The Super Kamionade Gadolinium Project

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Abstract. Super-Kamiokande (SK) will be upgraded to Super-Kamiokande Gd (SK-Gd). This modification will enable it to identify low energy anti-neutrinos for the world’s first observation of the Diffuse Supernova Neutrino Background (DSNB). On average, there is one core-collapse supernova somewhere in the universe each second. The neutrinos emitted from all of these supernovae since the onset of stellar formation have suffused the universe. The flux of the DSNB is expected to be several tens per square centimeter per second. Theoretical models vary, but as many as five diffused supernova neutrinos per year above 10 MeV are expected to interact in SK. However, in order to separate these signals from the much more common solar and atmospheric neutrinos and other backgrounds, we need a new detection method. In 2015, the Super-Kamiokande Collaboration approved the SK-Gd project. It is the upgrade of the SK detector via the addition of water-soluble gadolinium (Gd) salt. Since then, we have been conducting many dedicated studies and developments for deploying Gd to SK.

1. Neutrinos from Supernovae
On February 23 1987, Kamiokande [1], IMB [2] and Baksan [3] detectors recorded a pulse of neutrinos emitted by SN1987A. It had been predicted that almost 99% of the energy of the explosion is transported by neutrinos. The observation of neutrinos from SN1987A confirmed that this scenario is actually correct. The number of events observed in each experiment was 11, 8 and 5 in Kamiokande, IMB and Baksan, respectively. Although these are small numbers, it was possible to obtain some estimates on the binding energy of the neutron star remnant and the temperature of the neutrino sphere. The binding energy obtained from Kamiokande and IMB data assuming equi-partition (the released energy by each neutrino species is the same, i.e. the total energy is 6 times the energy released by $\bar{\nu}_e$) was $\sim 3 \times 10^{53}$ erg and is consistent with the standard scenario of the core collapse supernova. The $\bar{\nu}_e$ temperature obtained from Kamiokande and IMB data was $3.5 \pm 0.5$ MeV [4].

In order to know more details on the supernova burst mechanism, the “next” nearby supernova is necessary. Super-Kamiokande (SK) is a water Cherenkov detector which has 32,000 ton fiducial volume for supernova neutrinos above 4.5 MeV. SK has potential to detect about 3,100 $\bar{\nu}_e p \rightarrow e^+ n$ events, $\sim 170 \nu + e \rightarrow \nu + e$ scattering events, and $\sim 60^{16}$O charged current events for a 10 kpc supernova [5]. The $\nu + e \rightarrow \nu + e$ scattering events give the direction of the supernova with an accuracy of about $5^\circ$. The large statistics of $\bar{\nu}_e p \rightarrow e^+ n$ events gives a precise energy spectrum measurement, and it enable us to discuss models of supernova simulation. For the future, Hyper-Kamiokande (HK) [6], a 256-kton water Cherenkov detector, is proposed. Its fiducial mass for supernova neutrinos is 220 kton, 7 times larger than that of SK. In HK, about 20,000 inverse beta events, 1,200 $\nu e$-scattering events, and 400 $^{16}$O CC events are expected for...
Figure 1. Expected energy spectra of diffuse supernova neutrino background [7]. Each color corresponds to an effective neutrino temperature, and each range shows astrophysical uncertainties.

a 10 kpc supernova. Even for a supernova in M31 (Andromeda Galaxy), about 10 events are expected.

2. SK-Gd
Nevertheless, instead of waiting a nearby supernova there is another way to investigate the supernova. Supernovae have been occurring since the beginning of the universe, and the neutrinos from all the supernovae have been accumulated as diffuse neutrinos in our universe, called diffuse supernova neutrino background (DSNB). DSNB would tell us the star formation history of the universe. The predicted spectra of DSNB [7] are shown in Figure 1. Since reactor neutrinos and atmospheric neutrinos are dominant background below 10 MeV and above 30 MeV respectively, 10–30 MeV is an open window for the DSNB measurement. SK has been searching for DSNB not only by only detecting prompt positron signals but also by coincidence detection of positrons and delayed 2.2 MeV gammas from protons which captures neutrons; however, it is still constrained by background because the efficiency of the 2.2 MeV detection with Cherenkov lights is low. By adding 0.1% Gd into the 50 kton water tank, this situation should be significantly improved [8] as shown in Figure 2. Gd has a thermal neutron capture cross section of 49,000 barns (about 5 orders of magnitude larger than that of protons) and emits a gamma cascade of 8 MeV that can be easily detected using Cherenkov light. In order to obtain a 90% efficiency for neutron capture, the Gd concentration should be 0.1%, or 0.2% if Gd\textsubscript{2}(SO\textsubscript{4})\textsubscript{3} is used, as illustrated in Figure 2. Figure 3 shows expected signal spectra for DSNB models and conservative background estimation of atmospheric neutrinos with its component. Table 1 shows the expected number of events and background with 10 years observation. Here, we assume the $\nu_\mu$ CC background events are 1/4 of those of SK, $\nu_e$ CC background events are 2/3, and NC background events are 1/3 with neutron tagging, respectively. Topological information of events should allow to reduce the background further, but it is not included in this estimation.
Figure 2. Neutron tagging with gadolinium (left), and capture efficiency as a function of Gd concentration (right) [9].

