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SK-Gd looks forward

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From new electronics to changes in the PMT configuration, Super-Kamiokande (SK) has undergone several major phases along its history. The latest one, SK-VI, has been the dissolution of 13 tons of gadolinium sulfate octa-hydrate in the hitherto ultra-pure water. The goal of this new phase is to achieve a high neutron efficiency detection. This new capability allows to distinguish different neutrino reactions, enhance signals and remove backgrounds more efficiently. In fact, it has the potential to improve all analyses at SK. This new phase was preceded by the refurbishment of the detector in summer 2018 and then, the dissolution of gadolinium sulfate in summer 2020.

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1. Introduction

Super-Kamiokande (SK) is the running experiment of the Kamioka-saga. It started running in 1996 and as its predecessor, Kamiokande, it is a water Cherenkov detector. In its history it has undergone several changes and upgrades. The recent upgrade is a modification in the core of the water Cherenkov technology itself and SK does not contain just 50 ktons of ultra-pure water anymore. In 2020, 13 tons of Gd_2 $(SO_4)_3 \cdot$ $8H_2O$ (gadolinium sulfate octahydrate) were diluted. The motivation for this addition is the need of an efficient neutron tagging[1] which can be achieved by adding Gd: it has the largest cross section for thermal neutron capture. The neutron capture on Gd then produces a clear signal in the detector, a 8 MeV gamma cascade (to be compared to the 2.2 MeV single gamma when captured on a proton).

1.1 Physics

Adding an efficient neutron tagging to SK's toolkit will improve the selection of events in searches like the diffuse supernova background (DSNB), galactic core-collapse supernovae (SN) or reactor neutrinos. Here, the most important events are inverse beta decays (IBD): $\bar{\nu}_e + p \rightarrow n + e^+$. SK has searched for the DSNB but due to irreducible backgrounds it could only set limits, the best world limits. It is expected that effective neutron tagging will lead us to the discovery of DSNB[2, 3]. Without efficient neutron tagging the number of DSNB events was very small when compared to the background events but the detection of the prompt event followed by the spacial and timely close detection of the neutron, will largely cut the backgrounds. SK would easily detect a galactic SN even without neutron tagging as many events would be detected in a short time (about 10k events in about 10 seconds from a SN at the center of our galaxy). In this case, the benefit of neutron tagging comes from the increased amount of information at hand: the overwhelming number of IBDs (about 89% of the events) can be better distinguished from the far less numerous elastic scatterings (about 3%): $\nu + e^- \rightarrow \nu + e^-$, which carry information about the SN position in the sky. Thus, neutron tagging improves our SN pointing accuracy as well. By removing IBDs events when searching for the SN position in the sky, the pointing accuracy will be improved.

It also adds more information about the neutrino and the interaction type or energy[4]. Efficient neutron tagging can be used not only to look for signal events but also to reject background events. For example, in proton decay searches one of the most important backgrounds are atmospheric neutrinos interactions. These, often produce at least one neutron while most of the considered signals in proton decay searches do not (take as a reference the canonical mode $p \rightarrow e^+ + \pi^0$).

1.2 EGADS

The feasibility of diluting Gd was tested by mimicking the conditions in SK and were carried out in a dedicated facility for this purpose[4]: EGADS, for Evaluating Gadolinium's Action on Detector Systems, which features a 200-ton class detector with 200 PMTs and DAQ (now also running as an independent galactic supernova detector) and its own purification water system. Water transparency and Gd concentration were periodically monitored. Even with a concentration of 0.2% in mass of Gd sulfate octahydrate, the water transparency was keep to SK ultra-pure water levels, while the concentration was kept constant and homogeneous and no sign of negative impact

on the detector was seen. Different strategies on how to dilute and remove Gd were also tested at EGADS with the goal of using all this knowledge in SK.

1.3 Preparations in SK: towards SK-Gd

In preparation for this goal, in 2018, the SK detector was refurbished. This work included the cleaning of the detector walls and structures, fixing the previously existing water leak and the replacement of faulty PMTs both in the inner and the outer detector (ID and OD). Moreover, a new hall was excavated where a new water system installed. The in-tank piping was also modified in order to increase the total flow and to allow for an independent flow control between the ID and OD.

