Gadolinium study for Super-Kamiokande

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***Abstract*. Modification of large water Cherenkov detectors by addition of gadolinium has been proposed. The large cross section for neutron capture on Gd will greatly improve the sensitivity to anti-electron neutrinos from supernovae and reactors. We are performing various studies, including a material soak test in Gd solution, light attenuation length measurements, purification system development, and neutron tagging efficiency measurements using Super-Kamiokande data and a Geant4-based simulation. We present an overview of the project and the recent R&D results.**

***Keywords*: neutrino, Super-Kamiokande, Gadolinium**

I. Introduction

The Super-Kamiokande (SK) [1] is the largest light water Cherenkov detector that has been successfully observing solar, atmospheric and accelerator neutrinos. Recently the addition of 0.2% of a water soluble gadolinium (Gd) compound to SK has been proposed [2]. This modification can greatly improve the detection sensitivity of anti-electron neutrinos. The inverse beta interaction in the water, $\bar{\nu}_e + p \rightarrow e^+ + n$, emits a positron and a neutron. The positron, radiating Cherenkov photons, is immediately detected. The neutron is quickly thermalized in the water, and is then captured by Gd with a probability of 90%. Upon capturing a neutron the Gd emits 3-4 gamma rays having a total energy of about 8 MeV. The time and spatial correlation of the positron and neutron capture events (20 μs and 4 cm) can significantly reduce the backgrounds, and hence enhance the $\bar{\nu}_e$ signal events.

This modification of SK will enable us to increase the detectability of the supernova relic neutrinos (SRN). It is supposed that about 10^{17} supernovae have happened since the first star formation in the universe. These past supernovae ejected not only heavy elements but also a huge number of neutrinos. Therefore, the measurements of the SRN flux and energy spectrum provide information on the history of heavy element production, combined with the supernova neutrino generation mechanism. So far, SK has given the most stringent limit on the SRN flux: 1.2 $\bar{\nu}_e$ cm^{-2}s^{-1} at the 90% confidence level with a neutrino energy threshold of 19.3 MeV [3]. This flux limit is three times larger than the most likely theoretical predictions. Therefore, a sensitivity improvement of a factor of three or greater is highly desired.

The energy threshold was set to optimize the signal to background ratio. The dominant background is the radioactive spallation nuclei that are constantly created in the water by the collisions on the oxygen nuclei with high energy comic ray muons. The background level steeply increases as the threshold energy decreases. Another serious background is the invisible muons produced via the interactions of atmospheric neutrinos $\nu_\mu + \mathrm{N} \rightarrow \mu + \mathrm{N}'$. Some muons made by this process are invisible because their energy is lower than the Cherenkov threshold, and hence only the decay electrons are visible. Although the event rate can be estimated from data using the decay electron energy spectrum shape, the statistical uncertainty of the number of events decreases the SRN sensitivity. Because of the presence of the backgrounds, the current experimental sensitivity will only very slowly improve; using the published method we would need 40 years' operation to lower the flux limit by a factor of three.

Making use of neutron tagging with Gd can significantly reduce both spallation events and invisible muons; the energy threshold can be lowered to around 10 MeV and the invisible muon events can be reduced by a factor of five. The model dependent expected SRN event rate is 0.8 to 5.0 events per year in the 22.5 kton fiducial volume in the energy range of 10-30 MeV [4]. Five years' operation of SK with Gd can easily achieve the required sensitivity improvement.

By lowering the energy threshold further down to 3.0 MeV, SK with Gd could collect the world's largest sample of reactor neutrinos, thereby allowing the most precise possible measurements of the solar neutrino oscillation parameters. Neutron tagging can also be used to distinguish interactions between neutrinos and anti-neutrinos which preferentially emit protons and neutrons, respectively. This technique could prove to be quite important for neutrino oscillation studies with atmospheric and accelerator neutrinos.

As mentioned above,a Gd-loaded SK has the potential to open a new era of neutrino physics. On the other hand, a lot of research and development (R&D) work has to be conducted before the detector can be modified. This includes studies of: possible chemical reactions of the Gd solution with the material components in SK, various Gd solutions' transparency, water purification system adjustments, ambient neutron background fluxes, and neutron tagging efficiency. These studies have been under way for several years now, both in the US and Japan. In this paper we present the status of the R&D. Finally we will mention the future plan to construct a test facility consisting of a 100 ton Gd solution Cherenkov detector, a transparency measurement instrument, and a Gd-capable water purification system. The test tank detector performance is being studied using a Geant4-based Monte-Carlo (MC) simulation.

