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Measurement of cosmogenic ^{9}Li isotope production in SK-Gd

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Cosmic-ray muons that penetrate the Super-Kamiokande detector generate hadron showers in water, producing unstable radioactive isotopes through spallation reactions. These isotopes are major background sources for neutrino observation at MeV scale and the search for rare events. Super-Kamiokande has started observation using ultra-pure water since 1996, while gadolinium was loaded with 0.011wt% in 2020 aiming for improvement of neutron detection and the first observation of diffuse supernova neutrino background. In this study, we measured ^{9}Li isotope generated by the muon spallation. ^{9}Li decays with a lifetime of 0.26 seconds and emit an electron and a neutron with a branching ratio of 50.8%. These pairs of an electron and a neutron are difficult to distinguish from the inverse beta decay reaction caused by an electron antineutrino, and therefore become major background for the diffuse supernova neutrino background searches. In the data analysis, we selected ^{9}Li event candidates by searching for pairs of low energy events following cosmic-ray muons. Before the gadolinium loading, the Super-Kamiokande experiment had an energy threshold of 8 MeV for the measurement of electrons emitted from ^{9}Li. The threshold was lowered to 4.5 MeV by the reduction of the accidental background by requiring a total 8 MeV γ rays from neutron captures on gadolinium. In this article, we report the analysis method and the measured spectrum of electrons from ^{9}Li candidates.

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1. Super-Kamiokande

The Super-Kamiokande (SK) detector is a water Cherenkov detector located 1,000 m underground at Kamioka, Japan [1]. The detector is a cylindrical tank with a diameter of 39.3 m and a height of 41.4 m, filled with 50 ktons of gadolinium (Gd) loaded water. The detector consists of the inner detector (ID) and the outer detector (OD) surrounding it. The inner wall of the ID is equipped with 11,129 20-inch photomultiplier tubes (PMTs) and 1,885 8-inch PMTs are installed in the OD to identify entering and exiting muons. SK has been operated with ultra-pure water from April 1996 to July 2020. In August 2020, $Gd_2(SO_4)_3 \cdot 8H_2O$ was dissolved in the ultra-pure water, and observation phase with Gd-loaded water (SK-Gd phase) has started [2].

Gadolinium has been introduced to improve the neutron detection efficiency. In SK, diffuse supernova neutrino backgrounds (DSNBs) are searched via the inverse beta decay (IBD) reaction of electron antineutrinos ($\bar{\nu}_e + p \rightarrow e^+ + n$). In order to distinguish the DSNB signal from background, not only positrons but also the detection of neutrons is required. Once a neutron is captured on a proton in water, single γ ray with 2.2 MeV is emitted. As the number of hit PMTs for 2.2 MeV γ ray is ∼8 on average in the SK detector, neutron detection efficiency was ∼20%. This issue is resolved with Gd. Gadolinium has the largest cross section for thermal neutron capture among any stable nuclei. Once a neutron is captured on Gd, several γ rays totaling ∼8 MeV are emitted. Therefore, neutrons captured on Gd are observed more clearly than those on proton. In this study, the data acquired from September 2020 to April 2022 is used, corresponding to the livetime of 454 days. In this period, the mass concentration of Gd was 0.01%, and ∼50% of neutrons are captured on Gd.

2. Cosmogenic ^{9}Li productions

2.1 ^{9}Li properties

Cosmic-ray muon induce the secondary showers in water, which interact with ^{16}O and produce neutrons and various radioactive isotopes. Of those isotopes, ^{9}Li is one of the major background sources in the search for DSNBs below ∼14 MeV. ^{9}Li emits an electron and a neutron through β decay at a branching ratio of 50.8% with Q-value of 13.6 MeV (^{9}Li $\beta + n$ decay). This event is indistinguishable from IBD events. ^{9}Li is a long-lived radioactive isotope with the lifetime of 0.257 s. As cosmic-ray muons enter the SK detector with a frequency of $\sim 2\ \mathrm{s}^{-1}$, it is not feasible to apply muon veto for the time range enough to cover the lifetime of ^{9}Li. For this reason, the production rate and the energy spectrum of ^{9}Li $\beta + n$ decay should be measured in advance to estimate the amount of the background in the final sample of DSNB candidates. In the ultra-pure water period, the production rate of ^{9}Li has been measured with the energy threshold of 8 MeV [3]. In this study, the threshold was lowered to 4.5 MeV thanks to higher neutron tagging efficiency by the Gd-loading.

