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Measurement of cosmogenic ^{9}Li in Super-Kamiokande with gadolinium loaded water

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Super-Kamiokande is a large water Cherenkov detector located approximately 1,000 m underground in Kamioka, Japan. The detector is a cylindrical tank 39.3 m in diameter and 41.4 m high, filled with about 50 kton of gadolinium loaded water. We measured ^{9}Li isotopic nuclei produced by muon spallation using the data taken from 2020 to 2022 by the Super-Kamiokande detector with 0.011% gadolinium concentration in water. Cosmic-ray muons that penetrate the detector form hadron showers in water and secondary hadrons produce unstable radioisotopes through the spallation. Among those spallation products, ^{9}Li is a long-lived radioactive isotope with a lifetime of about 0.26 seconds. It emits an electron and a neutron at a branching ratio of 50.8%, which is difficult to distinguish from the inverse beta decay caused by electron antineutrinos. Therefore, ^{9}Li is one of the main background sources in the observation of diffuse supernova neutrino background. In this study, the energy spectrum of the electrons was measured with a threshold at 4.5 MeV which is lowered from the previous result with pure water. We will report the analysis method and results.

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1. Introduction

Most of neutrino detectors are built underground to suppress background from cosmic-ray muons. However, with a certain frequency, cosmic-ray muons penetrate the detector and often cause subsequent showers which produce unstable radioactive isotopes by the spallation interaction with the nuclei in the detector. These radioactive isotopes produced by the spallation are the major background in the searches for MeV-scale neutrinos, and among those, the observation of diffuse supernova neutrino backgrounds (DSNBs) has recently been eagerly awaited. DSNBs are searched for using inverse beta decay (IBD) reactions by electron antineutrinos. Among radioactive isotopes from the muon spallation, ^{9}Li is one of the major background sources for DSNB searches especially below 14 MeV. ^{9}Li is a relatively long-lived radioisotope with a lifetime of 0.257 seconds and therefore difficult to reject by the time correlations with muons. In addition, it is difficult to distinguish ^{9}Li from the IBD reaction because it emits an electron and a neutron via the beta decay at a branching ratio of 50.8%. In this study, the energy spectrum of the electrons from the ^{9}Li $\beta + n$ decays was measured using the Super-Kamiokande (SK) detector. The energy threshold in the previous analysis [1] was 7.5 MeV for reconstructed energy ($E_{\rm rec}$), while the threshold was lowered to 4.5 MeV in this study to cover the extended search region in the future DSNB searches at SK.

2. Super-Kamiokande

Super-Kamiokande is a large water Cherenkov detector located 1,000 m underground at Kamioka, Japan. The detector is a cylindrical tank 39.3 m in diameter and 41.4 m high [2], filled with approximately 50 kton of gadolinium (Gd) loaded water [3]. The detector is concentrically divided into two regions: the inner detector (ID) and the outer detector (OD). The ID is a cylindrical region with the volume of 32.5 kton and 11,129 inward-facing 20-inch PMTs on the wall. The OD is a region surrounding the ID with a thickness of approximately 2 m. The OD has 1,885 outward-facing 8-inch PMTs attached to the wall.

The Super-Kamiokande gadolinium (SK-Gd) experiment has been started in August 2020 with dissolving $Gd_2(SO_4)_3 \cdot 8H_2O$ at the Gd concentration of 0.01wt% in water. One of the main purposes of SK-Gd is the first observation of DSNBs with the improved neutron detection efficiency and suppressed background. Before the Gd-loading, pairs of a positron from the IBD reaction and a 2.2 MeV γ ray from neutron capture on proton have been searched for as the signals of the IBD reactions, although it was difficult to tag neutrons because the energy of γ ray is lower than the energy threshold of SK [4]. While, when Gd captures neutrons, several γ rays are emitted with a total energy of about 8 MeV that can be easily distinguished from the background due to radioactivity. The fraction of neutron capture on Gd is about 50% at the Gd concentration of 0.01wt%. The Gd concentration was increased in June 2022 to 0.03wt%, in which 75% of neutrons are captured on Gd.

3. Selection of ^{9}Li candidates

Three consecutive events are observed in the SK detector for a ^{9}Li: first, a muon penetrates the SK detector, then an electron is emitted in the beta decay of ^{9}Li (prompt event), and later neutron is captured on Gd (delayed event). In this study, ^{9}Li candidates are selected by requiring the triple coincidence, that is a pair of an electron and a neutron capture event, and a parent muon within one second before the pair. In this analysis, 454.2 days of data taken during the period of the 0.01wt% concentration is used.