Figure 3. Expected background components of SK-Gd (left), and expected DSNB spectra of some models [7] (right).

Table 1. Expected numbers of signals and backgrounds through SK-Gd 10 years observation

| Model [7]        | 10-16 MeV | 16-28 MeV | Total | Significance |
|------------------|-----------|-----------|-------|--------------|
| $T_{\text{eff}} = 8$ MeV | 11.3      | 19.9      | 31.2  | 5.3$\sigma$  |
| $T_{\text{eff}} = 6$ MeV | 11.3      | 13.5      | 24.8  | 4.3$\sigma$  |
| $T_{\text{eff}} = 4$ MeV | 7.7       | 4.8       | 12.5  | 2.5$\sigma$  |
| $T_{\text{eff}} = $SN1987a | 5.1       | 6.8       | 11.9  | 2.1$\sigma$  |
| BG               | 10        | 24        | 34    | –            |
3. Developments for SK-Gd

In order to realize the Gd implementation to SK, we need several developments from the various viewpoints, such as environmental safety, both positive and negative impacts to physics program of SK.

3.1. Stopping the leakage

The water tank of SK has a leak that is estimated to be about 1 ton/day. The impact of Gd leakage to the environment is not foreseen, therefore it is assumed that the impact is same as Hg leakage which has the most stringent regulations. Accordingly, the goal is to stop the leak or reduce it by a factor 30 at least. It is planned to use a two material strategy to stop the leak. A first sealant, BIO-SEAL™197, is designed to fill small gaps in the SK tank. As this epoxy-based material is not strong for displacement, a second stretchable material is planned to be used for overcoating it. MineGuard™ had been considered for the overcoat sealing, however it was found that the original formulation with poly-urethane undergoes hydrolysis. Then a new formulation with poly-urea was developed. It was also found that CaCO$_3$ which is added to MineGuard™ in order to increase its viscosity is contaminated with $^{238}$U. To improve the situation, a pure SiO$_2$ instead of CaCO$_3$ was selected. The newly developed material is named MineGuard C™. It is estimated that the total Rn emanation from the sealing material will be about one third of that emanated from all the PMTs of inner detector. Moreover, the sealing material will be present only in the outer detector, the Rn emanation from the sealing material should be acceptable.

3.2. Radioactive impurities

The usual Gd$_2$(SO$_4$)$_3$ on the market contains radioactive impurities. Since these impurities would be present in the whole detector volume and could mimic several signals, these would be potential background sources for low energy neutrinos including DSNB and solar neutrinos. For example, with the $^{238}$U contamination in Gd$_2$(SO$_4$)$_3$, spontaneous fission would lead to a sizable background for DSNB and the solar neutrino analysis would be affected by betas/gammas coming from $^{226}$Ra daughters. In order to reduce the radioactive impurities in the Gd$_2$(SO$_4$)$_3$, we are currently working in cooperation with several companies to produce high purity Gd$_2$(SO$_4$)$_3$ that could meet the requirements for low energy physics. While these companies provide us with new cleaner samples, we measure them with Ge detectors and an ICP-MS, the U, Th and Ra concentrations. The measurements with Ge detectors are performed in the Canfranc and Boulby laboratories, in Spain and the UK respectively, and the ICP-MS measurements are done in the Kamioka observatory. The current status of the impurities in Gd$_2$(SO$_4$)$_3$ is summarized in Table 2. As for the U contamination it is already achieved the required purity, while it is still needed to reduce Th and Ra contaminations by a further factor of 4.

3.3. EGADS

For studying all the effect of dissolving Gd$_2$(SO$_4$)$_3$ in the SK tank, an R&D project called EGADS (Evaluating Gadolinium’s Action on Detector Systems) has been running since 2014. A new hall was excavated near SK and a 200 m$^3$ stainless steel tank with ancillary equipment was constructed. The idea is to mimic the SK conditions inside the 200 m$^3$ tank. The tank is equipped with a dedicated water purification system that removes impurities while retaining the Gd$^{3+}$ and SO$_4^{2-}$, a 15 m$^3$ Gd$_2$(SO$_4$)$_3$ premixing and pretreatment plastic tank, and a device to measure the water attenuation length (called UDEAL). Figure 4 shows the history of the measured water transparency in the 200 m$^3$ tank since October 2014. It demonstrates that transparencies can be comparable to those achieved at the pure-water SK’s phases III and IV, and that in steady operation the measured transparencies are nicely stable at values very appropriate for physics analyses. The Gd$_2$(SO$_4$)$_3$ concentration in the 200 m$^3$ tank is monitored
Table 2. Physics-based requirements for radioactive impurities in Gd$_2$(SO$_4$)$_3$ and the current status of the purification.

