Super-Kamiokande Prepares for Gadolinium Loading – Tank Open Work Following 12 Years of Continuous Operation

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Introduction

Located in the mine at Kamioka-cho, Hida-city, Gifu prefecture, Super-Kamiokande (Super-K, SK) started taking data in 1996. Using the data collected during its first two years of operation, ICRR Professor and Kavli IPMU PI Takaaki Kajita was awarded the Nobel Prize in physics in 2015 for the discovery of atmospheric neutrino oscillations [1]. Super-K is still producing high level results such as neutrino observations from outer space and accelerators [2], as well as studies on proton decay [3].

Following the successful completion of the R&D phase of the EGADS project [4], Super-Kamiokande is now being prepared for one of Kavli IPMU's flagship experimental initiatives: the enrichment of Super-K's 50,000 tons of pure water with 100 tons of gadolinium (Gd) sulfate [5-7] to enhance its detection performance for thermal neutrons and the electron antineutrinos which produce them. This future phase of operation has been officially designated SK-Gd.

As shown in Figure 1, the in-tank work began on May 31, 2018, after 12 years of continuous detector operation. There are four main tasks:
1) Fix a small water leak in the Super-K tank.
2) Replace the photomultiplier tubes that have failed (a few hundred out of 13,000) since the previous in-tank refurbishment in 2006.
3) Clean any rust and other dirt that has accumulated in the detector since its original completion in 1996.
4) Install additional water piping to increase the total water flow for increased water purification, and to enable better control of the flow direction in the tank.

In the middle of October 2018, we started to refill the detector with pure water. Now (in December 2018) we are finalizing the in-tank work–which has required a total of thousands of person-days of effort–to prepare the detector for the next phase of its long and productive life. In this article we will describe the eventful work that has taken place during the last half year and some of the new physics which awaits Super-K once Gd-loading is a reality.

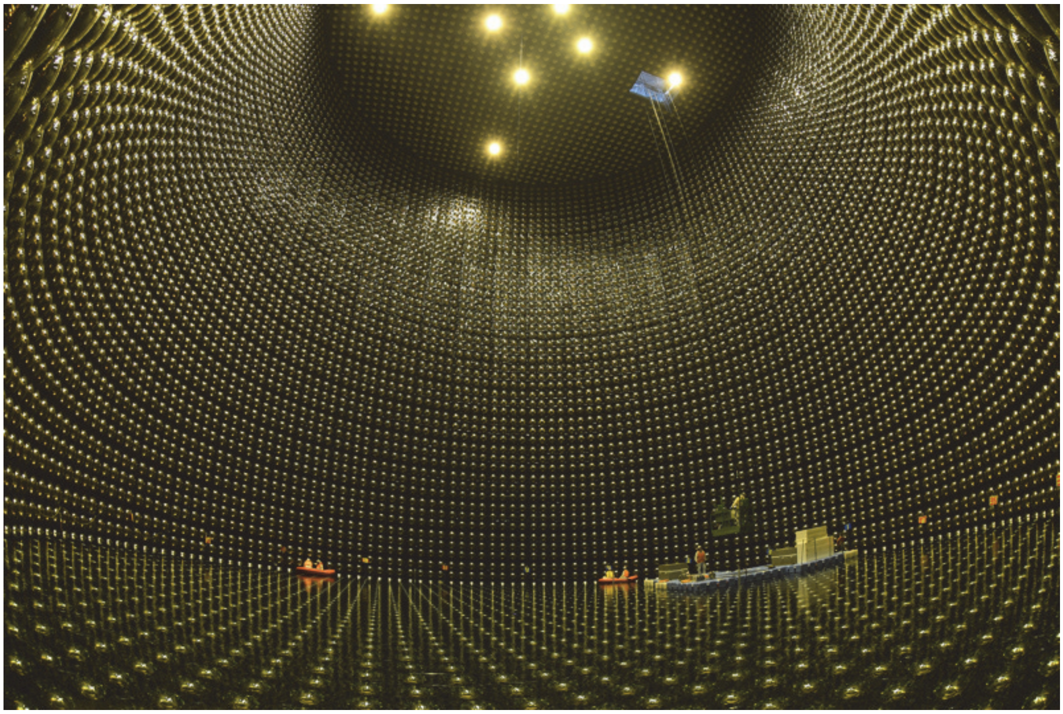

Figure 1: Working inside the Super-Kamiokande tank on August 18, 2018.

