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A search for cosmogenic production of β-neutron emitting radionuclides in water

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ABSTRACT

Here we present the first results of WATCHBOY, a water Cherenkov detector designed to measure the yield of β-neutron emitting radionuclides produced by cosmic ray muons in water. In addition to the β-neutron measurement, we also provide a first look at isolating single-β producing radionuclides following muon-induced hadronic showers as a check of the detection capabilities of WATCHBOY. The data taken over 207 live days indicates a ^{9}Li production yield upper limit of $1.9 \times 10^{-7}\ \mu^{-1}\ g^{-1}\ cm^{2}$ at ~400 m water equivalent (m.w.e.) overburden at the 90% confidence level. In this work the ^{9}Li signal in WATCHBOY was used as a proxy for the combined search for ^{9}Li and ^{8}He production. This result will provide a constraint on estimates of antineutrino-like backgrounds in future water-based antineutrino detectors.

1. Introduction

In recent years a number of water-based detector concepts sensitive to reactor antineutrinos through the inverse β decay (IBD) reaction have been proposed [1–4]. Unlike organic scintillator, water has better light propagation properties, is more benign environmentally, and can be more cost effective as detectors get larger. Furthermore, the advent of water-based liquid scintillator (WBLS) [5] offers the possibility of hybrid scintillator/Cherenkov detectors capable of directional charged particle sensitivity, efficient neutron tagging, low-energy-thresholds and excellent energy resolution for neutrino, double-β-decay, and proton-decay experiments [6].

Cosmic-ray muon spallation products are potential sources of backgrounds in such detectors. Radionuclide production via muon initiated spallation in organic liquid scintillator has been studied extensively in various detectors worldwide at varying depths [7–11]. For antineutrino experiments, the most dangerous radionuclides are long-lived isotopes that decay via simultaneous emission of a β and a neutron (β-neutron), such as ^{9}Li and ^{8}He. In principle these isotopes, and some others, can also be formed in water, and could contribute significantly to antineutrino backgrounds in water-based antineutrino detectors. Recently, the rates of ^{9}Li and ^{8}He production in water were measured for the first time at Super-Kamiokande (SK) [12]. Though neutron tagging at SK is inefficient due to the lack of a neutron capture agent such as gadolinium, the large volume and extended data-taking period enabled a measurement. The result $(0.51 \pm 0.07 \pm 0.09 \times 10^{-7}\ \mu^{-1}\ g^{-1}\ cm^{2})$, appears to be almost a factor four lower than the FLUKA-based predictions of Li and Beacom [13]. In the present study, we demonstrate a different approach, in which the neutron-tagging efficiency, and thus the efficiency for the β-neutron radionuclides of interest, is increased compared to SK, through the addition of a gadolinium dopant [14,15]. SK has recently announced that it will make use of this gadolinium-doping technique in a planned upgrade [16]. In this paper, we present the first results from a water detector using a gadolinium tag to measure β-neutron radionuclides at a depth of approximately 400 m water equivalent (m.w.e.) at the Kimballton Underground Research Facility (KURF) in the Kimballton mine in Virginia [17]. The measurement is significant since it demonstrates the technique for use in larger detectors like SK, and because it is at a different depth, permitting a constraint on the uncertain depth scaling factors that are used to extrapolate results between different overburdens.

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2. WATCHBOY detector

Conceived as a prototype to WATCHMAN [3], a kiloton-scale reactor antineutrino detector proposed for the Morton salt mine, 13 km from the Perry reactor, WATCHBOY was designed to measure the production yields of long-lived radionuclides that mimic the antineutrino induced IBD reaction in water-based media. WATCHBOY is a water-Cherenkov detector with a ~2 ton target filled with pure deionized water plus 0.2% $GdCl_3$. Natural gadolinium is an excellent neutron absorber, having a neutron capture cross-section of 49,000 barns [18]. Upon capture, the nucleus emits a gamma ray shower summing to approximately 8 MeV. At the base of the target, 16 upward looking 10 in. Hamamatsu R7081 photomutiplier tubes (PMTs) collect the Cherenkov light from particle interactions inside. The target walls are coated with a reflective Teflon based material (GORE® DRP®) that maximizes light reflection and detection at the PMTs. Surrounding the target is a ~40 ton pure water volume for identifying and tagging cosmic ray muons, instrumented by 36 10 in. Hamamatsu R7081 PMTs. Fig. 1 shows a schematic of the WATCHBOY detector.

The signal processing and triggering scheme for WATCHBOY is done as follows. Each PMT signal is sent to one of four Struck SIS3316 sixteen-channel digitizer boards, with 250 MHz sampling rate and 14 bit dynamic range. The PMT signals on each board are grouped into sets of four, with the sum from each set sent to an onboard discriminator. There are four discriminators per board. If any discriminator is triggered, a signal is sent to a CAEN V1495 FPGA, which in turn sends a global trigger to all 52 channels to read-out to disk. Fig. 2 shows a schematic of the trigger.

