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 ^9Li production yield upper limit of $1.9 \times 10^{-7} \mu^{-1} g^{-1} \text{cm}^2$ at ~ 400 meters water equivalent (m.w.e.) overburden at the 90% confidence level. In this work the ^9Li signal in WATCHBOY was used as a proxy for the combined search for ^9Li and ^8He 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

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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 ^9Li and ^8He . 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 ^9Li and ^8He 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 ($0.51 \pm 0.07 \pm 0.09 \times 10^{-7} \mu^{-1} g^{-1} \text{cm}^2$), 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 meters 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.

2. WATCHBOY detector

Conceived as a prototype to WATCHMAN [3], a kiloton-scale reactor antineutrino detector proposed for the Morton salt mine, 13km 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" Hamamatsu R7081 photomultiplier 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" 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 ^9Li normally forms the major component of the β -neutron background in liquid scintillator based antineutrino experiments [19, 20], and since both the ^9Li and ^8He β energy spectra, and mean lifetimes are very similar (^8He $\tau = 172$ ms, Q value = 10.7 MeV) (^9Li $\tau = 257$ ms, Q value = 11.9 MeV) [21], ^9Li will serve as a proxy for a combined search for both ^9Li and ^8He in WATCHBOY. To summarize the radionuclide signature in WATCHBOY, we search for a muon

Figure 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).

77 passing through the target, followed ~ 257 ms later by a correlated pair of events
 78 - a β followed by a neutron capture.

79 3. Data Selection and Run Stability

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

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

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

Figure 2: The Watchboy target trigger logic.

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

99 In addition to the charge balance cut, we define an “Event of Interest” as
 100 any event that passes the charge balance cut while producing a signal of be-
 101 tween 13 and 100 photoelectrons. As we shall see in Section 4, the “Event of
 102 Interest” dataset is a superset containing all the genuine ^9Li β -like or neutron-
 103 like candidates plus additional events that just failed to meet the strict criteria
 104 for a genuine candidate. The rate of “Events Of Interest” from July 2013 until
 105 August 2014 varied between 1.6 and 0.5Hz. Fig. 4 shows the rate of such events
 106 evolving over the data taking period. The drop in event rates around day #100
 107 was caused by the loss of a high voltage module and was not included in the
 108 analysis. The sudden drops in event rate around day #290 and again at day
 109 #350 were caused, in both cases, by the loss of target PMTs. Note that, af-
 110 ter day #290, the fractional loss of signal per neutron capture, as indicated by

Figure 3: A comparison of the evenness of the light distribution of events in the WATCHBOY target for physics and neutron capture events (left). The distributions that result from the simulation of ${}^9\text{Li}$ β -decay and neutron capture are shown for comparison (right). The evenness of the light distribution is measured using the “Charge Balance” parameter defined in Eq. 1, low values result from an even light distribution among the PMTs, large values result from high concentrations of the signal in a small number of PMTs. The horizontal line at charge balance = 0.6 indicates the upper limit for ${}^9\text{Li}$ candidate events in this analysis.

111 the end points of the neutron capture curve of Fig. 4, have a disproportionately
 112 large impact on the overall trigger rate, since for the purposes of the trigger,
 113 the PMT signals are grouped into groups of four (the trigger scheme is shown
 114 in Fig. 2). The loss of a single PMT in a group reduces the trigger rate from
 115 the whole group. Losses in detector sensitivity might also have been expected
 116 due to gradual degradation of water quality over time. Some evidence of this
 117 was apparent between days #290 and #350 (a $\sim 8\%$ drop), and between #350
 118 and #410 (a $\sim 6\%$ drop). However, the effect appears to be small relative to
 119 the abrupt PMT related losses already noted, indicating that water quality was

120 relatively stable over the data period.