Physics targets of SK-Gd

The SK-Gd program is SK's upgrade plan that enables more efficient detection of electron antineutrinos through the delayed coincidence of signals of positrons and neutrons. Reines and Cowan first discovered the neutrino using this technique at a nuclear reactor [8]. They were using cadmium as a neutron capture nucleus, while we are using the much less reactive gadolinium just as recent nuclear reactor neutrino experiments employ it mixed into liquid scintillator [9]. At ~49,000 barns the thermal neutron absorption cross section of naturally occurring Gd is the largest of any stable element; after absorption a cascade of gamma rays are emitted with total energy of ~8 MeV, well above SK's energy threshold. Therefore, Gd-doping makes it possible to detect neutrons even in a water Cherenkov detector (Figure 2).

The ultimate goal of SK-Gd is the world's first detection of neutrinos from the all the past supernova explosions. These are known interchangeably as the Supernova Relic Neutrino [SRN] or the Diffuse Supernova Neutrino Background [DSNB]. In the universe there are $10^{22\text{-}23}$ stars. Stars with masses of more than eight times our sun are believed to end their lives in supernova explosions: these as-yet unobserved neutrinos must suffuse the universe. Observing the DSNB would lead to a deeper understanding of the energetics of supernova explosions, since 99% of the energy produced by the supernova explosion is released by neutrinos. Also, since the DSNB is the accumulation of neutrinos emitted from all of the supernova explosions that have occurred since the beginning of the universe, we can use their properties to explore the history of massive stars as well as the source of heavy elements.

Figure 3 shows the range of expected energy distributions of the DSNB. Naturally the exact shape is model dependent, but the intensity is roughly several/cm^2/sec. Therefore it is estimated that

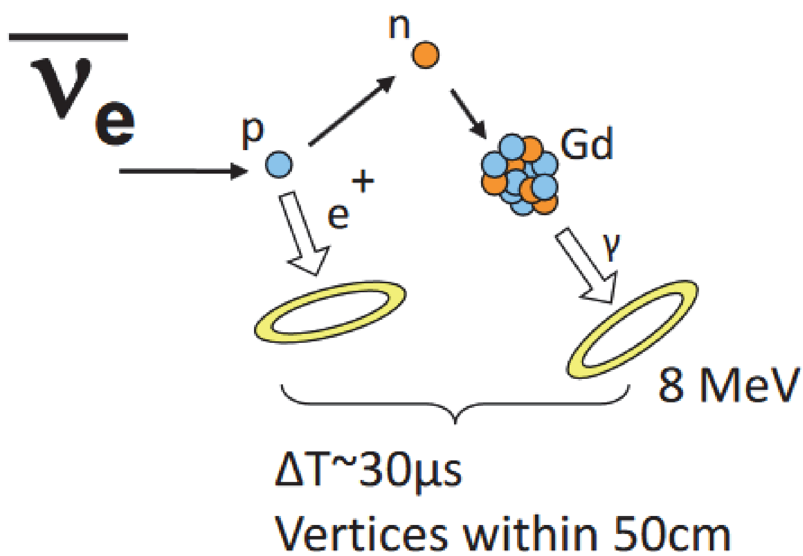

Figure 2: Principle of the delayed coincidence method with gadolinium for antineutrino detection.

verification of the DSNB flux will be possible with a significance level greater than three sigma within 10 years of observation.