| Chain          | $^{238}$U | $^{232}$Th | $^{226}$Ra | $^{228}$Ra | $^{228}$Th | $^{235}$U | $^{239}$Ac /$^{237}$Th |
|----------------|-----------|------------|------------|------------|------------|-----------|------------------------|
| Typical Gd$_2$(SO$_4$)$_3$ | 50 | 100 | 100 | 30 | 300 |
| Requirements   | < 50 | < 0.5 | < 0.05 | < 0.05 | < 0.05 | < 3 | < 3 |
| Detector        | Ge | ICP-MS | Ge | ICP-MS | Ge | Ge | Ge |
| Company A       | < 13 | 0.2 | 0.7 ± 0.4 | 0.3 | < 0.39 | 1.7 ± 0.4 | < 1.3 | < 3.1 |
| Company B       | < 25 | 0.2 | < 0.6 | 0.2 | < 0.7 | 0.9 ± 0.3 | < 3.1 | < 6.1 |
| Company C       | < 13 | 0.1 | < 0.3 | 0.2 | < 0.3 | < 0.4 | < 0.6 | < 1.9 |

Figure 4. Percentage of Cherenkov light remaining for water inside the instrumented 200 m$^3$ EGADS tank for increasing concentrations of Gd$_2$(SO$_4$)$_3$. The green, red, and blue lines correspond to data taken from the top, center, and bottom sample points of the 200 m$^3$ tank, respectively, while the light blue band shows the range of ultra-pure water transparencies during SK-III and SK-IV. The inset is the Gd$_2$(SO$_4$)$_3$ concentration history, as measured by the AAS, for the three sampling points in the top, center and bottom of the EGADS detector [10].

by using an Atomic Absorption Spectrometer (AAS). Water samples are collected by a pump from three points in the detector, at three different height, using the same pipe as the UDEAL sampling. The measured concentration since November 2014 is also shown in Figure 4. The four loadings are clearly seen as steps in the concentration. The concentrations at all three sampling points are: 1) very close to each other, indicating that there is a homogeneous solution in the 200 m$^3$ tank, and 2) stable between loadings or any other external intervention, demonstrating that there is no significant Gd loss during continuous water recirculation and purification. In order to see the positive effects of the Gd loading, i.e. the neutron tagging capability, an Am/Be neutron source with BGO crystal was deployed in EGADS detector. Through the process: $^{241}$Am $\rightarrow ^{237}$Np + α, $^9$Be + α $\rightarrow ^{12}$C + $\gamma$ (4.4 MeV) + n, the scintillation light from BGO by 4.4 MeV $\gamma$ can be used the prompt signal which mimics the Cerenkov light. Figure5 (a) shows the distribution of time differences between prompt and delayed (neutron captured) events after application of several simple analysis cuts. The exponential fit of the distribution indicates a
characteristic of $31.32 \pm 0.76$ (stat.) $\mu$s, which is consistent with the expectation for 0.1% Gd concentration. The flat component of the fit function indicate the BG rate in the data. In order to remove the remaining background (BG), a statistical background subtraction methods was applied. This method consists in the use of the data of delayed events rejected by the $\Delta t_{\text{prompt}} - \Delta t_{\text{delayed}} < 500 \mu$s cut as a background sample. Figure 5 (b) shows the spectrum of the number of hits from calibration run with Am/Be source deployed in the center of the detector after the background subtraction. The same distribution from a GEANT4 MC simulation is shown. The efficiency of the Gd neutron capture selection was measured to be $85.3 \pm 0.9%$ (stat) in data and $84.4 \pm 0.3%$ (stat) in MC. These results indicate the expected neutron tagging in 0.2% $\text{Gd}_2(\text{SO}_4)_3$ water.

4. Implementation in Super-Kamiokande
The current plan for the implementation of SK-Gd has three periods. The first period is for the tank refurbishment; the most critical item, pure water fill, and recirculation of pure water in the detector until good water transparency is achieved. The second period is for loading $\text{Gd}_2(\text{SO}_4)_3$ up to 0.02%, which corresponds to $\sim 50\%$ neutron capture efficiency on Gd. It will be run for a while at this concentration in order to study backgrounds and neutron capture efficiency. In the third period the remaining $\text{Gd}_2(\text{SO}_4)_3$ will be added to achieve the full target loading, 0.2%. T2K and SK collaborations have agreed to start the first period on June 1 2018. The scaling up of EGADS water system for SK-Gd is well under way.

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