II. R&D STATUS AND RESULTS

A. Soak tests with Gd solutions

The candidate water soluble Gd compounds investigated thus far are $GdCl_3$, $Gd_2(SO_4)_3$ and $Gd(NO_3)_3$. Soak test studies of stainless-steel samples in the various Gd solutions were performed with the accelerating conditions of elevated Gd concentrations and keeping the solution temperature at 60 °C. In the case of $GdCl_3$, cracks and corrosion have been found for some steel samples which were stressed and thermally activated artificially, a test designed to simulate the welded areas of the stainless steel support structure in SK. On the other hand, no steel damage was found for solutions of $Gd(NO_3)_3$ and $Gd_2(SO_4)_3$ [5]. However, in a separate test we found that the $Gd(NO_3)_3$ solution strongly absorbs short wavelength visible and near UV light, which unfortunately is the wavelength region of Cherenkov photons. Therefore, gadolinium sulfate $Gd_2(SO_4)_3$ has been determined to be the best candidate compound so far. We have begun a new soak test with the gadolinium sulfate solution for 37 material components currently used in SK, including the stainless steel, PMT support rubber, plastic tyvek, acrylic material, cables and so on. For large size components we have cut them into small samples of 3×3 cm^2. Each sample is encapsulated in a 500 ml plastic bottle filled with either the Gd solution or pure water, in both cases after nitrogen gas bubbling to get rid of dissolved oxygen. The bottles have been left at room temperature for three months. No damage has been found for any of the samples so far. Now we are measuring the concentration of any chemical contamination dissolved into the soak solutions.

B. Water transparency measurements

Light attenuation length in the water is a key quantity which determines the performance of water Cherenkov detectors. The current SK measures the attenuation length using natural sources of cosmic ray muons and muon decay electrons, and artificial light sources such as lasers. In order to continue the various successful physics programs in SK with Gd-loaded water, the attenuation length must be kept larger than 70 m, the lowest level used by the current SK. A water transparency measurement facility has been constructed at University of California, Irvine (UCI). Figure 1 depicts the device at the heart of the system. An array of lasers emitting light at six different wavelengths from 337 nm to 650 nm is placed on top of a long pipe. The pipe diameter and length are 16.5 cm and 6.3 m, respectively. The laser beams are reflected and split by a half mirror and injected down the pipe containing the pure water or Gd solution to be measured. Half of the beam is detected by a reference PIN photodiode to monitor the light intensity pulse by pulse. The intensity of the half of the beam injected into the pipe is also monitored by a PIN photodiode at the bottom of the pipe. By changing the water level in the pipe, we measure the light attenuation. The first measurement using pure water was performed, and the measured attenuation length is within the expectations based on pure water seen at SK. Currently, measurements with the Gd solution are being carried out.

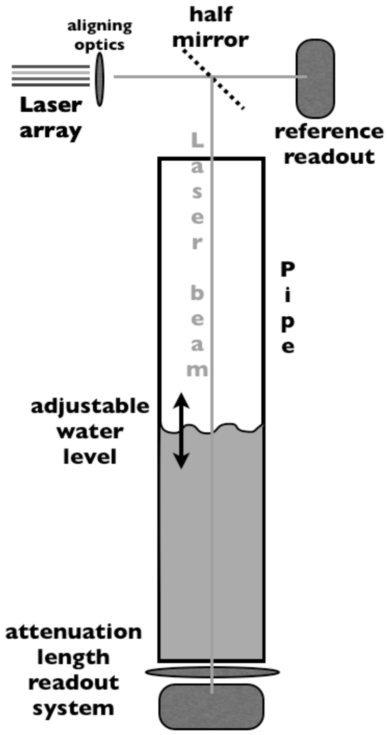

Fig. 1. The water transparency measurement device at UCI.

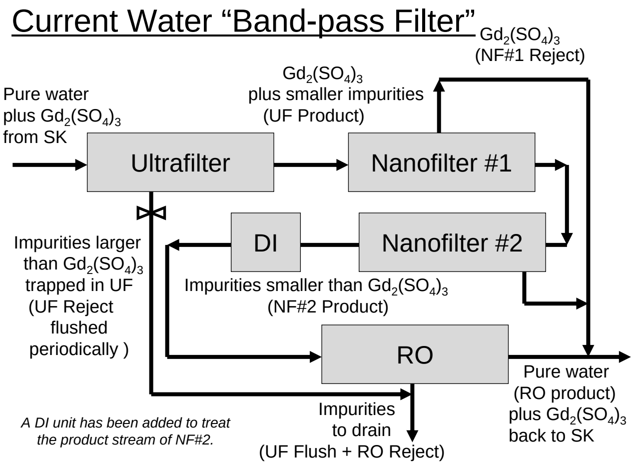

Fig. 2. The proposed water purification system.