For supernova explosions occurring in our galaxy, positive identification of electron antineutrinos via neutron tagging will improve the accuracy of directional determination to the supernova by allowing those neutrino events that do not preserve the directional information to be subtracted away. It has also been suggested that neutron detection could provide significant early warning–up to a week in advance–of very nearby explosions of very large stars [11]. In addition, the enrichment of SK's water with gadolinium is expected to enhance the sensitivity of virtually all of the measurements currently performed in SK, such as the Tokai-to-Kamioka long baseline neutrino oscillation experiment (T2K) and solar neutrino studies, as well as proton decay searches.

Open Tank work

Figure 4 shows the structure of the Super-K tank. Inside a cylindrical water tank, there is a stainless steel structure indicated by two parallel dashed lines supporting photomultiplier tubes (PMTs). The structure is two meters distant from the outer wall, bottom, and top of the tank. There are 11,129 inner detector (ID) PMTs and 1,885 outer detector (OD) PMTs mounted on the structure. On the inner surface of the support structure, spaces between PMTs are covered with black-colored PET sheets to suppress reflection of Cherenkov light. On the outer surface of the structure, white Tyvek sheets are used to enhance light-collection efficiency of OD PMTs. Since the sheets are loosely connected by staplers and pins, the water levels inside and outside are identical.

A so-called "floating floor" was used to work on the walls of the detector. During that phase of the refurbishment effort we drained two meters of water from the tank every three days, and worked to seal potential water leakage points on the outer wall as well as replace those failed PMTs which we could reach from the floor. This idea was originally provided by the University of Tokyo Professor Masatoshi Koshiba during the Kamiokande era; it is very beneficial in terms of cost savings when compared with assembling and working from standard scaffolding.

The Super-K tank is 40 m in diameter and 42 m in height and contains 50,000 tons of pure water. Its sides form an icosagon comprised of 400 pieces of four mm-thick stainless steel plates, each six

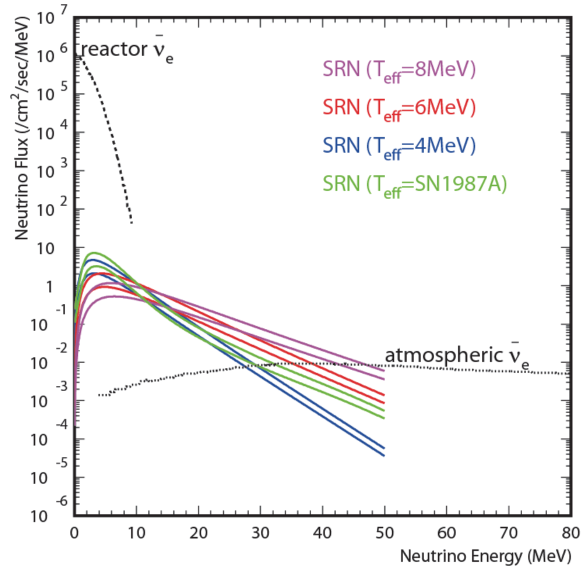

Figure 3: Expected energy spectra for the DSNB and other coincident events (reactor neutrinos and atmospheric neutrinos) [10].

meters wide and two meters tall. The bottom also consists of an assembly of stainless plates. The total submerged surface area is more than 6,000 m^2 and the total length of welding lines is more than 6.2 km. More than 3,200 bolts penetrate its sides. Given the complexity and size of the Super-K tank, therefore, it is not so surprising that there has always been a modest water leak; we observed about one ton of water leaking each day, corresponding to 700 cc per minute. This is not serious as long as we use only pure water. Although there is no official regulation regarding Gd-loaded water, it is necessary to stop the SK water leak to avoid release even in a case of a large earthquake. This is the first goal indicated in the introduction of this article.

To achieve a reliable leak fix, Super-K colleagues have developed a special sealant material. It needed to be soft, flexible, and able to stand an external stretching force. It had to meet requirements regarding small elution into water, low natural radioactivity, long-time stability during water exposure, and sufficient attachment strength to stainless steel plates. Another entire article could easily be filled describing the long and tireless efforts to realize this special sealant material and development of its primer.