121 We now describe the method used to track, and adjust for, such changes
122 using the neutron capture candidates that sometimes follow muon spallation
123 in the water. Since neutrons produced via muon spallation and spontaneous
124 fission in a ^{252}Cf source are correlated, either with the muon in the case of
125 muon spallation, or with other neutrons in a ^{252}Cf fission. the second event in
126 a correlated pair is highly likely to be a neutron capture. An ensemble of such
127 correlated pairs can be used to provide a statistically pure spectrum of neutron
128 capture events. Note, in muon spallation, the first event is provided by the muon
129 traversing the target. Pure neutron spectra can be obtained by searching for
130 energy deposits correlated with the muon candidates. Fig. 4 shows the neutron
131 capture spectrum accumulated from the period of data between day #140 and
132 #290. The ^{252}Cf calibrations shown earlier (Fig. 6), was also taken during this
133 time. In red we show a Gaussian fit to the spectrum. Note that the shape of the
134 neutron capture data is remarkably Gaussian. In order to quantify changes in
135 the detector response over time we use this Gaussian fit to determine the number
136 of photoelectrons corresponding to 3σ above the Gaussian mean, which is used
137 as a proxy for the detector response for a full 8 MeV energy deposit in the target.
138 The black points (with error bars) shown in Fig. 4 show the evolution of the 3σ
139 point over time. The number of photoelectrons corresponding to 8 MeV is used
140 to adjust the energy cuts associated with ^9Li β s and neutrons (and “events of
141 interest”) over the whole data taking period. Fig. 5 shows the rate of “Events of
142 Interest” once adjusted photoelectron cuts are applied. We note that the event
143 rate stabilizes to within $\pm 12\%$ after the application of the adjusted cuts. We
144 also note that the adjusted data rates near the transitions (day numbers 100,
145 290 and 350) remain somewhat unstable, even with the correction applied, and
146 are not included in the following analysis.

Figure 4: (Top: the spectrum of all neutron capture events that result from muon spallation in the target from day #140 to day #290, together with the Gaussian fit. Also shown are the mean and the upper 3σ of the Gaussian fit. Bottom: the evolution of the rate of “Events of Interest” (described in text) over the course of the data taking period (red), together with the evolution of the number of photoelectrons corresponding to the Gaussian 3σ point, which approximates an 8 MeV energy deposition in the target (black).

147 4. Calibrations, Signal Modeling and Analysis Criteria

148 The WATCHBOY detector is calibrated with LEDs, permanently mounted
 149 throughout the target and veto regions, and a ^{252}Cf fission source which can
 150 be positioned via a calibration tube next to the target. The LEDs produce sin-
 151 gle photoelectron pulses in the PMTs to allow matching of PMT gains and to
 152 determine the PMT anode charge per photoelectron. The ^{252}Cf source allows
 153 us to determine the detector response to neutron captures on gadolinium. The
 154 response spectra are then used to tune a GEANT4-based [22] detector model,
 155 which is used to determine the optimal analysis cuts and corresponding efficien-
 156 cies. Since the radionuclide sample of interest contains a final state neutron,
 157 this 8 MeV gamma ray cascade that results from neutron capture on gadolinium
 158 in the target is well-suited for the calibration.

159 The ^{252}Cf source produces neutrons via spontaneous fission, along with a set
 160 of gamma-rays whose energies sum to an average of 6.65 MeV [23]. The average
 161 neutron multiplicity per fission is 3.75 [24, 25]. During a calibration run, if
 162 two or more correlated events are detected in the target, the first event may
 163 be due to gamma-rays arising from a fission, or a neutron if the gamma-rays

Figure 5: The rate of “Events of Interest” following the application of adjusted energy cuts over the entire data taking period. Note that apart from some short term spikes, which were excluded from the analysis, the overall event rate is stable to within 12%.

were not detected. As described in Section 3, the second event in a correlated pair of events is highly likely to be a neutron capture, enabling the selection of a statistically pure spectrum of neutron capture events, which can be used to calibrate the detector response [26, 27]. The ^{252}Cf deployment tube is shown in yellow in Fig. 1. The source is placed near the end of the calibration tube. The tube itself touches the target wall and defines the minimum distance of the source from the wall. During a deployment the distance from the source to the target wall is very stable at 3.5 cm.

