PROCEEDINGS OF SCIENCE

SuperK-Gd

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Super-Kamiokande (SK) will be upgraded, to become SuperK-Gd, in order to be able to detect thermal neutrons. This will be achieved by dissolving 0.2% of gadolinium (Gd) sulfate in mass in the otherwise ultra-pure SK water. Gd has the largest cross-section for thermal neutron capture and emits a gamma cascade of about 8 MeV. This cascade is detected with much higher efficiency than the capture on protons which produces a single gamma of 2.2 MeV.
EGADS, a 200-ton water Cherenkov detector, was constructed using the same materials as SK and was the test ground for the future SuperK-Gd upgrade. Thanks to the extensive studies at EGADS the SuperK-Gd project was approved in June 2015. In this talk, we will report about the ongoing studies for SuperK-Gd and the plans for the refurbishment of SK.

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1. Introduction

Super-Kamiokande (SK) operations began in 1996 and since then it has gone through four different phases: SK-I, SK-II, SK-III and SK-IV. The latest upgrade was done in 2008 with the improvement of the data acquisition system. This upgrade provides a high speed signal processing and allows to read out every hit and process them by an online farm. It also allows to process higher event rates which is crucial in the case of a nearby core-collapse supernovae (ccSNe) explosions or in order to lower the energy threshold for solar neutrinos. Another important motivation to lower the energy threshold is to look for neutron captures on hydrogen. When a neutron is captured on hydrogen, a 2.2 MeV gamma is produced and thus, a very low energy threshold is required to detect them with high efficiency. However, with the current energy threshold (around E_{kin} = 3.5 MeV) the detection of these low energy gammas is still a difficult task.

One motivation to detect those neutrons is the search for relic SN neutrinos also know as Diffuse Supernova Neutrino Background (DSNB) from all previous ccSNe in the universe. The energy of these neutrinos should be around a few tens of MeV. The largest cross section in this search corresponds to inverse beta decay (IBD): $\bar{\nu}_e + p \rightarrow e^+ + n$ which is two orders of magnitude larger than ν_e elastic scattering. Theoretical predictions provide with several limits but although SK has the best world limit [1], DSNB has not been detected yet. The reason for that are the current irreducible backgrounds: at low energies by invisible muon decay (muons below Cherenkov threshold that decay into electrons) and at high energies by atmospheric neutrinos. The lower energy threshold is defined by our ability to remove spallation events. Because we can detect the positron with high efficiency only, this search is severely limited by these backgrounds. However, if we could detect neutrons efficiently, these backgrounds could be reduced significantly and thus, making the detection of the DSNB possible for the first time.

Having this in mind, John F. Beacom and Mark R. Vagins proposed the addition of gadolinium in GADZOOKS! [2]. In this paper, they proposed the addition of 0.2% of gadolinium (Gd) sulfate, $Gd_2(SO_4)_3$. When a neutron is captured on Gd it produces a gamma cascade of about 8 MeV and thus, can be detected with high efficiency. Because of the large thermal neutron capture cross section (49000 barns to be compared to the 0.33 barns for hydrogen and 0.0002 barns for Oxygen), about 90% of the neutrons would be captured on Gd. The neutron capture occurs very close to the prompt signal from positron and about 30μs later (it is about 200μs in case of pure-water), see figure 1. This characteristic signal for IBD reactions that resembles a heartbeat is difficult to mimic by backgrounds and therefore, very useful reducing backgrounds.

Of course, the benefits of neutron tagging are not limited to DSNB only. Obviously, it is applicable to galactic SN neutrinos too. Being able to distinguish IBD events from other types of reactions means we can determine its spectrum and efficiently separate them from other reactions. For example, we could better distinguish IBD from elastic scattering events. As a result, the pointing accuracy to a galactic SN from neutrino elastic scatters is expected to improve by a factor of about 2. Moreover, we can also detect a SN with just a few events from their unmistakeable IBD heartbeats throughout the detector or observe a late black hole formation. Another example, since in most of the proposed proton decay (PD) modes there is no accompanying neutron but the main background comes from atmospheric neutrinos where at least one neutron is expected, if a PD candidate is found, the confidence would increase if no neutron is found.