3.1 Selection of prompt and delayed event pair

A fiducial volume cut was applied for the reconstituted vertex to remove background due to radioactive decay near the ID wall. The fiducial volume is defined as the volume 2 m away from the ID wall, which corresponds to 22.5 kton. In addition, a cut by the effective distance from the ID wall $d_{\rm eff}$ was also applied to exclude the remaining background. The effective distance is defined by the reconstructed vertex and direction as the distance from the reconstructed vertex to the ID wall back along the reconstructed direction. The cut criteria for $d_{\rm eff}$ are set for each $E_{\rm rec}$: $d_{\rm eff} > 650$ cm ($E_{\rm rec} < 5.5$ MeV) and $d_{\rm eff} > 400$ cm ($E_{\rm rec} \geq 5.5$ MeV). In addition, reconstruction quality cuts are also applied with parameters that indicate the accuracy of reconstructions for the event vertex and direction.

Ranges of $E_{\rm rec}$ are set as $4.5 \leq E_{\rm rec} < 14.5$ MeV for the prompt event candidates and $3.5 \leq E_{\rm rec} < 10$ MeV for the delayed event candidates. The upper range of $E_{\rm rec}$ for the prompt event comes from the end point of the β spectrum.

Finally, a restriction is imposed on the distance Δr between the reconstructed vertices for candidates of the prompt and delayed events. In this study, event pairs satisfying $\Delta r < 350$ cm are selected.

3.2 Selection of the parent muon event

The SK detector consists of two volumes, the ID and the OD, and each is equipped with the PMTs. Since muons emit Cherenkov light when they enter the detector, both the OD and ID triggers should be issued for muons. In addition, the number of photoelectrons observed in the ID is strongly correlated with the energy deposit of muons in the water. In this study, a total number of photoelectrons is required to be greater than 1,000 for muon event candidates.

Once the prompt-delayed pair is found, the parent muon event candidate is searched within the last one second. As the muon rate is about 2 events/s at SK, there are often more than one muons within one second. Here, muons within 1 ms before the pair are excluded from the search in order to exclude multiple neutrons induced by the muon. Among those, the parent muon of the ^{9}Li isotope is selected with the following five variables which represent the characteristics of energetic muons and spallation interactions.

- L_t: transverse distance from the the prompt event vertex to the muon track.
- L_l: longitudinal distance between the vertex position of the prompt event and the point in the muon track associated with the maximum dE/dx.
- Q_μ: total number of photoelectrons observed by the ID PMTs for the muon track.
- $Q_{\rm res}$: difference between the observed number of photoelectrons and the expectation from the muon track length assuming a minimum ionization particle.
- N_n: number of spallation neutron candidates after the muon.