As described above, the GEANT4-based Monte Carlo model was constructed to determine the predicted detector response for any event type, the best analysis cuts, and the resulting efficiencies. Three optical parameters - photon attenuation length, wall reflectivity, and PMT light collection efficiency - were tuned to produce a good match, in terms of spectral response and total light yield, between the model and the neutron capture spectrum derived from the ^{252}Cf calibration.

The simulation tuning process was guided by initial boundary conditions. The average PMT quantum efficiencies were assumed to be slightly lower than the nominal factory specifications, since these are measured in ideal electromagnetic conditions and, for the purposes of simplicity, the model does not include the effect of various parts that support the PMT and mu-metal shielding, both

184 of which obscure the view of each PMT to a small degree. Wall reflectivity
 185 is dominated by the sidewalls of the target, coated in highly reflective Teflon
 186 (GORE® DRP®). The nominal reflectivity, in air, of this material is greater
 187 than 99% in the blue and near UV. The top surface of the target was white
 188 polypropylene with an unknown, but certainly lower, reflectivity. The simula-
 189 tion model simply assumes constant overall wall reflectivity, which was varied
 190 during the tuning process over a range between 90% and 99%. Finally, the
 191 water in WATCHBOY is not continually recycled or cleaned and it contains
 192 GdCl_3 . Therefore, the photon attenuation length was assumed to be short rel-
 193 ative to ideal water-based experiments such as SK, which has an attenuation
 194 length approaching ~ 100 m [28].

195 Using neutron capture events from ^{252}Cf calibration, we have two metrics to
 196 compare simulation and calibration. The first is the spectral response, which is
 197 used to adjust the simulated optical parameters to maximize agreement between
 198 the measured and simulated neutron capture energy spectra. The second is the
 199 proportion of light detected by each PMT on average in the target. Since the
 200 calibration source is positioned on the edge of the target, the mean fraction of
 201 light observed by each PMT is influenced by the PMT's position in the target
 202 and its proximity to the source.

203 Table 1 shows the central values and acceptable ranges for the attenuation
 204 length, reflectivity and light collection efficiency in the central detector, derived
 205 from a comparison of simulated and actual calibration data. We used the central
 206 values to fix our analysis cuts and predict the detection efficiency for the prompt
 207 beta and delayed neutron signatures of interest for our search. Using a χ^2 test,
 208 we checked the sensitivity of the simulated spectra to parameter variations over
 209 a range of input parameters encompassing the central values. For small χ^2
 210 values, indicating good fits, the resulting efficiency variations formed a fairly
 211 tight range about the ideal (nominal) efficiency of approximately $\pm 1\%$. This
 212 uncertainty was included in the estimated overall efficiency uncertainties shown
 213 in Table 2.

214 Fig. 6 compares the neutron capture spectra from simulated and real (cali-

Figure 6: A comparison of the detector spectral responses due to neutron captures in the target, obtained from a GEANT4 simulation after tuning (solid) and a ^{252}Cf calibration run (dashed). Trigger thresholding, not included in the simulation, probably accounts for a large part of the difference between the curves below ~ 15 pe.

Table 1: The tuned photon transport parameters implemented in the GEANT4 detector model.

Water attenuation length	24 meters
Wall reflectivity	94%
PMT Light collection efficiency	20%

215 bration) ^{252}Cf data after tuning. Since the trigger is not included in the simula-
216 tion, the two curves diverge below about 15 pe. Above 15 pe the spectra match
217 very well.

