PROCEEDINGS OF SCIENCE

The New Phase of Super-Kamiokande: SK-Gd

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With the addition of 0.02% Gd sulphate to its water in the summer of 2020, the Super-Kamiokande experiment entered a new phase: SK-Gd. Gd doping allows for far greater sensitivity to the detection of neutrons emitted in inverse beta decay than with just pure water. This is thanks to gadolinium's clear neutron capture signal and large neutron capture cross section. This long-awaited chapter in SK's story aims to deliver exciting new results in the realm of low energy electron antineutrinos, especially in measuring the diffuse supernova neutrino background. The supporting research and development leading up to SK-Gd, the Gd loading procedure and the current status of the detector are reported.

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1. Introduction

Super-Kamiokande (SK) is a large scale water Cherenkov detector with a long and rich history of neutrino physics research spanning more than two decades. The detector is comprised of a large stainless steel tank containing 50 kt of ultra-pure water separated into a 32 kt inner detector (ID) further fiducialised to 22.5 kt in most analyses, and an outer detector (OD) used to reject events which originate outside of the ID. SK detects Cherenkov light using over 11,000 50 cm diameter photomultiplier tubes (PMTs) in its ID and around 1,900 20 cm PMTs in the OD.

SK investigates a wide variety of neutrino sources, including (but very much not limited to) supernova relic neutrinos (SRNs). These are neutrinos that originated in core-collapse supernovae too distant to detect as individual bursts, but instead forming the diffuse supernova neutrino background (DSNB). The DSNB flux has yet to be measured directly but SK provides the world's most stringent upper limit [1].

2. A Gadolinium-Loaded Super-Kamiokande

Neutrinos from the DSNB as well as those produced in nuclear reactors, pre-supernova silicon-burning stars and supernova bursts are all predominantly low energy electron antineutrinos. At low energies of a few MeV, the dominant interaction channel for $\bar{\nu}_e$ is through inverse beta decay (IBD), given by

$$\bar{\nu}_e + p \rightarrow e^+ + n. \tag{1}$$

In SK, the IBD positron produces detectable Cherenkov light but the neutron is effectively invisible until it is captured on an atom. In ultra-pure water, the neutron typically captures on a hydrogen atom after $\sim 200\,\mu$s, producing a 2.2 MeV photon. Such a photon scatters atomic electrons, producing a small amount of Cherenkov light. Of SK's 11,000 PMTs, on average only 7 detect light from this event. Given the large amount of uncorrelated background in SK, primarily due to radioactive decay, detecting the delayed neutron capture in coincidence with the prompt positron serves as a powerful discriminator for IBD searches.

To greatly improve SK's ability to detect IBD interactions, as well as improve a range of other analyses involving neutrons, Beacom and Vagins proposed the doping of SK's water with gadolinium [2]. Gadolinium has a neutron capture cross section $\sim 100,000$ times larger than that of free protons and releases an 8 MeV gamma cascade on capture. This cascade results in around 23 PMTs registering a light hit on average, a far clearer signal compared to capture on hydrogen.

Beacom and Vagins' proposal became the SK-Gd project which saw successful first-phase deployment in summer of 2020 and constitutes the first major change to SK's detection principle in its long operational history [3]. In this phase, SK's ultrapure water has been doped with gadolinium sulphate octohydrate, $Gd_2(SO_4)_3 \cdot 8\,H_2O$ to a concentration of 0.02% by mass, with a planned final goal of 0.2% doping. Introducing a new chemical to the previously ultrapure water of SK presented a number of challenges.

3. Water Systems

One challenge when loading SK with Gd arises thanks to one of SK's strongest achievements: the purity of its water. The extensive systems supplying water to the SK tank are geared to remove any impurities that could harm both the radioactive background rate and Cherenkov light transparency in the detector. In the standard, ultrapure water configuration, these systems would remove the gadolinium sulphate before it reached the tank. To achieve the required water purity while retaining $Gd_2(SO_4)_3 \cdot 8\,H_2O$, new water systems were developed, specific to SK-Gd.