The first Gd loading goal for SK was set to load 0.02% in mass of Gd sulfate octahydrate. With this concentration, about 50% of the captures would be on Gd. In preparation, 13 tons of highly radio-pure Gd sulfate octahydrate, see figure 1, were acquired as well and screened in several laboratories: Kamioka (Japan), Canfranc (Spain) and Boulby (UK).

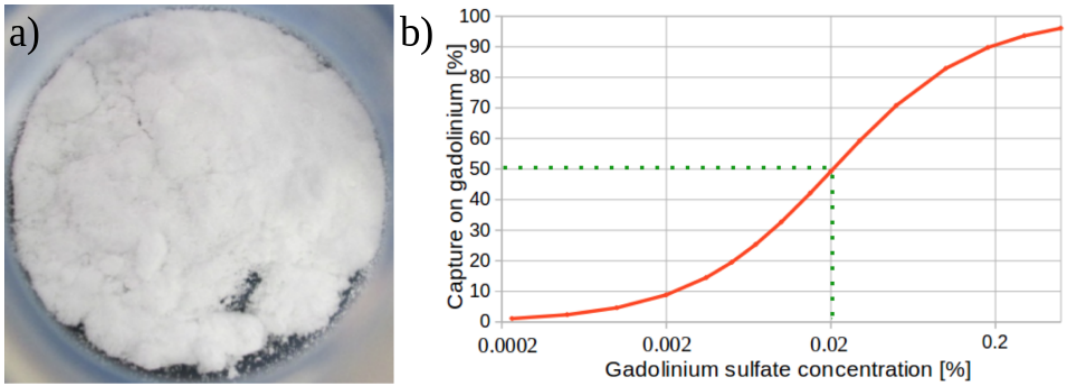

Figure 1: a) Sample of gadolinium sulfate octahydrate powder, b) fraction of neutrons captured on gadolinium as a function of gadolinium sulfate octahydrate concentration in water by mass.

Gd removal resins were also installed in a hall near SK ready for use in case of leak into the environment or any other problem at SK.

2. The beginning of a new era: SK-Gd

With everything in place and ready, Gd loading started in summer 2020. Pure water was drawn from the top of the SK tank, Gd sulfate octahydrate was dissolved to the goal concentration of 0.02% in mass and then injected back to the bottom of the SK tank.

Laminar flow was achieved through water flow and temperature control. This created two separated regions in the tank during injection: a Gd loaded in the lower region and a pure water upper region, the former gradually moving upwards at 1.5 m per day as water was being drawn from the top. Between these regions there was an intermediate layer of about 2 m. Within about 35 days, the Gd loading was finished.

3. Monitoring Gd concentration

During loading, the Gd concentration in the lower region, as well as the loading process (intermediate layer speed, thickness, etc and the Gd diffusion into the upper region) was being monitored[5]. The expected final Gd concentration was 110±1 ppm. After the loading, monitoring continued to check the final concentration, its homogeneity and stability. Two main methods were used: deploying an americium-beryllium (Am/Be) source and direct sampling in the detector.

3.1 Monitoring: Am/Be source

One of the main methods used an Am/Be source, see figure 2 a). This source was placed inside a bismuth-germanate crystal (BGO). Alpha particles from beryllium atoms are captured on americium which produces a 4.4 MeV gamma and a neutron. The 4.4 MeV gamma is converted into scintillation light by the BGO and the neutron can be captured outside the crystal.