Figure 5 shows the actual sealant work. Workers put thick tape along both side of the welding line to hold the sealant material on the line. They used trowels and paintbrushes to spread the sealant material over the weld with the same thickness as the surrounding tape. A double layer of sealant was required to allow for unexpected gaps or pinholes in one of the two layers.

There weren't any serious issues during the actual SK tank sealant work by company people since a mockup test had been done in advance in a high humidity environment. However, because of the cold temperature (~13 C) of the tank wall, stainless plates, and the solid rock behind them, we experienced condensation on the inner walls due to the warmer environment arising from the workers and lighting used inside the water tank. In the worst case the condensed water made it difficult to apply the thick tape. By trying various methods of ventilation and airflow, we finally overcame this problem.

Since the sealant material is produced by a special procedure, its viscosity tends to get lower as time goes by. Adequate viscosity was required for high-quality sealing work on the wall, avoiding dripping of the material. Because of this, careful arrangement of the detailed schedule of production, transfer, and consumption of the sealant was necessary.

Every time we drained the water, a team of 16

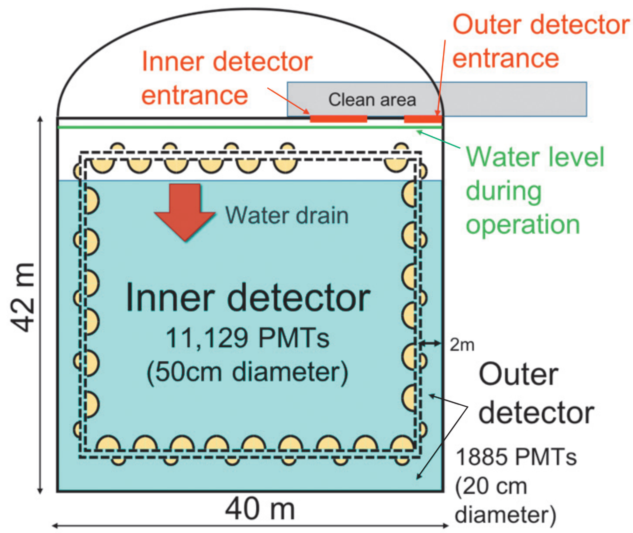

Figure 4: Structure of the Super-K tank. We drained two meters of water every three days in order to seal potential water leakage points as well as replace failed PMTs.

members cleaned up the wall, while 10 company employees sealed the welding line. We ultimately repeated this cycle 20 times.

The dirty wall and structures inside the Super-K tank required a large amount of human power to clean up. Since Super-K had been operated for the last 20 years, it was hard to know the situation in advance. In particular the top and outermost structures were covered by a heavy residue of exhaust gas and dust left over from the work in 1994 - 1995 during the detector construction. As for the cleaning tools, it was dangerous to choose arbitrary ones since most of them leave other types of dust which may then degrade the water target after restarting operation of Super-K. The water team tried, investigated, combined, and developed many kinds of cleaning tools; we found the cleaning itself was an important research topic.

Ultimately we maintained excellent quality of sealant attachment and removed a large amount of radioactivity; at least 100 Bq of radium was removed during the cleanup according to a measurement by a germanium detector. As the radon gas emitted from this radium is comparable to that arising from the PMTs themselves, the in-tank shiftworkers contributed to lowering the background for future solar neutrino observations.

As for the PMT replacement, we were required to work at full speed as soon as the tank was first opened since we could not delay the sealant work. In particular, US colleagues who were responsible to the OD PMT replacement performed admirably and completed all their jobs on time. ID PMTs are much heavier than the smaller OD tubes and their replacement requires a great deal of effort, especially as these inner tubes are encapsulated in anti-implosion covers made of FRP and acrylic to avoid a repeat of the chain reaction implosion that happened in 2001. Every time we replaced PMTs the tank needed to be closed and made dark inside so that we could test the newly-installed PMTs. The group in charge of DAQ and electronics then needed to come in early and complete the tests before the 8 a.m. start of that day's in-tank work.