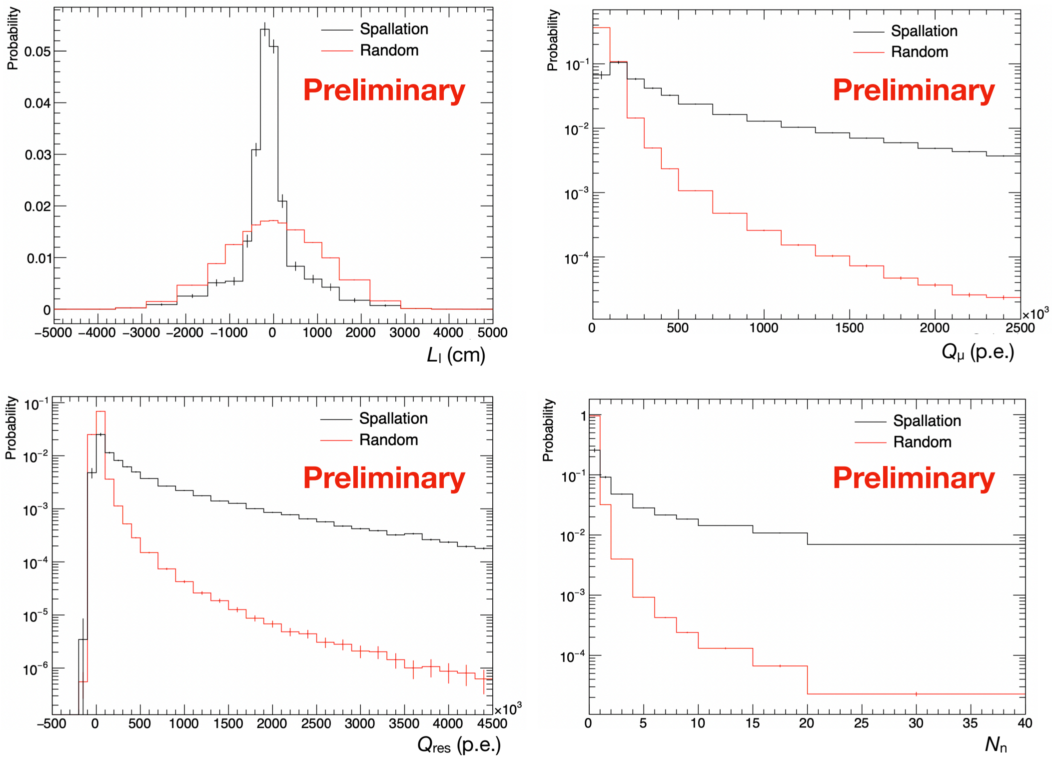

Figure 1: PDFs for L_l (top left), Q_μ (top right), $Q_{\rm res}$ (bottom left), and N_n (bottom right). The black and red lines show the spallation and random samples, respectively.

First, the parent muon candidate is selected with likelihood method using probability density functions (PDFs) for four variables L_l, Q_μ, $Q_{\rm res}$, and N_n. Second, triple coincidence of the prompt-delayed pair and the parent muon is selected as a ^{9}Li candidate if L_t for the muon candidate is less than 500 cm.

To generate PDFs for spallation variables, two different samples were prepared from the data. One is a "pre-sample" composed of prompt-delayed pairs and associated muons within one second before the prompt event candidate, and the other is a "post-sample" composed of prompt-delayed pairs and associated muons within one second after the prompt event candidate. If the prompt-delayed pair is a spallation event, the pre-sample contains muons that produced the prompt event and uncorrelated muons, while the post-sample consists of only uncorrelated muons. Probability density functions were generated for the spallation and random samples separately. The spallation sample was generated by subtracting the post-sample from the pre sample, while the random sample was taken directly from the post-sample. The PDFs from the spallation sample ($\mathrm{PDF}^i_{\rm spall}$) and random sample ($\mathrm{PDF}^i_{\rm rand}$) are shown in Figure 1, where i represents the variable $i = L_l, Q_\mu, Q_{\rm res}$, and N_n. Using these PDFs, the spallation likelihood $\mathcal{L}$ was defined as

$$\mathcal{L} = \log\left(\prod_i \frac{\mathrm{PDF}^i_{\rm spall}}{\mathrm{PDF}^i_{\rm rand}}\right). \tag{1}$$

The likelihood $\mathcal{L}$ was calculated for each muon within one second before the prompt event candidate, and the muon with the largest $\mathcal{L}$ was selected as the parent muon event if it satisfies $L_t < 500$ cm.

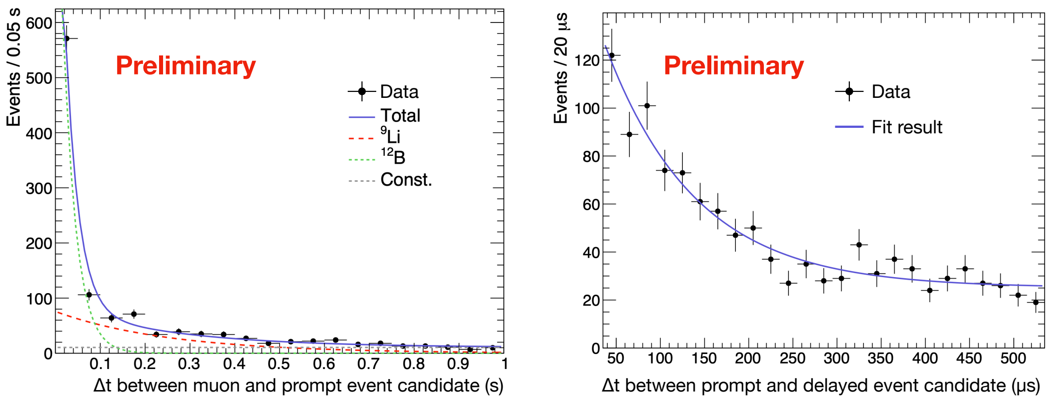

Figure 2: Δt_μ distribution (left) and Δt_n distribution (right). The black circles show ^{9}Li candidates and the blue solid lines are the fit results for each figure.

3.3 Extraction of ^{9}Li rates

Events that meet the triple coincidence of muon, prompt, and delayed event were obtained as ^{9}Li candidates. For the ^{9}Li candidates, following two time difference distributions are obtained (Figure 2).