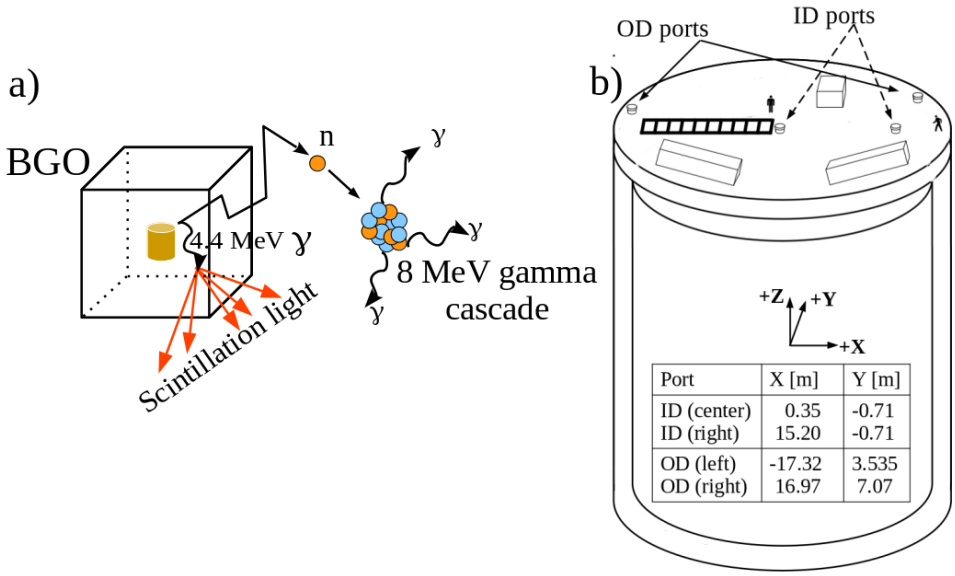

Figure 2: a) Schematic view of the Am/Be + BGO source and b) ports used for Gd concentration monitoring and SK coordinate system. The variable Z is the vertical distance from the center of the tank.

After detecting a prompt event, i.e. the 4.4 MeV converted into scintillation light in the BGO crystal, a search for a neutron candidate capture is done using a tight time and position coincidence between prompt and capture. The Am/Be source was deployed in the center port (see figure 2 b)) at three depth positions: Z=-12 m, Z=0 m and Z=+12 m. Figure 3 a) shows an example of the neutron candidate capture time distribution, i.e. time between the prompt event and the neutron capture candidate event. The function $f(t) = A(1 - e^{Bt})(e^{-t/C}) + D$ is then fitted and the constants extracted: normalization constant, neutron candidate thermalization and capture times and background level, respectively.

The relationship between neutron candidate capture time and the Gd concentration is extracted using a Geant-based MC, where the details of the experimental set-up are included. This relationship is shown in figure 3 b). The all-day average for the neutron candidate capture time is 116.2±0.4 μs.

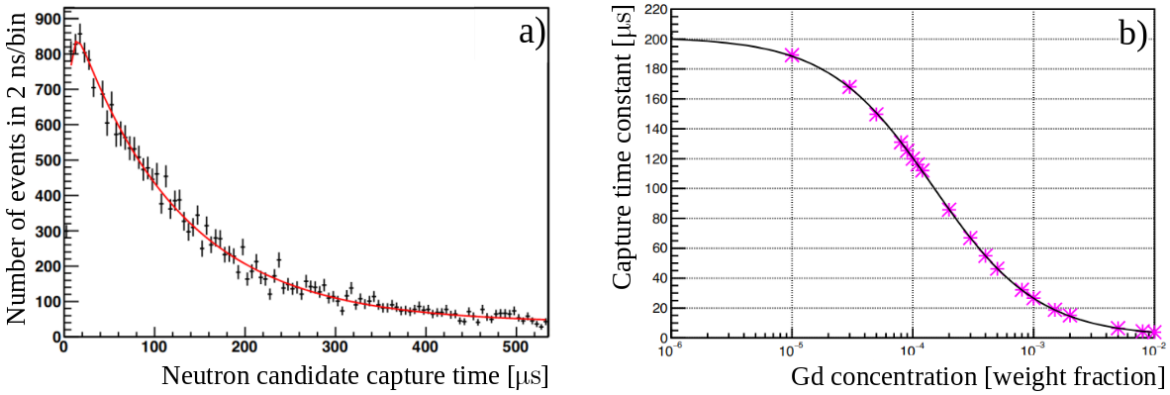

Figure 3: a) Example of neutron candidate capture time distribution, and b) relation between the neutron candidate capture time constant and the Gd concentration from MC (Geant4 based).

This converts into a Gd concentration of 105±2 ppm (where some potentially important systematic error contributions are not included).