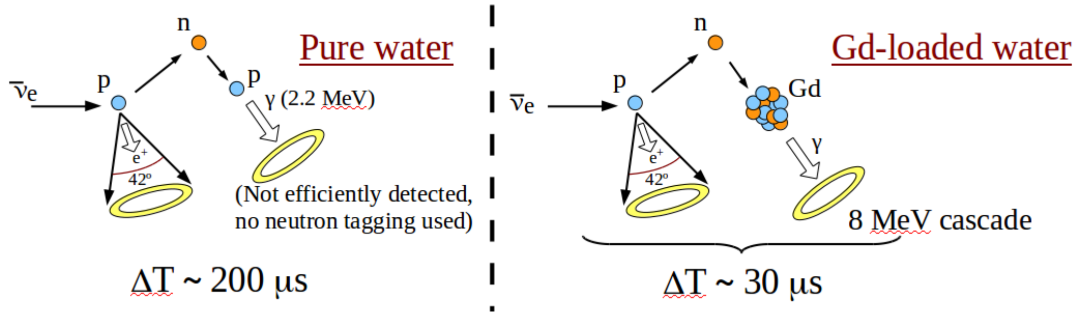

Figure 1: Inverse beta decay in pure water: neutrons are captures on hydrogen after about 200 μs and produce a single 2.2 MeV gamma. In Gd loaded water neutrons are usually captured on Gd after about 30 μs and produce a gamma cascade of 8 MeV.

To make GADZOOKS! possible, the EGADS project was funded in 2009. Since the start of this project, EGADS has worked on five clear goals: demonstrate that the filtration system can achieve and maintain a good water quality while keeping the Gd concentration in water constant, show that Gd sulfate has no adverse effects on the SK detector components, prove that we can add/remove Gd in a efficient and economical way, demonstrate that it will not affect other SK analyses and finally, study how to reduce the now visible neutron background (from spallation, U/Th fission chains from impurities in the Gd sulfate, ambient neutrons, etc). After several years of tests and improvements at EGADS, on June 27, 2015, the Super-Kamiokande collaboration approved the SuperK-Gd project.

In the next sections, I will summarize these tests at EGADS and discuss the present status of SuperK-Gd.

2. EGADS

The EGADS (Evaluating Gadolinium's Action on Detector Systems) project features a 200-ton tank with 240 photo-detectors and is located in the Kamioka mine near the SK site. Its water purification system was specially designed to remove all impurities in water but to keep Gd dissolved. In order to demonstrate the feasibility of the idea, all materials were chosen of the same type as in SK in order to mimic the conditions there. Because dissolved substances may reduce the transparency directly or indirectly (by directly absorbing or scattering the Cherenkov light or by degrading detector materials), it has been necessary to monitor water transparency continuously. This is being done in a daily basis and in three sampling positions of the EGADS detector. To prove that Gd dissolves homogeneously in the detector and that there are no Gd losses, we also monitor the Gd concentration at the same sampling positions.

The typical distance Cherenkov photons travel in SK is 15 m. The Cherenkov light left at 15 m is thus a good measure of the water transparency. This is shown in figure 2 in three sample positions: top, centre and bottom of the tank. The light left is compared with the typical SK values (blue band). The water transparency in EGADS is within the SK values even after full Gd loading. Also shown in this figure, is the Gd sulfate concentration at the same sampling positions as for the water transparency. The full Gd loading has been achieved in four steps as indicated by the four left-most grey vertical lines. The Gd sulfate concentrations in these steps were: 0.02%, 0.1%, 0.16% and 0.2%. After each loading, the water transparency decreases first but then rapidly recovers and returns to the typical SK values. When the running conditions are stable the water transparency is stable too and stays within the typical SK values. When this is not the case due to temporary stops of the water system (for maintenance) the water transparency decreases but then recovers again. After the last Gd loading the Gd sulfate concentration has been constant and homogeneously dissolved in the detector. This demonstrates that our water transparency is able to remove impurities, achieve and maintain a good water quality as well as keep the Gd.