First, a controlled amount of gadolinium sulphate powder is fed to a buffer tank where it is dissolved in water. From here the solution is sent to the pretreatment system. A one micron filter precedes a UV light treatment to remove organic impurities. To remove inorganic impurities, the specially prepared AMBERJET™1020 [4] and AMBERJET™4400 [5] ion exchange resins remove positive and negatively charged impurities respectively. The pretreatment system finishes with further UV treatment and a series of filters that aim to remove any bacterial contamination. This system is only used during the initial loading of gadolinium sulphate. Once loaded, the water is cycled through the recirculation system. This largely mirrors the pretreatment system with some modifications, including the addition of heat-exchange units to finely control the water's temperature, and a membrane degasifier which removes dissolved gases such as radon. The SK-Gd water systems are described in further detail in [3].

4. EGADS

Before full-scale deployment for SK-Gd, the unique water treatment systems were developed and tested first in small scale at the University of California, Irvine (UCI) before scaling up to a test bed known as EGADS (Evaluating Gadolinium's Action on Detector Systems) [6]. EGADS is a 200 t detector utilising the same components and construction techniques as SK, serving primarily as a test platform for SK-Gd, based in the Kamioka mine. It is instrumented with 240 50 cm PMTs, 224 of these are identical to those used in SK while the rest are various styles to potentially be used in the next generation water Cherenkov neutrino experiment Hyper-Kamiokande. As well as serving as a proof of the water systems' capabilities, EGADS also addressed two main challenges in regards to Gd loading.

First, SK's size introduces a particular importance in regards to retaining the Cherenkov light transparency; a significant loss of light attenuation length would affect all analyses utilising SK. To monitor this, the UDEAL (Underground Device Evaluating Attenuation Length) system was deployed to measure the light attenuation length in water from EGADS for a range of wavelengths. UDEAL showed that, outside of short reductions when first loading gadolinium, the light attenuation length remained within range of SK-III and SK-IV values.

Another challenge with Gd loading arises with a property of gadolinium in that it promotes rusting in untreated metals. SK's tank and structure are both constructed of stainless steel which should resist this, however understanding the effect of gadolinium-doped water on its numerous other submerged components as well as long term exposure to stainless steel is crucial. EGADS sought out to be as close an analogue of SK as possible, even down to its stainless steel bolts. Gadolinium was first loaded into EGADS in 2014 and after two and a half years of running in

SK-Gd conditions with full Gd loading, the tank was emptied and the inner structure was inspected. No deterioration was found.

5. Preparation

To house the extensive SK-Gd water systems, a new cavern named Hall G was excavated in the Kamioka mine in close proximity to the SK experimental hall. The existing water systems were also modified to accommodate the new water treatment process.

In 2018 the SK tank was opened for maintenance for the first time in 12 years. As well as the installation of new Gd systems and general maintenance and cleaning of the detector carried out experimental collaborators, SK's tank was serviced by employees of the Mitsui Engineering and Shipbuilding company. It is crucial that, when Gd-loaded, SK's water must not leak from the tank into the surrounding environment. Following the 2018 maintenance, measurements indicated no detectable leak, with a limit of $< 15\,\mathrm{kgd}^{-1}$.

After refilling, a minor modification of the ID inlet pipes was required to prevent a convection pattern forming, disturbing the water in the tank. A remotely operated underwater drone provided by the Mitsui company was employed to fit diffusers to the pipes found at the bottom of the ID. This operation was the first use of drones to carry out maintenance in SK and prevented a long downtime that would be needed to drain the tank to fit the diffusers by hand.

6. Deployment and Validation

Initially planned for April 2020, the COVID-19 pandemic delayed the first Gd loading to July 14th, 2020 at 10:29. Gd-loaded water was pumped to the bottom of the tank at a rate of $60\,\mathrm{th}^{-1}$. To monitor the rise of the gd-water front, water was sampled each day at a range of heights throughout the detector and the conductivity was measured. Ultrapure water has low conductivity, but the presence of gadolinium sulphate significantly increases this so the conductivity of the samples can be used to differentiate between pure and gd-loaded water. As shown in figure 1, a clear Gd front was observed during loading, advancing at a rate of approximately $1.5\,\mathrm{md}^{-1}$, as expected. Gd loading concluded on the 17th of August, 2020 with no major issues.