Figure 4 shows the neutron candidate capture time as a function of the measurement date and for the depth positions Z=+12 m, Z=0 m and Z=-12 m. At the beginning of the Gd loading we see that in the middle and upper half of the detector the neutron candidate capture time constant were still very high (as expected for the basically pure water in that region) while in the lower half very soon reaches a similar value to the current one (the Gd loaded region). The capture times at different heights converge very quickly and the detector becomes homogeneous.

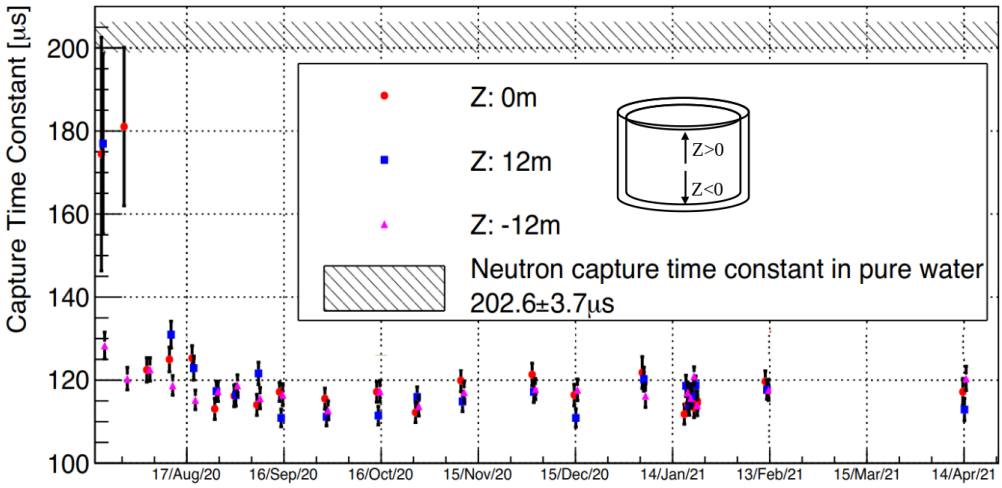

Figure 4: History of the measured neutron candidate capture time constant for the three Z positions in the tank: Z=+12 m, Z=0 m and Z=-12 m. The pure water capture time is about 205 μs (here shown as a band).

3.2 Monitoring: direct sampling

The other most important method to monitor the Gd concentration is the direct sampling in the detector. A sampling tube with a stainless steel tip to counteract the buoyancy of the tube is immersed in one of the ID or OD ports in 2 m steps (two ports in each region of the detector were

used to check possible discrepancies). A pump draws water up where flow, temperature and most importantly conductivity are measured, see figure 5. It also allows to take water samples which are later analysed with an atomic absorption spectrometer (AAS), a Hitachi polarized Zeeman AAS of the ZA3000 series, to measure the Gd concentration. The discarded water is then returned back to the water system.

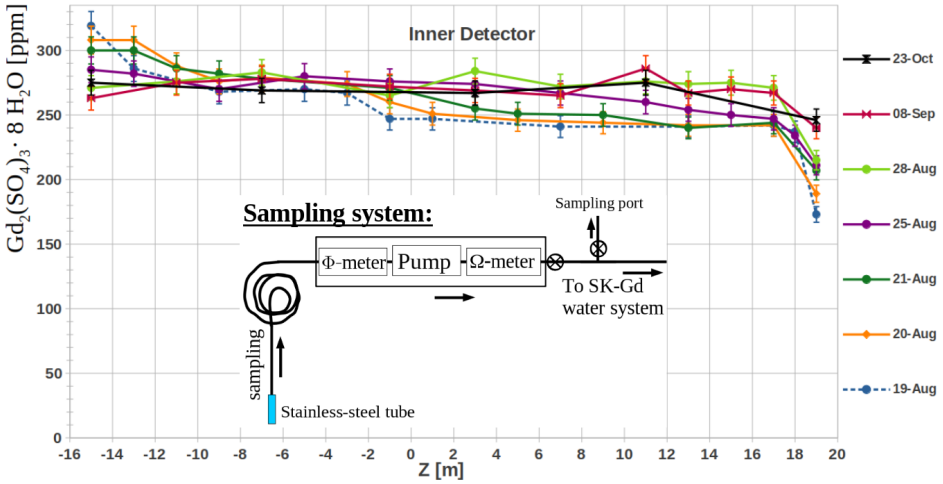

Figure 5: Gd sulfate octahydrate concentration as measured with an AAS and as a function of Z for different dates after Gd loading. It can be seen that, while at first the concentration is not homogeneous, with time, the differences level out.

