Introduction of Gadolinium into Super-Kamiokande and the Start of New Observations

August 21, 2020
Super-Kamiokande Collaboration

The rare earth element gadolinium has recently been introduced into the Super-Kamiokande (SK) detector, starting a new period of observations. The addition of gadolinium improves SK's ability to observe the sea of neutrinos, known as "supernova relic neutrinos", produced by supernova explosions that have occurred since the beginning of the universe. In addition, gadolinium will improve SK's ability to observe the burst of neutrinos from any supernovae occurring in our galaxy and will improve its other research topics, such as the discrimination of atmospheric neutrinos from antineutrinos and the observation of manmade neutrinos. This release explains the details of the recent gadolinium loading in SK.

[Super-Kamiokande detector]

The SK detector is a 39.3 m diameter by 41.4 m tall cylindrical tank filled with 50,000 cubic meters of water and located 1,000m underground in the Kamioka mine in Hida City, Gifu Prefecture, Japan. Super-Kamiokande detects neutrino interactions in the water using about 13,000 optical sensors (see Figure 1). The detector has been used to study the nature of atmospheric, solar, and manmade neutrinos, including the neutrino oscillation phenomenon, since 1996.

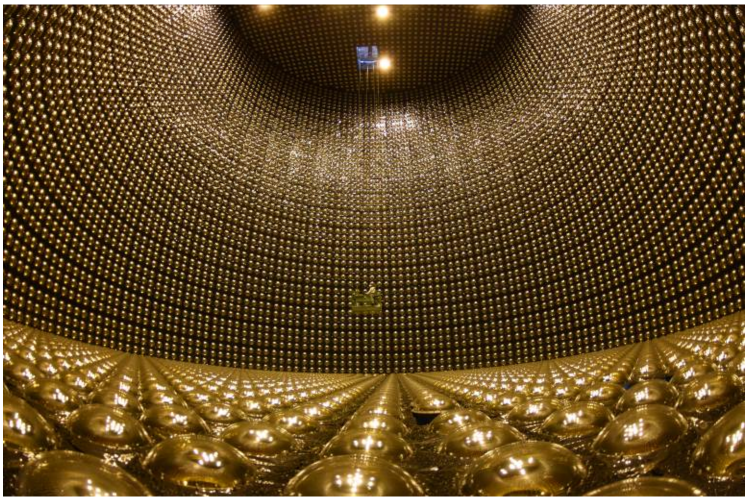

Fig.1 Super-Kamiokande detector

[Neutrinos from supernova explosions]

Supernova explosions occur when stars more than 8 times more massive than the sun reach the end of their life and are among the most energetic phenomena in the universe. The energy released during just the first 10 seconds of a supernova explosion is equivalent to 300 times the total energy released from the sun over its entire 10-billion-year lifetime. About 99 % of the supernova's energy is emitted as neutrinos and the remaining 1% is spent on energy that breaks the star apart. Light produced in the explosion accounts for only 0.01% of the total energy. Accordingly, neutrinos carry much more information than light about the nature of these explosions.

To date supernova neutrinos have only been observed once, following the explosion of SN1987A in the Large Magellanic Cloud. Super-Kamiokande's predecessor, the Kamiokande experiment, detected 11 neutrino events at that time. Although the number of observed events was small, they were sufficient to demonstrate that the estimated total energy and duration of the burst (about 10 seconds) are consistent with the basic theoretical mechanism of supernova explosions.

Understanding supernova explosions is ideal for verifying the basic laws of physics because the mechanism convolves the behavior of matter at ultra-high densities with general relativity. Though astrophysicists use the latest available data to simulate supernova explosions, a satisfactory understanding of the explosion mechanism is still lacking. For this reason, more neutrino data are necessary. Super-Kamiokande's volume is about 15 times larger than that of Kamiokande and accordingly, SK expects to observe many more neutrino events (roughly 8,000) from a galactic supernova. Such an observation would contribute significantly to elucidating the explosion mechanism. However, supernova explosions in our galaxy are thought to occur only once every 30~50 years, so perhaps only one or two can be observed while SK is running. In order to get more information about supernova explosions it is therefore important to study those occurring in galaxies far from the Milky Way.

[Searching for supernova relic neutrinos]

There are hundreds of billions of galaxies in the universe and it is thought that there are supernova explosions happening somewhere in the universe every second. Since neutrinos are emitted in all such supernova explosions, they diffuse out into and accumulate in the universe (Figure 2). These neutrinos are called "Supernova Relic Neutrinos" (SRN) or the “Diffuse Supernova Neutrino Background”. According to theoretical calculations, there are thousands of these neutrinos or more passing through an area the size of a human hand every second. This corresponds to several neutrino interactions in the SK tank each year. Though such interactions have been occurring inside the SK detector since its observations started, they were indistinguishable from noise and could not be identified until now.