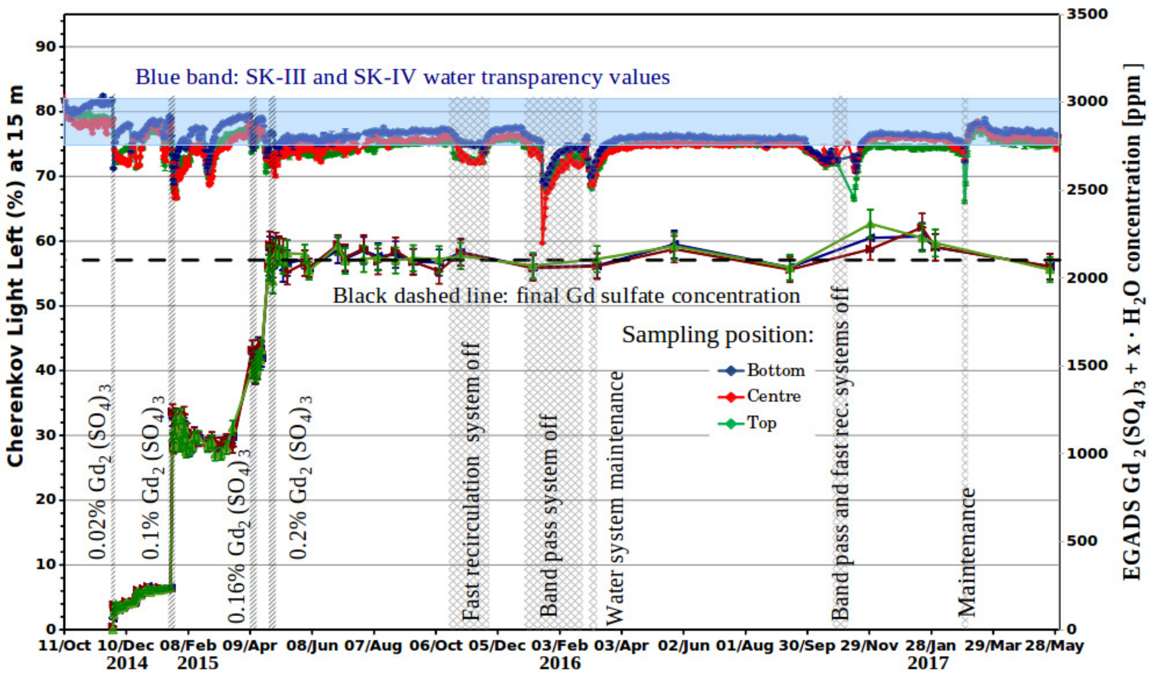

Figure 2: Cherenkov light left after 15 m is shown for three different sampling positions (top, centre and bottom) in the EGADS detector. The blue band indicates typical values for SK-III and SK-IV. In the same figure, Gd sulfate concentration for the same sampling points is shown. The black dashed line indicates the final Gd sulfate concentration while the vertical bands indicate the Gd sulfate loadings and other relevant events.

If the addition of Gd sulfate would decrease the water quality, it could potentially affect some of the current SK analyses. However, the water quality achieved at EGADS would clearly not affect them. Furthermore, when adding Gd sulfate there exists the possibility of radioactive contamination. Radioactive impurities could represent a new background. This will be discussed in the next section.

For the removal of Gd we have tested a cation ion-exchange resin. To remove Gd the we pass through this resin the loaded water. The Gd is then captured by the resin and Na^+ ions are released. At SuperK-Gd we plan to use pressurized plastic tanks (diameter: 1.6 m, height: 3 m) each containing 4 tons of this resin. The location of these tanks as well as the detailed strategy on how to run them is now under discussion.

After 2.5 years of full Gd loading, we opened the EGADS tank for inspection last May. The tank, the structure and the PMTs look perfect. We also recovered a PMT for close inspection. No deterioration or change was seen.

3. Radioactive impurities

As mentioned above, if we do not do anything to prevent it, radioactive impurities like uranium (U) or thorium (Th) would be added along Gd sulfate. We have measured these impurities for the current Gd sulfate used at EGADS in the Canfranc laboratory (Spain) with low background germanium (Ge) detectors, see table 1.