- Time difference between the muon and prompt event (Δt_μ).
- Time difference between the prompt and delayed event (Δt_n).

First, the Δt_n distribution was fitted by the following simple exponential function.

$$f(\Delta t_n) = A_n \exp\left(-\frac{\Delta t_n}{\tau_n}\right) + B_n, \tag{2}$$

where τ_n is the neutron capture time constant on Gd, A_n represents the normalization of neutron capture events, and B_n represents the background events. The parameter τ_n is fitted as $\tau_n = 102.3 \pm 14.7\ \mu$s, which is consistent with the capture time constant obtained by the measurements using the americium beryllium (Am/Be) source, $116.4 \pm 0.3\ \mu$s.

Next, the Δt_μ distribution was fitted with a combination of two different exponential functions

$$f(\Delta t_\mu) = A \exp\left(-\frac{\Delta t_\mu}{\tau_{^{9}\mathrm{Li}}}\right) + B \exp\left(-\frac{\Delta t_\mu}{\tau_{^{12}\mathrm{B}}}\right) + C, \tag{3}$$

where $\tau_{^{9}\mathrm{Li}}$ and $\tau_{^{12}\mathrm{B}}$ represent the lifetimes of ^{9}Li and ^{12}B isotopes, which are 0.257 s and 0.029 s, respectively. The parameter A and B represent the normalizations of ^{9}Li and ^{12}B events, and C is the background rate. In order to measure the β spectrum from the ^{9}Li $\beta + n$ decay, the fitting is performed for each range of the reconstructed kinetic energy E_{kin} ($= E_{\mathrm{rec}} - 0.511$ MeV) of the prompt event as shown in Figure 3. The number of ^{9}Li candidates $N_{^{9}\mathrm{Li}}$ is calculated by the integration of the fitting results for each E_{kin} as follows.

$$N_{^{9}\mathrm{Li}} = \int_{0.001\,\mathrm{s}}^{1\,\mathrm{s}} A \exp\left(-\frac{\Delta t_\mu}{\tau_{^{9}\mathrm{Li}}}\right) d(\Delta t_\mu) \tag{4}$$