Since ^{9}Li normally forms the major component of the β-neutron background in liquid scintillator based antineutrino experiments [19,20], and since both the ^{9}Li and ^{8}He β energy spectra, and mean lifetimes are very similar (^{8}He $\tau = 172$ ms, Q value = 10.7 MeV) (^{9}Li $\tau = 257$ ms, Q value = 11.9 MeV) [21], ^{9}Li will serve as a proxy for a combined search for both ^{9}Li and ^{8}He in WATCHBOY. To summarize the radionuclide signature in WATCHBOY, we search for a muon passing through the target, followed ~257 ms later by a correlated pair of events - a β followed by a neutron capture.

3. Data selection and run stability

The WATCHBOY detector began taking data in late July 2013. Early data was used to characterize and tune the data acquisition rates. The PMT gains were adjusted for the final time in September 2013 after an LED calibration.

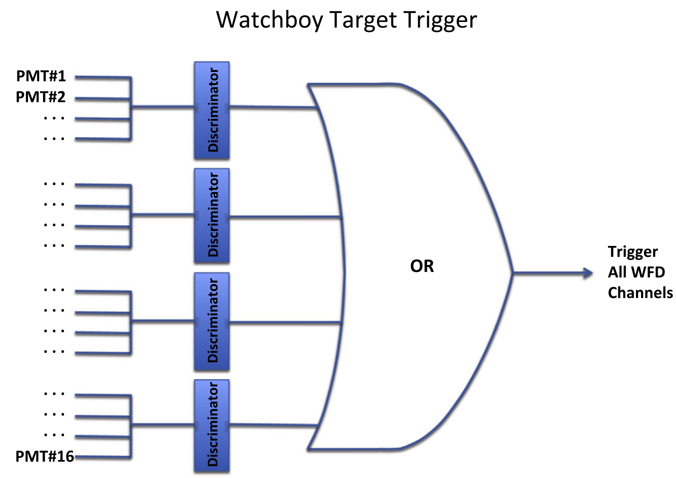

Fig. 2. The WATCHBOY target trigger logic.

A data selection criterion was implemented in order to reject the large rate of instrumental-noise events, while retaining the majority of the physics signal. Fig. 3 shows a scatter plot of total event charge versus a measure of the evenness of the light distribution among the target PMTs for physics and ^{252}Cf calibration data. Simulation of neutron capture and ^{9}Li beta decay in the target are also included for comparison. The evenness of the light distribution (charge balance) is defined as

$$\text{Charge Balance} = \sqrt{\frac{\Sigma Q_i^2}{(Q_{sum})^2} - \frac{1}{N}} \qquad (1)$$

where N is the number of PMTs, Q_i is the charge of the ith PMT, and Q_{sum} is the summed charge of all the PMTs. Events with an even distribution of light among all 16 target PMTs will produce charge balance values approaching zero. Values close to one indicate the opposite extreme (i.e. most of the signal concentrated in one or two PMTs). Note that the neutron capture and ^{9}Li β events tend towards low charge balance values, especially as the total charge increases. This effect is replicated by the simulation also. We therefore further require that genuine physics events of interest have a relatively even distribution parameter (< 0.6).

In addition to the charge balance cut, we define an “Event of Interest” as any event that passes the charge balance cut while

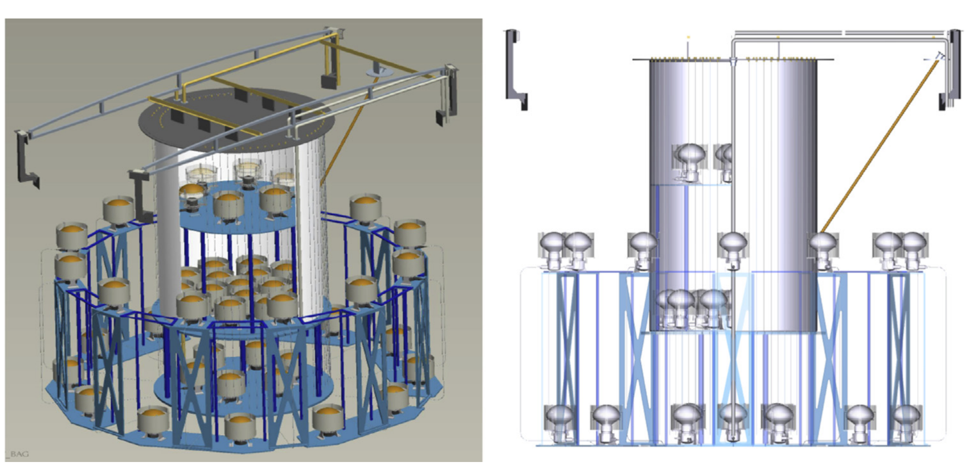

Fig. 1. The PMT arrangement and supporting structure inside the WATCHBOY detector. The gadolinium doped target region containing 16 tightly packed upward facing PMTs is shown at the center of the detector, visible through an illustrated cutout of the target containment bag, which physically and optically separates the inner target from the veto. The veto PMTs are mounted on the far outside and base. At the top, inside the bag is another optically separated region that forms part of the veto (this region of the veto contains Gd). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)