Radioactive chain	Part of the chain	mBq/kg
^{238}U	^{238}U	50
	^{226}Ra	5
^{232}Th	^{228}Ra	10
	^{228}Th	100
^{235}U	^{235}U	32
	^{227}Ac / ^{227}Th	300

Table 1: Current values of radioactive impurities in untreated Gd sulfate powder at EGADS.

Since these impurities would be present in the whole detector volume and could mimic several signals (including IBD), these would represent a potential background for several ongoing analyses like DSNB or solar analysis. For example, with the ^{238}U contamination in current Gd sulfate at EGADS, spontaneous fission would lead to a sizeable background for DSNB. The solar neutrino analysis would be affected in its lowest energy range due to gammas coming radium daughters. We determined that the measurement of the DSNB would not be severely impacted. Moreover, we plan to use a resin (AJ4400) that is able to reduce U levels by a factor 200 which would reduce the impact of this impurity. As for the solar analysis, we would need a factor 10^3-10^4 reduction for ^{228}Th/^{228}Ra and ^{238}U/^{226}Ra. The requirements are summarized in table 2.

Radioactive chain	Part of the chain	SRN (mBq/kg)	Solar ν (mBq/kg)
^{238}U	^{238}U	< 5	-
	^{226}Ra	-	< 0.5
^{232}Th	^{228}Ra	-	< 0.05
	^{228}Th	-	< 0.05
^{235}U	^{235}U	-	< 3
	^{227}Ac / ^{227}Th	-	< 3

Table 2: Physics-based requirements for radioactive impurities. Where no number is given (-), the corresponding requirement is less restrictive than that for the other physics analysis.

To meet our goals further R&D is needed in order to reduce the radioactive impurities in the Gd sulfate. We are currently working in cooperation with several companies to produce a cleaner Gd sulfate that could meet these requirements. While these companies provide us with new cleaner samples, we measure with Ge detectors and an ICP-MS, the U, Th and Ra concentrations in the Gd sulfate. 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 facilities, Japan. By providing them with this information they can improve their purification methods and we are getting closer to our goals. Apart from the already mentioned resin AJ4400, we also plan to use a resin for Ra removal (DOWEX) of commercial use. However, to prevent this resin from removing Gd, we would need to replace the Na^+ ions in the resin by Gd itself. We expect that after the reduction of impurities from the Gd sulfate before dissolving in combination with resins like AJ4400 and DOWEX our goals will be met. Further studies and improvements are ongoing in this field.

The SK tank has a water leak that is estimated to be about 1 ton/day and its location near the bottom of the SK tank. Our goal is to stop the leak or reduce it by a factor 30 at least. We plan 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. However, the radon (Rn) emanation from this material was found to be too large. We plan to use a second material overcoating the first to block radon emanation. After discarding other materials for the overcoat sealing, MineGuard^{TM} is being considered now although it was found that the original formulation would not meet our goals. The main material of MineGuard is either poly-urethane or poly-urea. However, it was found that the formulation with poly-urethane undergoes hydrolysis and therefore, we will use the poly-urea formulation. We also found that $CaCO_3$ which is added to increase its viscosity, is contaminated with ^{238}U. To improve the situation, we plan to use pure SiO_2 instead of $CaCO_3$. With this the Rn emanation is largely reduced.

The newly developed material is named MineGuard C^{TM}. We estimate that the Rn emanation from the sealing material will be significantly about one third of that emanated from the inner detector PMTs. Thus, since the sealing material will be present in the outer detector only, we consider the Rn emanation from the sealing material acceptable.

4. SuperK-Gd

As discussed above, we plan to use a two material strategy to stop the current leak at SK. One of the leading hypothesis about the origin of the leak is that it is caused by the distortion of the tank weld seams, see figure 3 right. Since these weld seams were checked with a sensitive vacuum box when the tank was empty and no leaks were found if this is the origin of the leak its cause must come from the water pressure distortion after filling the tank. In this case, the more flexible MineGuard C is indicated.

Pin-hole leaks around the PMT support structures is another possibility, see figure 3 left. In this case, we will use the two material strategy. First, apply BIO-SEAL 197 in these areas which is better capable of filling small gaps. Second, since small distortions cannot be discarded here either apply the more flexible MineGuard C.