C. Water purification system

The water purification system employed in the present SK rejects all the contamination in the water. Without modification, dissolved Gd and SO_4 would also be removed from the detector. A selective filtration system has been proposed to prevent that [6]. Figure 2 shows the proposed system. The SK water containing gadolinium sulfate is first fed to an ultrafilter, where all contamination larger in size than Gd and SO_4 is removed. The water with $Gd_2(SO_4)_3$ plus smaller impurities is then sent to the two nanofilters. Since the nanofilter hole size is (just) smaller than Gd and SO_4, almost all the gadolinium sulfate is removed. Then the water containing impurities smaller than Gd and SO_4 goes through deionization and reverse osmosis (RO), where only H_2O can pass through the membrane. The pure water from the RO and the concentrated gadolinium sulfate solution diverted by the nanofilters are combined, and then returned to SK.

A prototype selective filtration system has been constructed at UCI. Figure 3 shows an earlier version of the system with a single nanofilter stage. The Gd and SO_4 rejection efficiency of the two-stage nanofilter is measured to be greater than 99.99%, while the output pure water from the RO contains Gd and SO_4 below the detection limits of 0.05 part per million (ppm) and 1 ppm, respectively. Therefore UCI's prototype system has demonstrated that selective filtration can work very well.

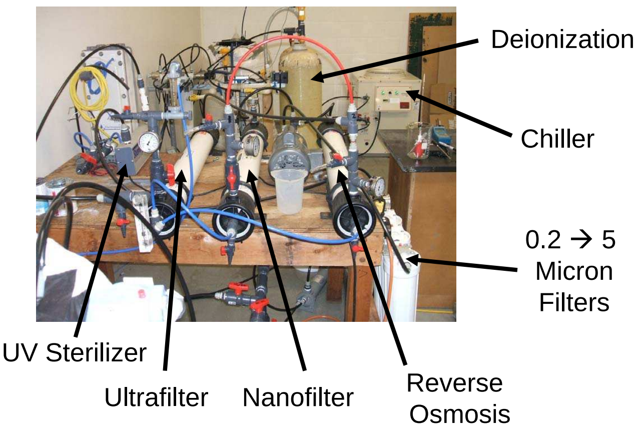

Fig. 3. The water purification system at UCI.

D. Neutron tagging efficiency measurements at SK

We have performed neutron tagging efficiency measurements at SK using a test vessel as shown in Fig. 4 [7]. The diameter and height of the vessel is 18 cm. The vessel frame is made of acrylic and a BGO scintillator is centered within it. In the BGO scintillator an Am/Be source is incorporated, where ^{241}Am alpha decays and the reaction $\alpha + ^9\mathrm{Be} \rightarrow ^{12}\mathrm{C}^* + n$ takes place. The excited carbon rapidly de-excites and produces a 4.43 MeV gamma ray. Therefore a gamma ray and a neutron are (nearly) simultaneously emitted. The gamma ray is detected by the BGO scintillator, which generates the prompt trigger in SK, simulating the positron from an inverse beta reaction. The space between the BGO scintillator and the acrylic wall of the vessel is filled with 2.4 liters of 0.2% $GdCl_3$ solution. The liberated neutron is quickly thermalized in the Gd solution and then captured by Gd. Three to four gamma rays per neutron capture are emitted into the SK tank, and detected by the Cherenkov light radiated from their Compton-scattered electrons. The event data were collected using a delayed coincidence trigger condition, and the vessel was placed at various positions inside SK.

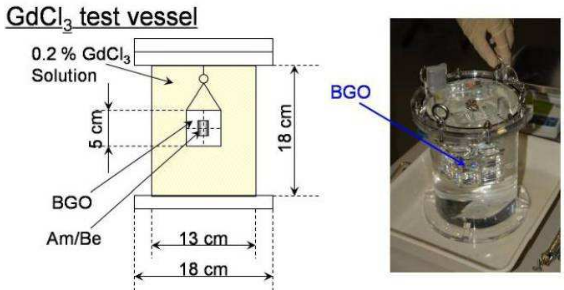

Fig. 4. The test vessel used for the neutron tagging efficiency measurements in SK.

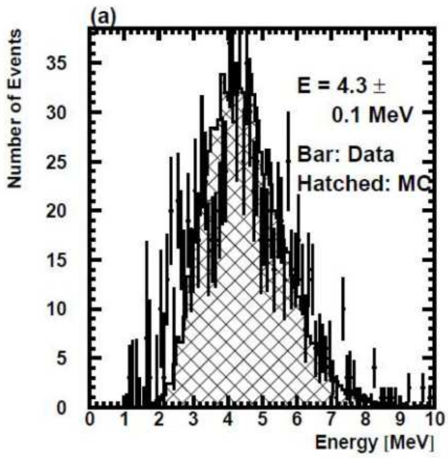

Fig. 5. The energy spectrum of the gamma rays from Gd capturing a neutron. The points with bars represent data, while the histogram shows the MC prediction.

