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First measurement of spallation production in Super-Kamiokande IV

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Spallation-induced radioactive isotopes can be produced when cosmic ray muons pass through the matter. The decay $\beta^{\pm}$ products (sometimes with γ emission) from these radioactive isotopes are one of the major background for the study of solar, reactor and supernova relic neutrinos. Unlike scintillator experiment, such isotope production has not been exclusively measured in water experiment. We present here the first measurement of the production yields of radioactive isotopes induced by cosmic ray muon spallation in water using the low energy trigger data by fixing their lifetimes. Furthermore, the ^{9}Li rate (yield) is better measured to be $(0.86 \pm 0.12 \pm 0.16)$ /kton/day or $(0.51 \pm 0.07 \pm 0.09) \times 10^{-7} \mu^{-1} g^{-1} cm^{2}$ by tagging the delayed neutrons. The measurement demonstrates for the first time that the ^{9}Li would have a negligible effect on SuperK-Gd project for the search of supernova relic neutrinos. Agreement between data and theoretical calculations is generally better in water than in scintillator, except the case of spallation products ^{8}Li/^{8}B and ^{9}Li, which eject many nucleons from ^{16}O.

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1. Introduction

Cosmic-ray muon spallation on nucleus could generate a large number of radioactive isotopes. The $\beta^{\pm}$ products (sometimes with γ emission) from the decays of radioactive isotopes are one of the major background for the study of supernova relic neutrinos (SRN), solar neutrinos and reactor neutrinos experiments. Although the spallation yields were extensively measured in liquid scintillators [1, 2, 3], there was lack of these measurements in water. Recently, theoretical calculations [4, 5, 6] were done on the production and properties of the spallation background. The experimental study of these background could provide valuable information and thus improve the analysis for the physics of rare signal experiment in water. SRN are mostly to be detected by inverse-beta-decay (IBD) reaction in hydrogen-rich detectors. Among all the produced isotopes, ^{9}Li is of particular interest since its decay can mimic the IBD reaction of SRN $\bar{\nu}_e$ through the β energy tail to the "golden" SRN search window of 9.5-29.5 MeV of β kinematic energy. Theoretically, ^{9}Li is produced by secondary π^- interacting with ^{16}O, where ^{9}Li has a lifetime of 0.26 s and a probability of $(50.8 \pm 0.9)\%$ decaying to $\beta + n$. A detailed study of cosmogenic radioactive isotopes at Super-Kamiokande (SK) IV is presented in this article.

SK is a 50-kton pure water Cherenkov detector, which is $\sim$1,000 m (2700 m.w.e.) underground. The experiment is separated into four phases, SK-I to SK-IV. A new electronics and online system was installed in the summer of 2008. Data here after is referred to SK-IV. The new online system also introduces the installation of correlated trigger scheme [7]. The primary trigger is issued when the electron/positron energy exceed 9.5 MeV (lowered to 7.5 MeV after the summer of 2011) of the kinematic energy, followed by a delayed trigger with 500 μs time window without any threshold to record the possible 2.2 MeV γ signal emitted from neutron capture on hydrogen ($n + p \rightarrow d + \gamma$). More information related to the SK experiment can be found in Ref. [8].

2. Measurement of isotope rates from lifetime distribution

The live time of the data set for this measurement is 1890 days using the low energy trigger data above 6 MeV. The information of the data reduction can be found in Ref. [9]. After all the reduction, the distribution of time difference (dt) between the preceding muons and the low energy events is shown in the left panel of Fig. 1. Define N_i as the number of ith radioactive isotope, and the fit function can be written as:

$$F(t) = \sum_i \frac{N_i}{\tau_i} e^{-dt/\tau_i} + const, \tag{2.1}$$

where τ_i is the lifetime of the ith isotope and $const$ represents the accidental events. The corresponding production rate R_i for the ith isotope is calculated by

$$R_i = \frac{N_i}{FV \cdot T \cdot \varepsilon_i}, \tag{2.2}$$

where FV is the fiducial volume of 22.5 kton, T is the live time and ε_i is the selection efficiency. The fit results are shown in Fig. 1.

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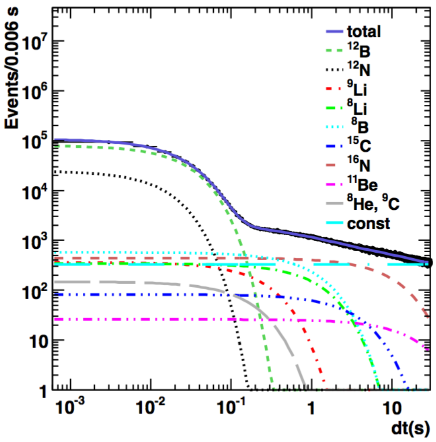

isotope	R_i(/kton/day)
^{12}B	19.8± 0.1±1.0
^{12}N	2.8± 0.1±0.1
^{16}N	39.7±3.3 ± 2.8
^{11}Be	<16.9
^{9}Li, ^{9}C, ^{8}He	0.9±0.3±0.3 <1.4
^{8}Li , ^{8}B	8.3±0.3±0.3
^{15}C	<6.7

Fig. 1: Left panel: The fit results using the dt distribution. Right panel: The production rate R_i for the ith isotope. The fitted rates of ^{11}Be, ^{8}He/^{9}C and ^{15}C are consistent with zero, so upper limits at 90% C.L. are set.