218 The tuned detector model was used to predict the response to ^9Li decay
219 throughout the target volume and then compared with the measured back-
220 ground spectrum. The ^9Li signal can be separated into its β and neutron
221 components and compared with the background distribution to determine the
222 optimal analysis cuts and evaluate the resulting efficiencies. The input energy
223 spectrum [29] for the β decay has a Q value = 11.9 MeV. A mean neutron energy
224 of ~ 2 MeV was also used, though the neutron energies do not strongly influence
225 the neutron capture detector response since the neutron usually thermalizes be-
226 fore capture. The top panels of Fig. 7 show the simulated spectra for the β s
227 and the neutron captures that result from ^9Li decays in the target. Also shown

Figure 7: Top: the simulated detector response due to the β (left) and the neutron (right) compared with the measured background. Bottom: the “quality factor” (defined in the text), that would result from an analysis cut at the corresponding number of detected photoelectrons. Higher quality factors following the imposition of a cut indicate improved signal efficiency and background rejection compared to cuts resulting in lower quality factors.

is the background spectral shape. Since the β and neutron capture spectra are quite different from the background, we can maximize the statistical likelihood of detecting ${}^9\text{Li}$ by an optimal choice of analysis cuts. All possible energy cuts, in terms of detected photoelectrons, were applied in turn, and the statistical advantage recalculated each time. The statistical advantage, represented by a “quality factor” at each possible cut, is calculated in a similar manner to Ref. [14] and defined as:

$$Q_C = \left(\frac{S_C - B_C}{\sqrt{B_C}} \right) \left(\frac{\sqrt{B_T}}{S_T - B_T} \right) \quad (2)$$

where S_C and B_C correspond to the signal and background remaining after the cut respectively, while S_T and B_T are the corresponding values before the application of the cut. Q_C is defined to be equal to 1 if no cut is applied, or if there is no statistical advantage from the cut. The best analysis cuts for the β and the neutron, and the corresponding detection efficiencies, were evaluated by maximizing the quality factor.

Timing cuts are also applicable since the β and neutron are correlated. A $1 - 200 \mu\text{s}$ timing window was defined, with the lower limit set by the detector

Table 2: The analysis cuts and corresponding efficiencies determined from the detector simulation. See text for further discussion of how the efficiencies were calculated.

Source	Minimum	Maximum	Efficiency (%)
$^9\text{Li } \beta$	20 pe	100 pe	62.8 ± 9.4
Neutron	16 pe	53 pe	42.2 ± 6.3
β -Neutron inter-event time	$1 \mu s$	$200 \mu s$	95.8 ± 3.6
1ms muon veto analysis cut			99.2
Combined Total Efficiency			25.2 ± 5.4

243 dead-time after a trigger, and the upper limit fixed large enough to ensure
 244 efficiency close to 100%. The timing cuts were evaluated using the Monte Carlo
 245 and contributed an efficiency loss of $4.2 \pm 3.6\%$. There was a further efficiency
 246 loss of 0.8% due to the 1 ms analysis veto which follows each muon in either the
 247 target or the veto. For the purposes of this analysis, a “muon” was defined as
 248 any event resulting in more than 100 photoelectrons in the target. A summary
 249 of all the ^9Li analysis cuts is given in Table 2. Note, the efficiencies for “ ^9Li
 250 β ” and “Neutron” in Table 2 include the charge balance < 0.6 cut. From the
 251 simulation, approximately 6% and 3.5% of the $^9\text{Li } \beta$ and neutron capture events
 252 respectively are lost as a result of the charge balance cut, while the background
 253 is reduced by 95%. This cut therefore eliminates virtually all the events that
 254 originate from sources of electronic noise, while retaining nearly all the $^9\text{Li } \beta$ -like
 255 or neutron-like candidates. In addition to the analysis cuts described above, if
 256 an “Event of Interest” occurs within 1 millisecond of a ^9Li -like correlated pair,
 257 the multiplet of events is considered to be a correlated triple, disqualifying it as
 258 a ^9Li candidate.

