Gadolinium study for a water Cherenkov detector

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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 antielectron neutrinos from supernovae and reactors. A five-year project to build and develop a prototype detector based on Super-Kamiokande (SK) has started. 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 SK data and a Geant4-based simulation. We present an overview of the project and the recent R&D results.

1. Introduction

Super-Kamiokande (SK) is the largest light water Cherenkov detector that has been successfully observing solar, atmospheric and accelerator neutrinos. Recently the addition of 0.2% gadolinium in the SK detector has been proposed. This modification can greatly improve the detection sensitivity of anti-electron neutrinos. The 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 captured by Gd with a probability of 90% within 20 \( \mu s \) and 4 cm. The neutron captured Gd emits 3–4 gamma rays having the total energy of about 8 MeV. The time and spatial correlation of the positron and neutron captured events can significantly reduce the backgrounds, and hence enhance the \( \bar{\nu}_e \) signal events.

The modification of SK enables us to increase the detectability of the supernova relic neutrinos (SRN). It is estimated that about \( 10^{17} \) supernovae have happened since the first star formation in the universe. All the past supernovae ejected not only the heavy elements but also huge numbers of neutrinos. Therefore, the measurements of the SRN flux and energy spectrum provide the information of history of the heavy element production, combined with the supernova neutrino generation mechanism. So far, the SK experiment has given the most stringent limit on the SRN flux: \( 1.2 \bar{\nu}_e \text{ cm}^{-2} \text{s}^{-1} \) at the 90\% confidence level with the energy threshold of 19.3 MeV. The flux limit is three times larger than the theoretical predictions. Thus we need the sensitivity improvement with a factor of three.

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 collisions on the oxygen nuclei with high energy cosmic 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 \( \nu_{\mu} \) + \( N \rightarrow \mu + N' \). The muon is invisible because its energy is lower than the Cherenkov threshold, and hence only the decay electron is visible. Although the event rate can be estimated from data using 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 not be improved; we need 40 years’ operation to lower the flux limit by a factor of three.

Making use of the neutron tagging with Gd can significantly reduce both spallation events and invisible muons; the energy threshold can be lowered to 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. Five years’ operation of SK with Gd can easily achieve the required sensitivity improvement.

By lowering the energy threshold further down to 2.5 MeV, SK with Gd could detect the reactor neutrinos with the best precision, allowing the accurate measurements of the neutrino oscillation parameters. The neutron tagging can be used to distinguish the interactions between neutrinos and anti-neutrinos that preferably emit protons and neutrons, respectively. This technique is important for neutrino oscillation studies with atmospheric and accelerator neutrinos.

As mentioned above, the Gd loaded SK has a possibility to open the new era of the neutrino physics. On the other hand, a lot of research and development (R&D) studies have to be conducted: studies on the chemical reactions of the Gd solution to the material components comprised in SK, the Gd solution transparency measurements, the water purification system, measurements of the ambient neutron background fluxes and measurements of the neutron tagging efficiency. We have already started those studies. In this paper we present the status of the R&D. Finally we will mention the current plan to construct a test facility consisting of a 200 ton Gd solution Cherenkov detector, a transparency measurement instrument and a water purification system. The test tank detector performance is studied using a Geant4 based Monte-Carlo (MC) simulation.
2. The R&D status and results

2.1. The soak tests with Gd solutions

The candidates of the Gd compounds that can be resolved in water are GdCl$_3$, Gd$_2$(SO$_4$)$_3$ and Gd(NO$_3$)$_3$. It has been shown that the transparency of the GdCl$_3$ doped water in stainless steel lined tank decreases rapidly in the UV wavelength region. The soak test studies of stainless-steel samples in the GdCl$_3$ solution were also performed with the accelerating condition keeping the solution temperature at 60 °C. Cracks and corrosion have been found for some samples which are stressed and thermally activated artificially. For those samples, we simulate the welding of the stainless steel support structure in the SK tank. On the other hand, no damage is found for the solution of Gd(NO$_3$)$_3$ and Gd$_2$(SO$_4$)$_3$. However in the Gd(NO$_3$)$_3$ solution, strong absorption by Ni-trate was evident below 350 nm, in the wavelength region matched with those of Cherenkov photons. Thus, gadolinium sulfate Gd$_2$(SO$_4$)$_3$ is found to be the best candidate so far. We have started the soak test with the gadolinium sulfate solution for 37 material components currently used in SK, including the stainless steel, PMT support rubber, plastic tyevk, acrylic material, cable and so on. For large size components, we have cut those to small samples of 3 x 3 cm$^2$. Each sample is encapsulated in a 500 ml plastic bottle with the Gd solution or pure water after nitrogen gas bubbling to get rid of oxygen. The bottles are left in room temperature for three months. No damage has been found for all the samples so far. Now we are measuring the concentration of any chemical contamination dissolved into the Gd solution.