Both during and after the loading, the concentration of $Gd_2(SO_4)_3 \cdot 8\,H_2O$ was accurately measured with an atomic absorption spectrometer (AAS) using water sampled at various positions throughout the tank, alongside the conductivity measurements. Once loaded, the average $Gd_2(SO_4)_3 \cdot 8\,H_2O$ concentration was found to be (114 ± 2) ppm, with uniformity throughout the tank. This confirmed the desired homogeneity and concentration of the Gd loading.

To further verify the presence of gadolinium sulphate at the expected concentration, the neutron capture time was measured using an Americium-Beryllium (AmBe) source embedded in a bismuth germanate (BGO) crystal. AmBe produces a 4.4 MeV gamma and a neutron when it decays. The gamma scintillates in the BGO crystal and the resulting scintillation light can be used to fix the neutron's emission time and tag the decay event. Neutron capture times were measured in November of 2020 using AmBe in various positions throughout the detector, an example of which is shown in figure 2. Fitting provides a neutron capture time of $(115 \pm 1)\,\mu$s which corresponds to a $Gd_2(SO_4)_3 \cdot 8\,H_2O$ concentration of (111 ± 2) ppm in agreement with the AAS measurements.

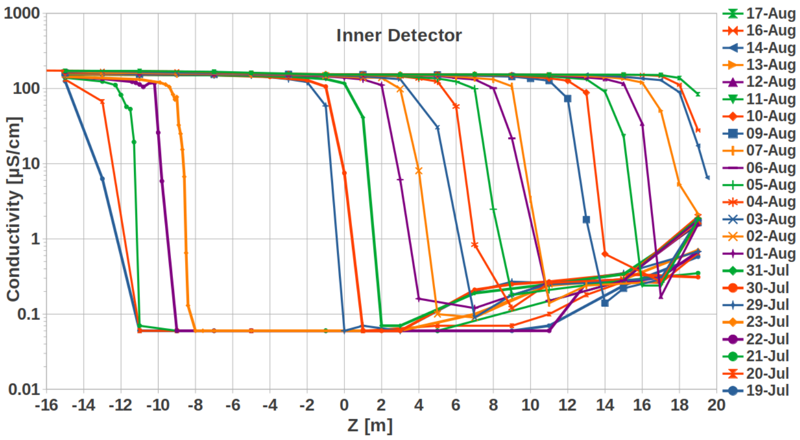

Figure 1: The conductivity of water samples taken at a range of heights throughout the SK ID over the course of Gd loading. The sampling system encountered issues between the 23rd and 29th of July.

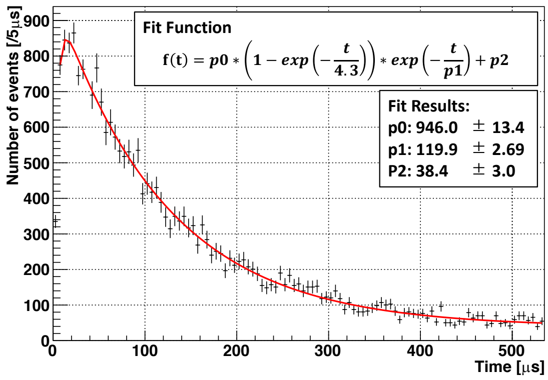

Figure 2: An example of neutron capture times and the resultant fit for 30 mins of AmBe calibration data with the source placed in the centre of the detector. Measurements were carried out for a range of source placements.

7. Summary and Future

After a long process of research and development, SK's water has been successfully doped with 0.02% gadolinium sulphate by mass to provide a clear neutron capture signal. This is the culmination of years of work, beginning with small scale experiments at UCI, expanding to the EGADS test detector before finally being deployed in SK. The Gd loading proceeded smoothly with AmBe calibration demonstrating the improved signal from neutron capture, and confirming the expected Gd concentration via the shortened neutron capture time in agreement with AAS measurements.

A wide range of analyses utilising neutron capture are now underway with vastly improved sensitivity, especially the attempted measurement of the DSNB and efforts to identify an increase in IBD rate corresponding to the restart of distant nuclear reactors. Additionally a pre-supernova early warning alarm is currently in its testing phase, based on work by C. Simpson *et al.* [7], which potentially offers warning hours ahead of a nearby supernova neutrino burst.

References

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