259 The uncertainty assigned to the neutron efficiency (in Table 2) was estimated
 260 by comparing the simulation with ^{252}Cf calibration data. Since the ^{252}Cf source
 261 is not tagged, the calibration by itself does not provide an unambiguous mea-
 262 surement of the neutron efficiency. However, the inter-event time distribution
 263 obtained is highly sensitive to this efficiency. ^{252}Cf fissions produce neutrons in
 264 bunches, with a known multiplicity distribution of mean 3.75 [25]. The time

intervals between the neutrons detected in each bunch form an inter-event time distribution with a correlated and an uncorrelated component. The magnitude of the correlated component, the exponential slope of the uncorrelated component, and the observed multiplicity distribution are particularly sensitive to neutron efficiency. A simple neutron capture timing model, consisting of the sum of three independent exponential terms, was used to model the inter-event time distribution. The three terms represent the following effects:

1. Thermal neutron capture in the target
2. The thermal capture time behavior of neutrons caught in the veto, but transition into the target
3. A subtracted component representing the thermalization of ~ 2 MeV neutrons in water

The terms above describe the probability of capture of each neutron following emission from the source as a function of time in this model. Detection depends upon the efficiency. Prompt fission gamma-rays, if detected, occur at $t=0$ by definition. Fission delayed gamma-rays can occur at any time. The fission rate of the source in the model was fixed at 564 Hz, since it was measured independently at NIST to an accuracy of 1.6% [30]. The parameter space defined by a range of neutron efficiencies, prompt fission gamma-ray efficiencies, and delayed gamma-ray efficiencies was scanned to identify values that reproduced both the observed inter-event time and neutron multiplicity distributions. A number of viable solutions were found - all with neutron efficiencies in the range 10.5% to 11.5%. The best solution overall was found at 11.0%. The predicted neutron efficiency from the simulation was 12.6%, almost 15% higher. We therefore assigned an uncertainty of $\pm 15\%$. We note that the observed 15% difference can be accounted for by including a small uncertainty in the source position relative to the target wall.

The uncertainty in the neutron detection efficiency arises from three independent processes - the fraction of neutrons from the calibration source that capture in the target, the fraction of neutron capture gamma rays that Compton scatter

295 inside the target, and the uncertainty in photon production from scattered β
 296 particles. If we assume, conservatively, that the observed uncertainty was en-
 297 tirely due to uncertainties in photon production, rather than neutron transport
 298 or Compton scattering, then the ${}^9\text{Li}$ β uncertainty can also be assigned the
 299 same value. We stress that this is a very conservative assumption, enforced by
 300 the lack of suitable ~ 10 MeV calibration sources. If the neutron transport or
 301 Compton scattering uncertainties were to contribute significantly to the total,
 302 the photon production component, which forms the major part of the ${}^9\text{Li}$ β
 303 uncertainty, would be reduced. New calibration sources will be deployed in the
 304 near future in an attempt to reduce this uncertainty for future publications. For
 305 now we assigned the conservative value ($\pm 15\%$) for ${}^9\text{Li}$ β detection also.

306 While the primary objective of WATCHBOY was to measure β -neutron
 307 emitting radionuclides, the detection of single β emitting radionuclides provides
 308 an important additional check on the radionuclide detection capabilities of the
 309 detector. Our data show robust evidence for these single β events. The ability
 310 to identify them helps confirm WATCHBOY's suitability for isolating the ${}^9\text{Li}$
 311 β -neutron signature. In Appendix A we present a method for tagging so-called
 312 "showering" muons and study the resulting single- β radionuclide production for
 313 WATCHBOY. A more complete analysis, including efficiency estimates, will be
 314 presented in a separate paper.

315 5. ${}^9\text{Li}$ β -Neutron Result

316 We now describe the ${}^9\text{Li}$ β -neutron analysis. As described in Section 2, a
 317 ${}^9\text{Li}$ decay candidate in WATCHBOY is defined as a pair of correlated events,
 318 consistent with a β -neutron pair, correlated with an earlier showering or non
 319 showering muon passing through the target. The β -neutron candidates must
 320 have higher energy than typical background, with charge balance values consis-
 321 tent with relatively even light distribution among the PMTs. A target muon
 322 is any target event producing more signal than the upper energy limit of ${}^9\text{Li}$
 323 (> 100 photoelectrons). The first of the correlated events must have total charge

Figure 8: A plot of the elapsed time since last muon through the target for the entire set of ${}^9\text{Li}$ candidates (top). The ${}^9\text{Li}$ candidates are correlated event pairs that satisfy the charge requirements of Table 2. Below are the residuals after subtracting the exponential, shown as a dashed line.