We aimed to remove most potential sources of rust during the cleaning work. Though we are supposed to have only stainless steel parts inside Super-K, we sometimes found plain iron bolts and nuts covered by rust. We also found a clamp made of iron that had been immersed for 12 years inside the tank. Scratches on the stainless steel tank wall and support structure also had rusted during the long exposure to pure water. As much of this rust was removed as possible. Because rust was

Figure 5: Sealant work on the SK tank wall being conducted from the floating floor. An outer detector PMT can be seen at the right side.

a large concern before opening the tank, many young researchers investigated various tools and countermeasures from well before the work. We worked very carefully in order to achieve better water transparency and stable operations even after the loading of gadolinium sulfate.

Tyvek sheet installation on the side wall was another big job. The non-PMT area of the inner detector is covered by black sheets so that we can reconstruct events based on arrival time of photons, but the outer detector is covered by reflective white Tyvek sheets so that we can achieve higher detection efficiency for entering muons. One hundred twenty 40-meter long, one-meter wide sheets were pulled up using gondolas and adjacent Tyvek sheets were connected by staples. After the completion of sealing work on the bottom, we placed Tyvek sheets over the bottom stainless steel plates as well. A young Japanese researcher and US leaders worked together and completed the bottom Tyveking in a very short time. This cooperative work was necessary to avoid any damage of the recently-applied sealant.

The total shift count this summer was 2,683. Every day of the week except Sundays, 40 to 50 members worked on Super-K until the middle of September. These members include not only shift members, experts, managers, leaders, and company people. Shift members came from Super-K, T2K, and the Hyper-Kamiokande "proto-collaboration", involving researchers from all around the world. We appreciate the many volunteers who did not belong to any of these collaborations, but chose to help us anyway.

One of the challenges we faced involved the OD gondola due to its limited capacity. Though at least 30 members needed to enter the outer detector every morning, the single available gondola and its 300-kg capacity caused a long queue of workers. When we needed to work close to the bottom, it took 20 minutes for one round trip. It was like a puzzle to stagger the start time and end time of shift groups and car assignments to avoid interference with company people.

Since the first priority is always safety for workers, we made constant efforts to provide sufficient safety education, utilizing e-learning before their visits, and guidance just before staring their work. Efforts to improve the working environment also included listening to workers, and discussion at the daily morning meeting. We realized it was not sufficient to simply tell people not to cause any accidents; sharing information concerning potential dangers was also important.

Water systems and the future

In addition to the tank cleaning, leak sealing, and PMT replacement work, the SK water system

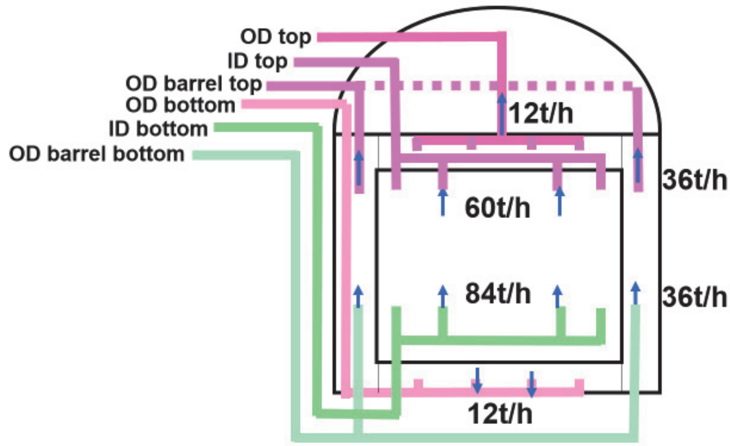

Figure 6: Improvement of plumbing for better water flow inside the tank.