Figure 5 shows the measured energy distribution of the gamma rays from the Gd, in good agreement with the MC prediction indicated as the hatched histogram. The mean energy is about 4.5 MeV, which is lower than the total emission energy of 8 MeV. This is because only part of the energy is translated into Cherenkov photons due to Compton scattering. The neutron tagging efficiency is estimated to be 66.7% with a 3 MeV energy threshold, taking into account the standard SK event reduction (80%) and the Gd capture efficiency (90%) in the solution. The accidental background rate is estimated to be 2×10^{-4} with an energy threshold of 10 MeV for the prompt $\bar{\nu}_e$ events. The time interval between the prompt and neutron capture events are measured, and we obtain the thermal neutron capture time constant of

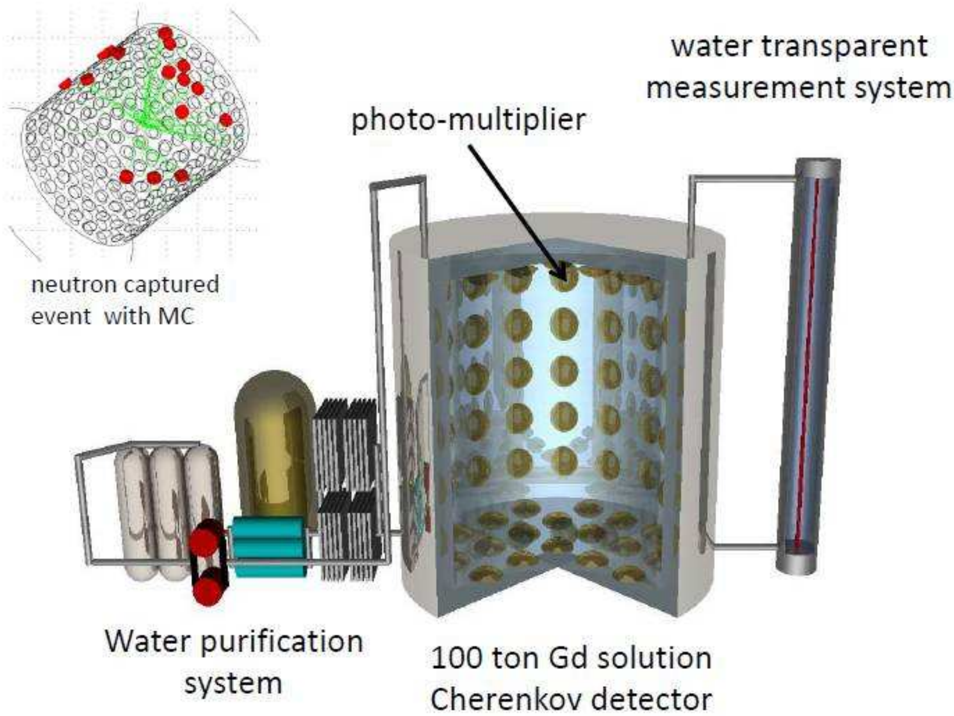

Fig. 6. A planned test facility for the Gd Cherenkov detector demonstration.

20.7 ± 5.5 μs, in good agreement with the MC prediction of 20.3 ± 4.1 μs.

This study has clearly demonstrated that SK with dissolved Gd can detect neutrons with high efficiency and low background level, sufficient to achieve the required sensitivity improvement to the SRN search.

III. Future plan

At present, the R&D studies mentioned above are performed individually. To verify the neutron detection principle and to measure the ambient neutron background rate, we have a plan to construct a test facility containing a water purification system, a water transparency measurement instrument, and a 100 ton-scale Cherenkov detector at the Kamioka mine. Figure 6 shows an overview of this new facility. The detector size is not decided yet, and will in part depend on the budget approved. Studies with a Geant4-based MC simulation are being carried out. A detector 8 m in diameter and 8 m in height has a reconstructed vertex resolution of 1.3 m for Gd neutron capture events, sufficient for measurements of the ambient neutron background rate and neutron tagging efficiency. The inset in the left hand upper side in Fig. 6 shows an event display of a neutron capture event in the MC. Studies with the test facility are planned to continue $3 \sim 5$ years, depending on the progress of the T2K experiment which has just started. The expectation is that Gd will be loaded into SK after all the R&D studies are successfully concluded.

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