324 in the target consistent with the ${}^9\text{Li}$ β of Table 2, the second consistent with
 325 neutron capture on gadolinium. We further require that the correlated pair not
 326 occur within 1 ms of any other “event of interest” in the target, or a muon in
 327 either the target or veto, which excludes spallation neutrons. In Fig. 8 (top),
 328 the time to the most recent target muon is plotted for all of the remaining ${}^9\text{Li}$
 329 β -neutron candidates. If ${}^9\text{Li}$ forms a significant proportion of these events, we
 330 expect to see a subset of events correlated with target muons with a lifetime
 331 consistent with the lifetime of ${}^9\text{Li}$ (257 ms). In Fig. 8 (bottom), the residuals
 332 are plotted. The magnitude of the observed ${}^9\text{Li}$ component (20.2 ± 25.4 events)
 333 was calculated from a double exponential fit to Fig. 8 (top), fixing the slopes to
 334 the known ${}^9\text{Li}$ and background exponentials (the target muon rate is 0.9 Hz),
 335 while allowing the magnitudes to float. No significant excess consistent with ${}^9\text{Li}$
 336 decay is observed in this data set. The observed statistical significance of the ${}^9\text{Li}$
 337 component was therefore $+0.8\sigma$. The total number of background event pairs
 338 recorded over 207 live days was 799. Given these results the 90% upper limit
 339 on the total number of ${}^9\text{Li}$ created in the target was 266 assuming a detection
 340 efficiency for the β -neutron branching ratio of $25.2 \pm 5.4\%$. From these results

Figure 9: The 90% upper limit on ${}^9\text{Li}$ production from this work compared to the recent SK measurement [12] and the prediction of Li and Beacom [31]. The measurements and predictions, both at the SK depth, were scaled with depth according to the mean muon energy, shown as the hashed and striped regions. The allowed range of scaling factors were from Hagner et al. [32] ($< E_\mu >^{0.5}$ to $< E_\mu >^{0.93}$).

we can calculate the upper limit on the ${}^9\text{Li}$ yield using the relation

$$Y < \frac{N}{\epsilon B_{\beta n} T L_\mu R_\mu \rho} = \frac{266}{T L_\mu R_\mu \rho} \quad (3)$$

where N is the upper limit on the number of observed ${}^9\text{Li}$ candidates, ϵ is the efficiency, $B_{\beta n}$ is the ${}^9\text{Li}$ β -neutron branching ratio ($50.8 \pm 0.9\%$), T is the live-time (17.9×10^6 seconds), L_μ the average muon path length through the target ($87.0 \pm 3.1\text{cm}$), R_μ the muon rate (0.9 ± 0.007 Hz) and ρ the target density (1.0 g/cm^3). The average muon path length was calculated from the muon angular distribution at WATCHBOY, determined using the muon flux parametrization as a function of depth and θ defined by Mengyun et al. [33]. The uncertainty on the rate was determined using the GEANT4 simulation assuming the 15% uncertainty on Cherenkov photon production and the $\cos\theta$ distribution calculated earlier. The 90% upper limit on the β -neutron branching ratio of ${}^9\text{Li}$ at the WATCHBOY depth (400 m.w.e.) is therefore $0.97 \times 10^{-7} \mu^{-1} \text{g}^{-1} \text{cm}^2$. This translates to an upper limit on total ${}^9\text{Li}$ production of $1.9 \times 10^{-7} \mu^{-1} \text{g}^{-1} \text{cm}^2$.