The water system was designed to remove all impurities in water except for the recently added Gd sulfate. Therefore, virtually all ions in water are either Gd ions or sulfate ions and thus, conductivity is very well related to Gd sulfate concentration. Conductivity measurements were used to have a quick and indirect measurement of the Gd concentration inside the tank and at different positions and depths in the SK tank. In addition, AAS measurements were carried out for a direct measurement of the Gd concentration.

Figure 5 shows the Gd sulfate octahydrate concentration after the Gd loading was finished. While right after finishing the loading the concentration difference between to bottom-most measured position in the ID and the uppermost position is about 100 ppm, the difference flattens out later until achieving homogeneity throughout the detector. This can be seen in figure 6. The current Gd sulfate octahydrate average value is 271±4 ppm. The Gd concentration can be calculated from this value: 114±1 ppm (some errors sources like differences in hydration states in different Gd sulfate batches are not included).

4. SK-Gd next steps

At each step in the experimental path towards SK-Gd there was something to be learned. The first Gd-loading at SK was no less in this regard. As mentioned above, as each lot was delivered, they were screened in three laboratories: Cranfranc (Spain), Boulby (UK) and Kamioka (Japan). It was found that in the second half of the Gd-loading process, the ^{228}Ra concentration was higher. The reason for this was that the Gd sulfate powder feed-stock, Gd oxide, was of a different quality.

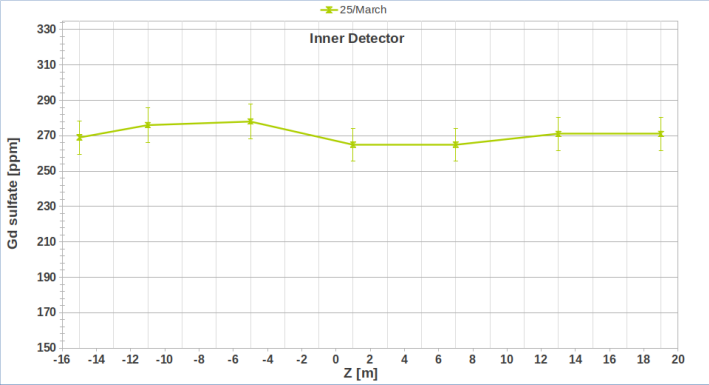

Figure 6: Gd sulfate octahydrate concentration in the inner detector as measured with an AAS in one of the latest samplings shows that the concentration in the SK detector became homogeneous. Also shown, the sampling system scheme: sampling tube, flow-meter, pump, conductivity-meter (also thermometer) and sampling port.

To improve the situation for the next Gd-loading, we have been working in two lines: search for a cleaner feed-stock and, together with the manufacturing company, improve the purification methods in the Gd sulfate powder production facilities.

The Gd-loading process itself needs to be improved. For the next stage a larger amount of Gd sulfate will be loaded and thus, it is needed to increase the loading speed. These include, from improving the packaging of the lots, so as to handle them easier and faster than before, to improving the facilities where they are fed in, diluted and finally injected into SK.

In the process of purifying the SK water, i.e. removing all impurities except Gd sulfate, custom modified resins are being used. After the Gd-loading, the production lines were discontinued and we have been working with companies to find a substitute product, which are being currently tested at EGADS.

Planning to add more Gd into SK means we must be ready to remove it. This means that more capacity to the current resin-removal facility must be added.

All the above improvements seem promising and therefore, we currently plan for a new Gd-loading in 2022. This time, we plan to dilute 26 ton of Gd sulfate octahydrate. This will make up 39 ton total. The production of Gd sulfate powder has just started. With a production about 3 ton/month we expect to start loading Gd again in May 2022.

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