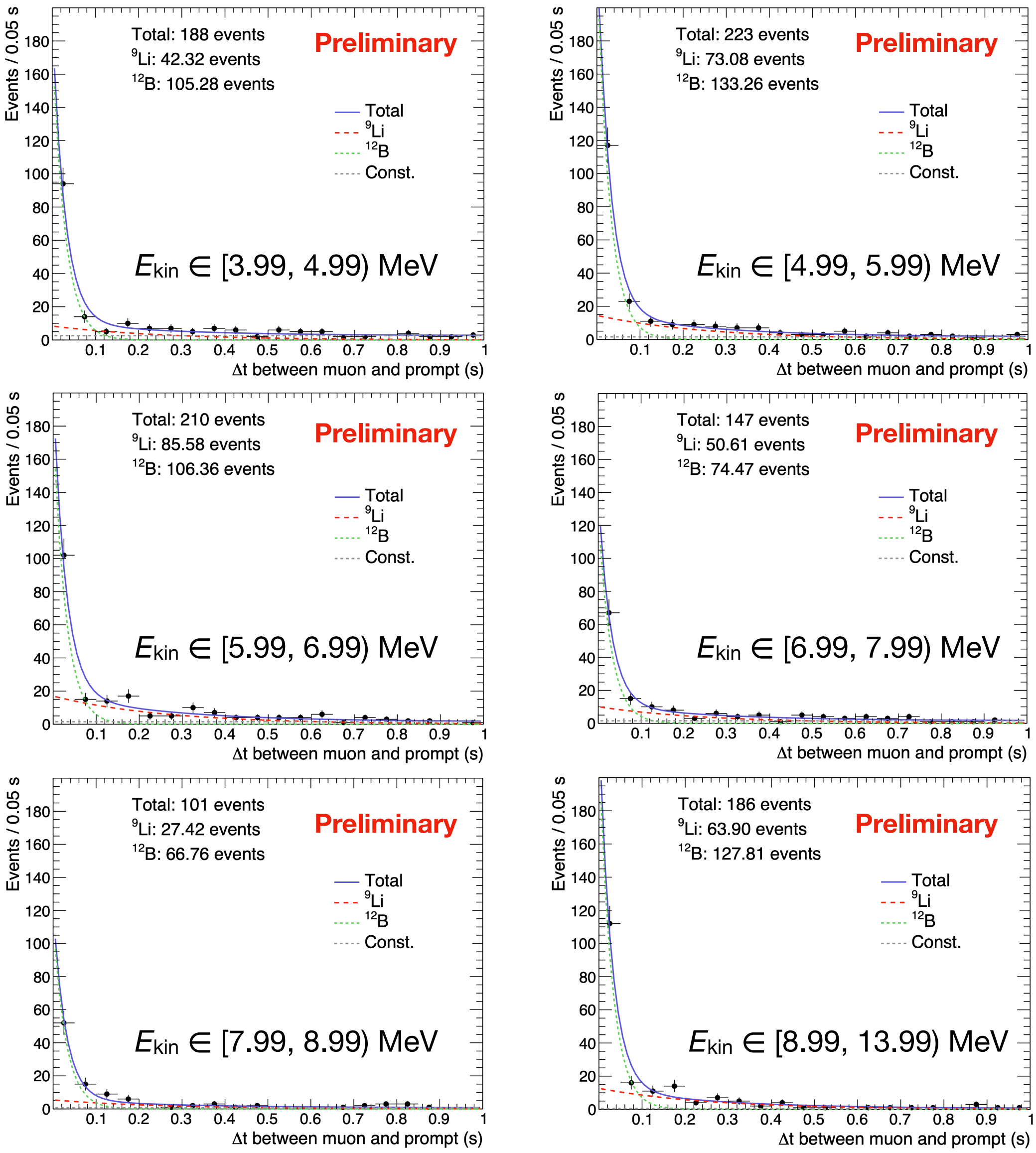

Figure 3: Δt_μ distribution for each reconstructed kinetic energy $E_{\rm kin}$.

The β spectrum from the ^{9}Li $\beta + n$ decay was extracted using $N_{^9\rm Li}$ for each $E_{\rm kin}$ region. The result is shown in Figure 4 and comparable with the Monte-Carlo (MC) simulation using GEANT4 [5]. The result is normalized by the fiducial volume and the live-time, while the correction for the efficiency is not yet applied.

4. Conclusion

The SK-Gd experiment had been started with Gd solved in water since August 2020 aiming for the first observation of DSNB. In the search, cosmogenic isotopes, mainly ^{9}Li, will be major

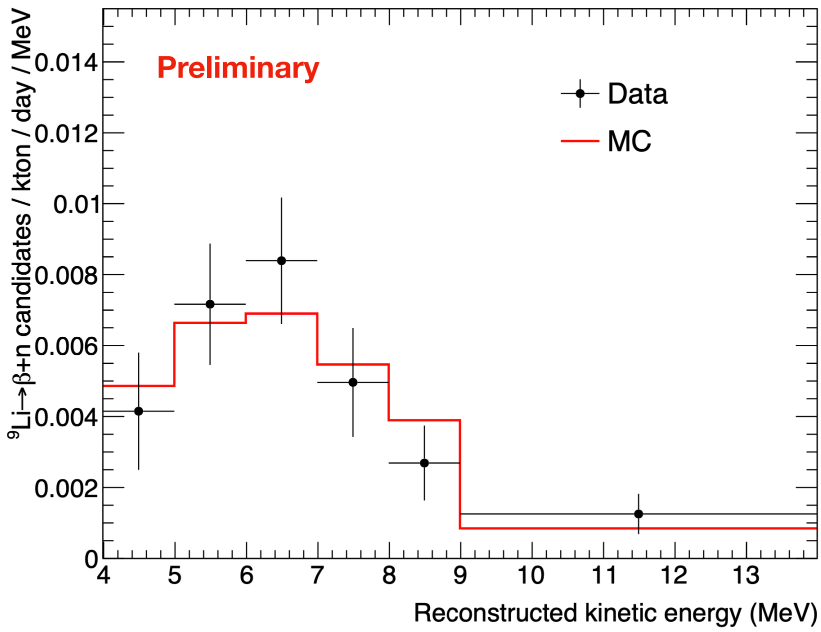

Figure 4: The β spectrum from the ^{9}Li $\beta + n$ decay. The black circle shows the data and the red line shows the MC.

background source. The cosmogenic ^{9}Li production was measured with 454.2 days of the data. The β spectrum from ^{9}Li $\beta + n$ decay was measured with the energy threshold of 4.5 MeV which is lower than the previous results using the data taken with pure water. As the future prospect, ^{9}Li production rate and the spectrum will be evaluated including the correction for the efficiency and the systematic uncertainties.

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