2.2 Search for ^{9}Li $\beta + n$ decay

^{9}Li event candidates are selected by the triple coincidence of muon, electron (prompt), and neutron capture (delayed) events. In this analysis, a prompt-delayed pair is searched from the correlations in time and space, and then the muon is searched within the last 1 s. The selection criteria for the prompt and delayed events are (1) $4.5 \leq E_{\mathrm{rec}} < 14.5$ MeV for prompt events, (2) 3.5

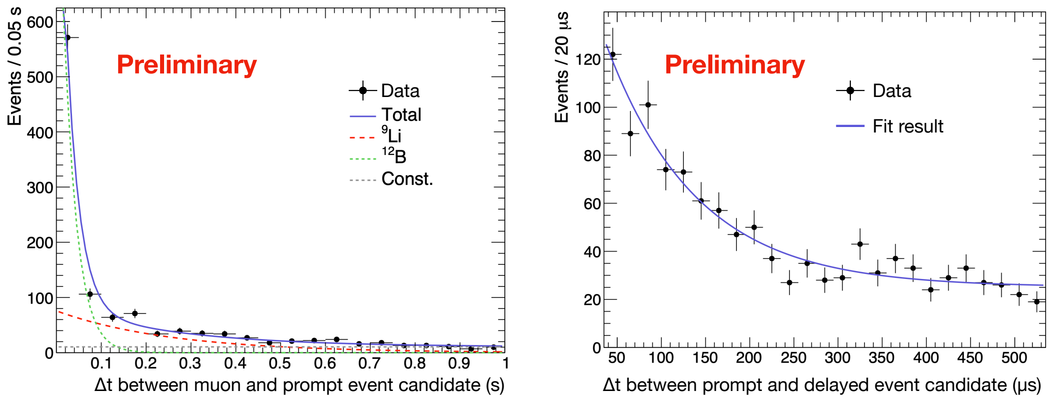

Figure 1: Distributions of $\Delta t_{\mu\mathrm{p}}$ (left) and Δt_{pd} (right). The black circles show the data and the blue solid lines are the fit results for each figure.

$\leq E_{\mathrm{rec}} < 10\,\mathrm{MeV}$ for delayed events, (3) $35\,\mu\mathrm{s} \leq \Delta t_{\mathrm{pd}} \leq 535\,\mu\mathrm{s}$, and (4) $\Delta r_{\mathrm{pd}} < 350\,\mathrm{cm}$, where E_{rec} represents the reconstructed total energy. Δt_{pd} and Δr_{pd} represent the time difference and distance between the prompt and delayed events. If the pair is found, the muon is searched from 1 ms to 1 s before the prompt event. In order to reject contamination of the muon-induced neutrons, prompt events that had muons within the preceding 1 ms are rejected. The selection criteria for muons are (1) the likelihood which is defined using the probability density functions of the features related to the energy and dE/dx of the muons and (2) $\Delta L < 500\,\mathrm{cm}$, where ΔL represents the transverse distance between the muon track and the prompt event vertex.

2.3 Results

Two types of the time difference are evaluated for the selected events: the time difference between the muon and the prompt events ($\Delta t_{\mu\mathrm{p}}$) and the time difference between the prompt and the delayed events (Δt_{pd}). Figure 1 shows distributions of $\Delta t_{\mu\mathrm{p}}$ and Δt_{pd}. $\Delta t_{\mu\mathrm{p}}$ is used to calculate the number of $^{9}\mathrm{Li}$ $\beta + n$ decay events. Δt_{pd} is used to confirm the selection of neutron capture events on Gd.