The WATCHBOY 90% upper limit on the yield is shown in Fig. 9 together with the ${}^9\text{Li}$ prediction of Li and Beacom [13], the recent measurement from SK [12] and their expected yield as a function of depth. Both the Li and Beacom

357 and SK depth projection include a scaling uncertainty with respect to average
 358 muon energy (depth) using the range of acceptable scaling factors ($< E_\mu >^{0.5}$
 359 to $< E_\mu >^{0.93}$) given by Hagner et al. [32]. The SK measurement is seemingly in
 360 conflict with the Li and Beacom prediction by a factor of ~ 4 , though factor ~ 2
 361 disagreements are common in liquid scintillator [20]. WATCHBOY, while not
 362 yet able to distinguish between these results due to the small data set, is a more
 363 efficient detector due to the capability to tag neutron captures on gadolinium.
 364 This proof of concept suggests that larger Gd-doped water detectors should be
 365 able to efficiently and definitively measure β -neutron radionuclide rates, and,
 366 if deployed at a different depth than SK, help reduce uncertainties in the yield
 367 scaling factors between different depths.

368 Extrapolating the WATCHBOY result to the WATCHMAN depth (1500
 369 m.w.e.), we obtain an upper limit on the ^9Li yield of between $3.3 - 5.4 \times$
 370 $10^{-7} \mu^{-1} \text{g}^{-1} \text{cm}^2$. This corresponds to a rate of between 13 and 21 detected
 371 ^9Li per kiloton per day assuming 50% detection efficiency and accounting for
 372 the β -neutron branching ratio. The KamLAND and SK [7, 20, 31, 34] detectors
 373 have both achieved $> \sim 90\%$ ^9Li veto efficiency (KamLAND 99%) by vetoing
 374 events within 2 seconds and 3 meters of each muon track. At 90% efficiency, the
 375 ^9Li background contribution to the antineutrino signal at WATCHMAN would
 376 be less than ~ 2 events per day, sufficiently low to allow for the successful
 377 detection of antineutrinos from the nearby Perry reactor.

378 6. Conclusion

379 We have presented the first results of the WATCHBOY detector, designed
 380 to determine the rate of cosmogenically produced radionuclides, such as the β -
 381 neutron emitting isotopes ^9Li and ^8He , that may act as backgrounds in future
 382 water-based antineutrino detectors. The ^9Li detection efficiency was determined
 383 via a GEANT4 simulation, which was tuned from calibrations. From 207 live
 384 days, the WATCHBOY detector observed 20.2 ± 25.4 ^9Li events. The 90% upper
 385 limit on the yield of ^9Li , derived from these results was $1.9 \times 10^{-7} \mu^{-1} \text{g}^{-1} \text{cm}^2$,

386 at a depth of approximately 400 m.w.e. The primary source of backgrounds in
 387 WATCHBOY were correlated pairs of neutron captures, initiated by fast neu-
 388 trons from the surrounding rock. WATCHBOY observes a total of 799 of these
 389 events, at a rate of 3.9 per day. In addition, WATCHBOY observes a clear
 390 excess of single β emitting radionuclide candidates following showering muons,
 391 where showering muons are defined as muons followed by at least two correlated
 392 neutron captures (see Appendix A). Though these single β emitting radionu-
 393 clides are not antineutrino detector backgrounds, their detection does serve as
 394 a verification of the detector's capabilities. A more complete study, including
 395 a determination of the total radionuclide yield following showering muons, will
 396 be provided in a later paper. In the near future the rate of correlated neutron
 397 backgrounds will be compared with measurements of the fast neutron energy
 398 spectrum currently being completed by the WATCHBOY's sister project called
 399 MARS [35] (Multiplicity and Recoil Spectrometer), as a cross check. The pre-
 400 dicted rate of ${}^9\text{Li}$ backgrounds at WATCHMAN, based on these measurements is
 401 less than ~ 2 events per day, sufficiently low to allow for the successful detection
 402 of antineutrinos from the nearby Perry reactor.