2.2. The water transparency measurements

The light attenuation length in the water is the key quantity that determines the performance of the water Cherenkov detector. The current SK experiment measures the attenuation length using natural sources of cosmic ray muons and muon decay electrons, and artificial light sources such as the laser. In order to continue the various physics programs in SK with the Gd-loaded water, the attenuation length must be kept larger than 70 m, the level in the current SK. The water transparency measurement facility has been constructed at University of California, Irvine (UCI). Figure 1 depicts the facility. An array of lasers that emits a light beam with six different wavelengths from 337 nm to 650 nm is placed on the top. The beam is reflected by a half mirror and injected to a pipe containing water or Gd solution to measure. The half of the beam goes through the half mirror and is detected by PIN photo-diodes to monitor the light intensity pulse by pulse. The pipe diameter and length are 16.5 cm and 6.3m, respectively. The intensity of the light beam injected to the pipe is also monitored by PIN photo-diodes 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. The measured length is within the expectations. Currently, measurements in the Gd$_2$(SO$_4$)$_3$ doped water are being carried out.

2.3. The water purification system

The water purification system employed in the present SK rejects all the contamination in the water. Without modification, Gd and SO$_4$ would also be removed from the detector. A selective filtration system has been proposed to prevent that. Figure 2 shows the proposed system. The SK water containing gadolinium sulfate is fed to the ultrafilter, where all impurities larger than Gd$_2$(SO$_4$)$_3$ are removed. The treated water is then passed through the nanofilter and DI to remove the remaining impurities. The purified water is then used in the SK experiment.
of Gd and SO$_4$ is removed. The water with Gd$_2$(SO$_4$)$_3$ plus smaller impurities is sent to the two nanofilters. Since the nanofilter hole size is smaller than Gd and SO$_4$, almost all the gadolinium sulfate is removed. The water containing impurities smaller than Gd and SO$_4$ is deionized (DI) and then sent through the reverse osmosis (RO), where only H$_2$O molecules can pass through the membrane. The pure water from the RO and the gadolinium sulfate solution from the nanofilters are combined to be sent to the Cherenkov detector.

The prototype of the selective filtration system was constructed at UCI.

### 2.4. Neutron tagging efficiency measurements at SK

We have performed the neutron tagging efficiency measurements at SK using a test vessel as shown in Fig. 3 [8]. The diameter and height of the vessel is 18 cm. The vessel frame is made of acryl. In the vessel a BGO scintillator is placed at the center. In the BGO scintillator, an Am/Be source is incorporated, where the $^{241}$Am alpha decays and a reaction $\alpha + ^9$Be $\rightarrow ^{12}$C$^* + n$ happens. The excited carbon $^{12}$C$^*$ emits a 4.43 MeV gamma ray. Therefore a gamma ray and a neutron are simultaneously emitted. The gamma ray is detected by the BGO scintillator, generating the prompt trigger in SK. This prompt event simulates the positron from the 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 one neutron capture are emitted to the SK tank, and detected as the Cherenkov light radiated from the Compton-scattered electrons. The event data were collected using the delayed coincidence trigger condition. The vessel was placed at various positions in the SK detector.

Figure 4 shows the measured energy distribution of the gamma rays from 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 the part of the energy is translated to the Cherenkov photons due to the 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 $2 \times 10^{-4}$ with the energy threshold of 10 MeV for the prompt $\bar{\nu}_e$ events. The time interval between the prompt and neutron capture events are measured. An exponential function is fitted to the distribution, and we obtain the lifetime of the thermal neutron of $20.7 \pm 5.5 \mu$s, in good agreement with the MC prediction of $20.3 \pm 4.1 \mu$s.

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

![Figure 3: The test vessel used for the neutron tagging efficiency measurements in SK.](image)

![Figure 4: 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.](image)

### 3. R&D test facility construction

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 started the construction of a test facility containing the water systems and a small scale prototype water Cherenkov detector. Full budget for this facility is approved. Laboratory space of about $15 \times 10 \times 9$ m will be excavated in the Kamioka mine. The size is large enough to contain a cylindrical tank of size 6.5 m (diameter) $\times$ 6.2 m
(height), a 6.3 m water tower for the transparency measurement with a space for a worker on the top, and the water purification system. The water Cherenkov detector will be constructed with the same materials used in the SK detector including 240 20-inch PMTs. Figure 6 shows an overview of the facility. The reconstructed vertex resolution of the Gd neutron capture events is estimated to be about 1.5 m with a Geant4 based simulation. This resolution is sufficient to the measurements for the ambient neutron background rate and the neutron tagging efficiency. Studies with the test facility is planned to continue for five years. Gd will be loaded to SK after all the R&D studies are concluded.

Figure 6: A planned test facility for the Gd Cherenkov detector demonstration. Left to right: A water purification system; a cherenkov detector with photo-multiplier tubes; a water transparency measurement system.

4. Summary

The SK detector with Gd solution has been studied. The ability of tagging neutron can greatly improve the sensitivity of the anti-electron neutrino detection, enabling us to reach the theoretical predictions of the SRN flux. Several R&D studies are being performed. The best compound known so far is gadolinium sulfate Gd$_2$(SO$_4$)$_3$. No material damage with the solution is found. The attenuation length measurements of the Gd solution are in progress. The prototype of the selective filtration system demonstrates the Gd solution can be purified without loss of Gd. The studies with the test vessel in SK have verified the neutron capture event can be detected by SK with the high neutron tagging efficiency and the low background level. The test facility composed of the purification, transparency measurement systems and a 200 ton water Cherenkov detector will be constructed in the Kamioka mine. Once the prototype detector has proven to work as expected after these R&D studies, modification of SK with the Gd option will be proposed.

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