Distribution of Δt_{pd} is fitted by the exponential function as follows:

$$f(\Delta t_{\mathrm{pd}}) = A_n \exp\left(-\frac{\Delta t_{\mathrm{pd}}}{\tau_n}\right) + B_n, \tag{1}$$

where τ_n represents the neutron capture time constant on Gd, A_n is normalization of neutron capture events, and B_n is the background rate. As the result of the fitting, τ_n is determined to be $102.3 \pm 14.7\,\mu\mathrm{s}$, which is consistent with the measurement of the americium-beryllium neutron source, $116.4 \pm 0.3\,\mu\mathrm{s}$. The fit result is shown in the right-hand side of Figure 1.

Distribution of $\Delta t_{\mu\mathrm{p}}$ is fitted by the exponential function with two components:

$$f(\Delta t_{\mu\mathrm{p}}) = A \exp\left(-\frac{\Delta t_{\mu\mathrm{p}}}{\tau_{^{9}\mathrm{Li}}}\right) + B \exp\left(-\frac{\Delta t_{\mu\mathrm{p}}}{\tau_{^{12}\mathrm{B}}}\right) + C, \tag{2}$$

where $\tau_{^{9}\mathrm{Li}}$ and $\tau_{^{12}\mathrm{B}}$ represent respectively the lifetimes of ^{9}Li and ^{12}B isotopes, 0.257 s and 0.029 s. The $\Delta t_{\mu\mathrm{p}}$ distribution is fitted with these lifetimes fixed. The parameters A and B are normalizations

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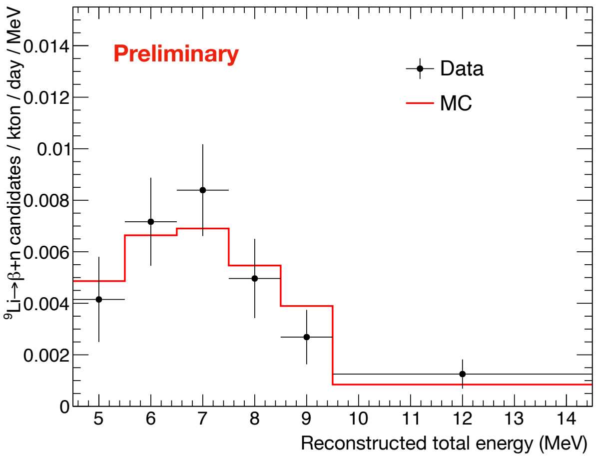

Figure 2: The β spectrum of the ^{9}Li $\beta + n$ decay. The black points show the data after the event selections. The red line shows the spectrum estimated using the Monte Carlo simulation. Electrons are generated following a prediction of the spectrum of ^{9}Li $\beta + n$ decay, which is given in [5], and the event reconstruction and selections are applied.

of ^{9}Li and ^{12}B components, and C represents the background component. The fit result is shown in the left-hand side of Figure 1. The number of events for ^{9}Li $\beta + n$ decay, $N_{^9\mathrm{Li}}$, is calculated from the fit results as follows:

$$N_{^9\mathrm{Li}} = \int_{10^{-3}\,\mathrm{s}}^{1\,\mathrm{s}} A \exp\left(-\frac{\Delta t_{\mu\mathrm{p}}}{\tau_{^9\mathrm{Li}}}\right) d(\Delta t_{\mu\mathrm{p}}). \tag{3}$$

The β spectrum of the ^{9}Li $\beta + n$ decay is obtained by applying the fitting with Equation (2) and calculation with Equation (3) for each reconstructed energy region of the prompt event. The energy spectrum is shown in Figure 2. It is normalized by the fiducial volume of 22.5 kton and the livetime of 454 days. The number of events are not corrected for the selection efficiencies.

3. Conclusion

The SK-Gd experiment had been started with Gd loaded in water since August 2020 aiming for the first observation of DSNBs. ^{9}Li $\beta + n$ decay of the cosmogenic ^{9}Li isotope is one of the major background sources to search for DSNBs. In this study, ^{9}Li candidates are selected by requiring triple coincidence of muon, electron, and neutron capture on Gd. The β spectrum from the ^{9}Li $\beta + n$ decay is measured from the ^{9}Li candidates with the energy threshold at 4.5 MeV, which is lower than the previous study with pure water. As the future prospects, ^{9}Li production rate will be evaluated to estimate the background of the DSNB searches.

References

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