including in-tank piping was totally redesigned this summer. The water purification system was originally designed with a supply and circulation capacity of 30 m^3/h, and the piping inside the tank was made without separate lines for the inner region and the outer region. During the previous SK reconstruction periods in 2001 and 2005 this interior piping was not substantially improved, even though the circulation rate was raised to 60 m^3/h from the middle of SK Phase III (SK-III). This time, as shown in Figure 6, we decided to improve the water flow in the tank by separating not only the pipes of the inner volume and the outer volume, but also the pipes on the side, top, and bottom of the outer volume so that all the flow rates can be adjusted independently. Up until now the effective detector volume for solar neutrino analysis has been limited by the inflow of background radon, but this plumbing improvement makes it possible to control and optimize the flow of water in the tank. The findings obtained through this upgraded system are also being applied to the design of Hyper-Kamiokande.

Incidentally, when the water level in the tank was lowered down to the surface of the bottom PMTs, we got a surprise. The 12 water inlets at the bottom should all be made of low background acrylic pipes, but we found that three of them near the center of the tank actually were made of conventional transparent polyvinyl chloride (PVC) tubes. In the analysis of SK-IV (which began in 2008), there are three event "hot spots" corresponding to the PVC pipe positions. Prior to this discovery various hypotheses have been discussed; perhaps the flow balance had been destroyed or some broken PMT glass which is a radon source became clogged in the plumbing. Now we know the answer: PVC containing lots of radioactive impurities was used. It seems that the three pipes broke during the accident in 2001 and were then quickly restored using material in hand at the time of the emergency repair work in 2002, but this was forgotten by the time of the full reconstruction work in 2005. We again realized the importance of recording, reporting, seeing, and checking.

Mixing gadolinium sulfate with ultrapure water easily produces a high purity gadolinium sulfate aqueous solution. However, since the SK water purification system is designed to remove all impurities from water, if gadolinium sulfate is dissolved and the system is operated as it is, the desirable ions will be quickly removed along with all the undesirable ones. Consequently, we had to develop a brand new purification system to keep only water, gadolinium ions and sulfate ions, and to remove all other impurities.

Details cannot be described here, but for the last few years small prototype systems have been evaluated and demonstrated. Based on these tests, a new system for SK-Gd was constructed in 2016. Commissioning this system has been conducted in parallel with the in-tank work. The new flow rate will be 120m^3/h, which is double the rate in SK-IV: another reason for the water pipes in the tank to have been upgraded.

Previous water fills have taken place at a rate of 30 m^3/h using the original SK water purification system; this took 2.5 months to fill the tank. As the water which had been fed to the tank was never circulated and repurified until after the tank became full, it took another two months or so after the tank was full before the water quality improved to the point that useful data could be collected. This time, the new SK-Gd water system is to be temporarily operated as an ordinary water purification/ recirculating system by installing conventional ion exchange resins made for producing ultrapure water into the modules in the system. This special operation should make it possible to start observations as soon as the tank is filled. Then, the resins in the new system will be replaced with the ones safe for use with a gadolinium sulfate solution. The new system will be operated with pure water at first; the start of SK-Gd, i.e., the introduction of the gadolinium sulfate, is planned during the 2019 fiscal year taking into account the running schedule of the T2K experiment.

Toward the next step

During the tank open period, we had to stop shift work three times since the access road to Super-K was closed due to heavy rain or typhoon. A more serious but related issue is the danger of damaging the Super-K tank itself due to an extended power failure when the tank is not full. Since Super-K is located below the water level in the mine, we continuously drain the water surrounding the Super-K tank through the spiral tunnel providing access to the bottom of the tank. If the power line for these pumps is cut due to bad weather and the tank is partially empty, it may result in the destruction of the Super-K tank from rising external water pressure. To cope with this situation, we prepared an independent power line, a power generator, and a method of gaining emergency entrance into the mine. Though we had already filled up most of the water by December 2018, we still hope that no power failure due to heavy snow happens. After some final in-tank work in December and January 2019, we will close the tank, and then can finally start a new phase of operation, Super-K-V.

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