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412 Appendix A. Single β Production Following Muon-Induced Hadronic 413 Showers

414 Li and Beacom [31] assert that essentially all radionuclides in the SK (un-
415 doped) water Cherenkov detector are produced during muon-induced hadronic
416 showers. A “showering” muon is characterized by multiple hadronic interactions,
417 which generate multiple neutrons and pions along the muon’s track. In addition,
418 certain radionuclide production processes themselves create secondary neutrons.
419 Based on these assumptions, we identify showering muons in WATCHBOY us-
420 ing the following method: if two or more neutron-like events occur in the target
421 within 1 ms of a muon, the muon is tagged as a showering muon and subsequent
422 β events (at times greater than 1 ms) are identified. The muon may traverse ei-
423 ther the target or the veto. We require at least two neutron-like events to reduce
424 the likelihood of accidental coincidences and ensure a clean sample of shower-
425 ing muons. The reduction in background that results from this requirement is
426 illustrated in Fig. A.10. If the claim is true, an excess of single β -like events
correlated with showering muons should be observed. We observe an average of

Figure A.10: The distribution of event times following muons in WATCHBOY. A showering muon is identified by the presence of 2 or more neutron-like events within 1 ms. This tagging procedure allows the removal of nearly all backgrounds due to pile up of other muons. The uncorrelated events were fitted in the region of 1 ms to 2 second, where good agreement is observed between the data and the uncorrelated expectation.

427
428 9.8 showering muons per day tagged in this fashion. Because of the low rate of
429 these muons, a good separation between correlated events and non-correlated

430 events can be achieved, as is shown in Fig. A.10 and Fig. A.11. Tagging random
 431 non-showering muons was done as a crosscheck on the potentially correlated β
 432 spectrum; this spectrum is shown in Fig. A.11. There is a selection of events
 433 that show correlation to showering muons, revealed as the excess when compar-
 434 ing the uncorrelated and correlated spectra. In addition to the correlated events
 435 shown, we include the time profile of a GEANT4 simulation of neutron capture
 436 events throughout the target assuming a flat input neutron energy spectrum
 437 extending up to 1 GeV. These events follow an exponential curve consistent
 438 with neutron thermalization and capture on gadolinium. The measured and
 439 simulated time profiles are consistent above $\sim 30\mu s$. Below $30\mu s$ the number
 440 of detected correlated events is below expectation. The difference is due to the
 441 presence of baseline variability which tends to follow extremely bright events,
 442 such as muons. Baseline variability is revealed by anomalously high or low
 443 baseline levels immediately preceding a physics event (a sample of the baseline
 444 charge of every PMT is taken for approximately $100ns$ prior to every trigger).
 445 Events which show evidence of baseline variability are identified and eliminated,
 leading to some loss of efficiency following muons.

Figure A.11: Time of events of interest with respect to both showering and randomly selected muons. Radionuclides are expected in the 1 ms to 10 s range. We observe an excess of events in a time window between 1 ms and 1 s. The sub-ms time scale muogenic particles defining the presence of a shower are shown as the shaded distribution to the far left. The expected time signature of sub-ms muogenic particles was evaluated with Monte Carlo and is shown as a solid line, the measurement is attributed to a delay in baseline recovery following a muon.

446

447 In addition to the time-correlations in the showering muon population, Fig. A.12
 448 shows that the energy spectra of the showering and non-showering samples differ
 449 significantly. A surplus of events at higher energy is observed in the shower-
 450 ing muon sample, consistent with a signature from β emission of radionuclides.
 451 Fig. A.12 (bottom) also shows the energy distribution of the excess events sub-
 452 tracted by a normalized selection of uncorrelated events found in the 1 ms to
 453 1 second time window.

454 Since this paper focuses on the time-correlated β -neutron background to
 455 reactor anti-neutrino detection, further analysis of the single β emitter is rel-
 456 egated to a separate paper. Summarizing this analysis, we have observed an
 457 excess of events consistent with single- β radionuclide production, correlated to
 458 muon induced showers. This result supports the hypothesis advanced by Li and
 459 Beacom [31], and helps confirm the ability of WATCHBOY to trigger on the
 closely analogous β -neutron radionuclide population.

Figure A.12: The top panel shows the energy spectra of correlated and non-correlated events within 1 second of a showering muon compared to the uncorrelated/accidental background. The uncorrelated spectrum was normalized by the number of uncorrelated events expected from the fit shown on Fig. A.11. The bottom panel shows the background subtracted energy distribution of the excess events. This forms the single- β radionuclide candidate spectrum in WATCHBOY.

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