.13 ± 0.59	0.359
15.5–23.5	2	0.98 ± 0.35	0.258
23.5–29.5	1	0.98 ± 0.41	0.597



There is no significant excess over expected background
➡ Upper limit extraction

Flux Upper Limit

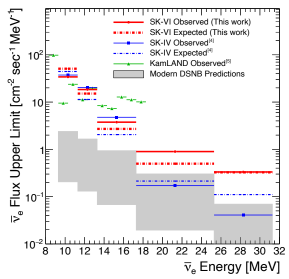
Flux limit calculation

$$\phi_{90}^{limit}\ [\text{cm}^{-2}\,\text{sec}^{-1}\,\text{MeV}^{-1}] = \frac{N_{90}^{limit}}{N_p \cdot T \cdot \bar{\sigma}_{IBD} \cdot \varepsilon_{sig} \cdot dE}$$

- N_{90}^{limit} : Num. of event w/ 90% C.L.
- N_p : Num. of prompt event
- σ_{IBD} : IBD cross-section
- ε_{sig} : Signal efficiency
- T : Live time

✓ Comparable with SK-IV limit[4] with 20% of live time

Proves SK-Gd is most sensitive to DSNB search in the world



4. Summary and prospects

- We performed first search for astrophysical $\bar{\nu}_e$ flux search with neutron ID efficiency of 35.6% using 552 days of SK-VI data.
- No significant excess was observed over expected background → Flux upper limit is placed below 31.3 MeV of neutrino energy.
- Flux limit in SK-VI is comparable level with SK-IV search, which has the world best sensitivity. → **Proves that SK-Gd is the world most sensitive to DSNB.**
- SK-Gd aims first observation of DSNB with 0.03w% Gd conc. (SK-VII).

Reference

[1] J. F. Beacom and M. R.Vagins, Phys. Rev. Lett. 93, 171101 (2004)
[2] K. Abe et al., Nucl. Instrum. Methods Phys. Res. A 1027 166248(2022)
[3] M. Harada PoS(ICHEP2022), Vol. 414, p. 1178 (2022)
[4] K. Abe et al., Phys. Rev. D 104, 122002 (2021)
[5] Abe et al. ApJ, 925, 14 (2022)