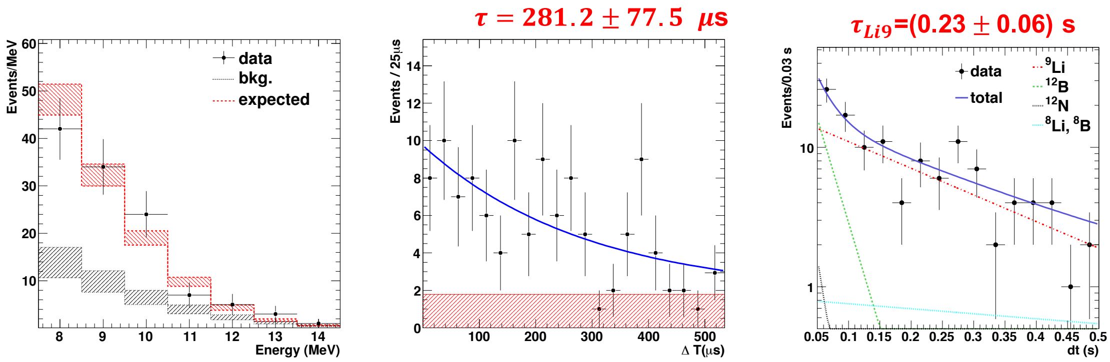

Fig. 2: Detected β spectrum for all the ^{9}Li $\beta+n$ candidates (left), the distribution of neutron capture time (ΔT) (middle) and the ^{9}Li lifetime (right). All are in good agreement with the expectations.

3. Improvement of the ^{9}Li yield measurement

The ^{9}Li rate from Section 2 has large uncertainty due to the relative small rate and the close lifetime with ^{9}C and ^{8}He. To further improve the precision of ^{9}Li yield measurement, we detect a triplet of cosmic ray $\mu+\beta+n$. The neutron tagging with the efficiency of $(9.6\pm1.0)\%$ introduces the non-neutron-related accidental background level of $(0.070\pm0.016)\%$, which can greatly suppress the isotope events without delayed neutrons in the decay. To reduce the systematic uncertainty, only data set of 7.5 MeV primary trigger with a live time of 998 days are used in this analysis. The β energy spectrum, the distribution of neutron capture time (ΔT) and ^{9}Li lifetime are shown in Fig. 2. All are in good agreement with the expectations. The number of ^{9}Li $\beta+n$ events is measured to be 77.8 ± 10.8 events with the subtraction of estimated number of 38.2 ± 8.8 isotope events without neutrons in the decay. The ^{9}Li production rate is finally measured to be

$$R_{^{9}\mathrm{Li}} = (0.86\pm0.12_{\mathrm{stat.}}\pm0.16_{\mathrm{syst.}})\ \mathrm{kton}^{-1}\mathrm{day}^{-1}. \quad (3.1)$$

where the first and second uncertainty are statistical and systematic, respectively. With the numbers of R_i ($R_{^9\mathrm{Li}}$) in Fig. 1 (Eq. 3.1), the yield of ith radioactive isotope (Y_i) is calculated by

$$Y_i = \frac{R_i \cdot FV}{R_\mu \cdot \rho \cdot L_\mu}, \tag{3.2}$$

where R_μ is the muon rate, ρ is the density of water and L_μ is the muon path length. The results are listed in Table 1, together with the comparison of theoretical calculations [4] and the results from Kamland scintillator experiment [2].

Table 1: Measured spallation-induced radioactive isotope yields (Y_i's) in SK, together with the comparison of theoretical calculations [4] and the results from Kamland scintillator experiment [2]. The unit is $10^{-7}\mu^{-1}g^{-1}cm^2$.

Isotope	Y_i in water	Expected [4]	Y_i in scintillator [2]	Expected [2]
^{12}B	11.7±0.1±0.6	12	42.9±3.3	27.8±1.9
^{12}N	1.6±0.1±0.1	1.3	1.8±0.4	0.77±0.08
^{16}N	23.4±1.9±1.7	18	-	-
^{11}Be	<10.0	0.81	1.1±0.2	0.84±0.09
^{9}Li w/o n-tag	0.5±0.2±0.2	1.9		
^{9}Li w/ n-tag	0.51±0.07±0.09	1.9	2.2±0.2	3.16±0.25
^{8}He/^{9}C	<0.9	1.1	0.7±0.4/3.0±1.2	0.32±0.05/1.35±0.12
^{8}Li/^{8}B,	4.9±0.2±0.2	18.8	12.2±2.6/8.4±2.4	21.1±1.4/5.7±0.4
^{15}C	<3.9	0.82	-	-

4. Summary and outlooks

The study herein presents the first measurement of radioactive isotope production through cosmic-ray muons in water. Agreements between the data and the theoretical calculations are generally better in water than those in scintillator, except that the isotopes produced by the ejection of many nucleons of ^{16}O significantly deviate by about a factor of four. We demonstrate for the first time that ^{9}Li will have a negligible effect on the SRN search for SuperK-Gd project [9].

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