Several tests to check the performance of these materials were conducted. The first test consisted in a flange mounted in a pipe containing Gd loaded water. The flange was penetrated by bolts and then coated and then pressurized. After several months no leak was found. The second was a tension test. Basically, two pipes glued with MineGuard C to check its elasticity. No breaking was observed until a few centimetres displacement (more than expected to fix the leak or even avoid larger leaks in case of earthquakes). Another check is a long term stability test consisting in

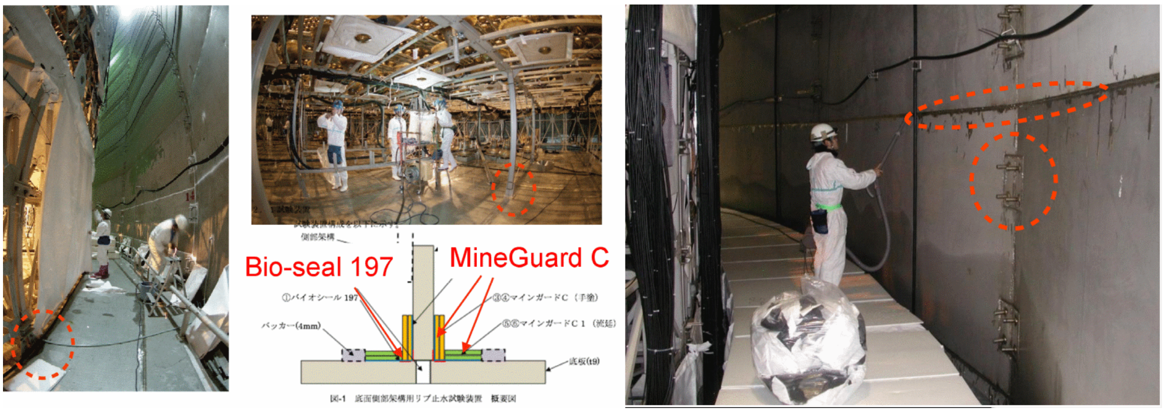

Figure 3: Pin-hole leaks around the PMT support structures (right) and the distortion of the tank weld seams from water pressure after filling the tank (right) are two of hypothesis to explain the observed leak.

samples with Gd loaded water and sealed from the inside (outside) and applying 5 atm (0.15 atm from within) pressure. All these tests have yielded good results. More tests (long term leak and soak tests) are ongoing with promising results so far.

Preparations for a new purification system for SuperK-Gd have started with the excavation of a new cavern near SK, see figure 4. In the design, we have taken into account the large experience collected in EGADS in dissolving Gd and water purification of Gd loaded water with the band-pass system. The installation of equipment for the dissolution of Gd, piping and controlling system, etc has been recently finished.

Figure 4: A new cavern was excavated in April 2016 for the new SuperK-Gd water system new the SK site. Installation of the new water system started (piping, Gd dissolution, controlling system, etc). In the next months other relevant parts like the band-pass system will be installed.

5. Conclusions and outlook

The tests and measurements done with the EGADS detector have demonstrated that we can achieve and maintain a very good water transparency even after loading 0.2% of Gd sulfate. We have also shown that the Gd sulfate dissolves quickly and homogeneously in our detector and that in addition to the good water quality the Gd concentration is constant, i.e. no Gd is being removed.

We are currently working in the further reduction of the radioactive impurities that may affect the current SK analyses as well as hinder the newly proposed measurements and benefits from the neutron tagging capabilities after adding Gd sulfate. We have developed a close collaboration with chemical companies in order to reduce the original radioactive levels and we are working to further reduce them and meet our physics-goals.

For the leak fix we also have a basic strategy. Employ MineGuard-C for the barrel welding seams and a two layer strategy around the PMT support structures at the bottom of the tank: a gap-filling BIO-SEAL 197 and a more flexible MineGuard-C on top. More long term tests for these two materials are ongoing.

Given the good results that we have achieved so far, we are confident we will be able to accomplish these goals and thus, we plan to start the leak repair at SK from June 1st, 2018.

References

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[2] J. F. Beacom and M. R. Vagins, Phys. Rev. Lett. **93** (2004) 171101 doi:10.1103/PhysRevLett.93.171101 [hep-ph/0309300].