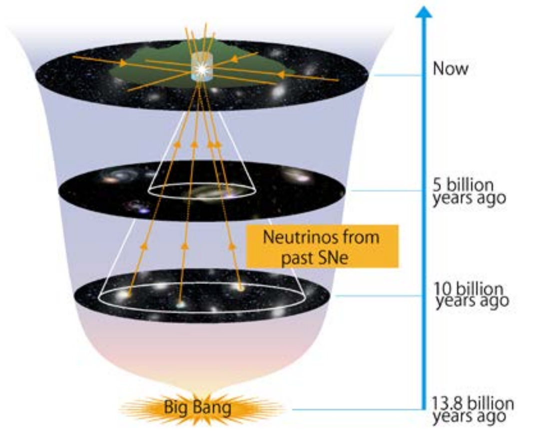

Fig.2 Supernova Relic Neutrinos

All types of neutrinos (electron-type, muon-type, tau-type and their anti-particles) are produced in supernova explosions. Anti-electron neutrinos are most reactive with the water in the SK detector, interacting with a proton, the hydrogen nuclei in H_2O, to produce a positron and a neutron. Until now SK has searched for SRN using only the positron information since the neutrons could not be detected easily. As a result, the search sensitivity was limited by the tens of thousands of cosmic ray and solar neutrino interactions that produce a similar signal and thereby drown out the few SRN events expected each year.

[Improved observations with gadolinium]

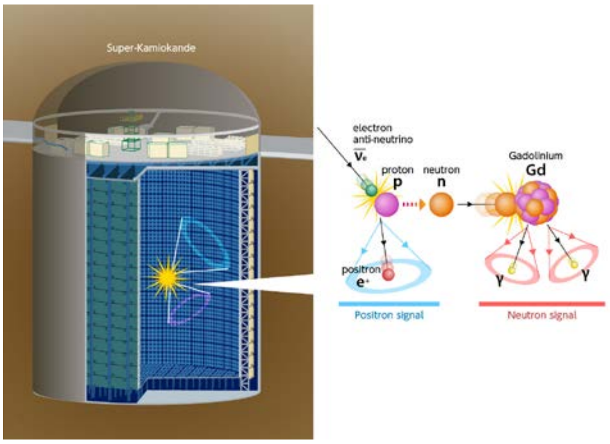

Fig.3 Anti-electron neutrino interaction and the expected signals in the Gd-loaded SK tank

Gadolinium (Gd) is a rare earth element and has the highest affinity for capturing neutrons among all elements in nature. With the addition of gadolinium to the SK water, neutrons generated by SRN interactions are captured by Gd, producing observable gamma rays as shown in Figure 3. This creates a characteristic signal in SK that can be used to identify SRN events. First, Cherenkov light from the emitted positron is seen within the tank and then a fraction of a millisecond later Cherenkov light from the gamma rays is observed within about 50 cm of the same location. Since noise events rarely mimic this kind of signal, it's possible to isolate the SRN events. This is the reason that Gd is being added to SK. Even with only a 0.01% concentration, 50% of neutrons will be captured by Gd and this number becomes 90% with a 0.1% concentration.

What can be learned when SRN are observed? Observing SRN will allow for the study of general features of supernova explosions because the neutrinos from a large number of supernovae contribute to the SRN arriving at SK now. Further, if the energy spectrum of SRN can be measured then the history of supernova explosions can be studied and used to understand when most supernova explosions occurred during the history of the universe. During a supernova explosion the core of a massive star collapses due to gravity and in some cases a black hole is formed, preventing light from being emitted. However, even in this case theory predicts that a large number of neutrinos will still be emitted. Therefore, comparing the intensity of the observed SRN signal with the frequency of optically-observed supernovae provides information about the rate at which black holes are created, further enhancing our understanding of supernovae. Finally, many of the elements around us are thought to have been created during fusion reactions within massive stars, during supernova explosions, and during the merging of neutron stars (high-density celestial bodies formed after some supernova explosions). Understanding supernova explosions will therefore advance our understanding of how elements are produced in the universe.

[Gadolinium and its safe handling]

Gadolinium (Gd) is a rare earth element with atomic number 64. In addition to having a large affinity for capturing neutrons (large capture cross section), Gd has a large magnetic moment and is used as a contrast agent in MRI (magnetic resonance imaging) scans. It exists naturally in Japanese soil at a concentration of about 3 to 7 ppm. Though there are no environmental regulations for Gd in Japan, since the natural concentration in the Jinzu river near SK is small, only 4~10 ppt downstream of Kamioka city, Gd in SK should be handled carefully. The SK tank was refurbished in 2018 for this purpose. Prior to this refurbishment SK leaked about one ton out of its 50,000 tons of pure water each day, so a waterproofing agent was applied to all weld joints of the stainless steel panels that form the wall of the tank (Figure

4). Since then no significant leak has been observed and the detector is now continuously monitored to ensure there is no leak of Gd-loaded water to the environment.

[Introduction of gadolinium]

Following the refurbishment of the SK tank in 2018 it was filled and operated with pure water until February 2019. During this period the original SK water system was used to circulate and purify the water. At the same time a separate purification and circulation system was developed to handle Gd-loaded water. This new system has been shown to provide the same level of purity and transparency as the original system, while allowing Gd to remain dissolved in the SK water. The most important element in the new system is a special ion exchange resin that was jointly developed by the University of Tokyo and the Organo Corporation to remove all ionic impurities in the water except those related to Gd, Gd^{3+} and SO_4^{2-}.

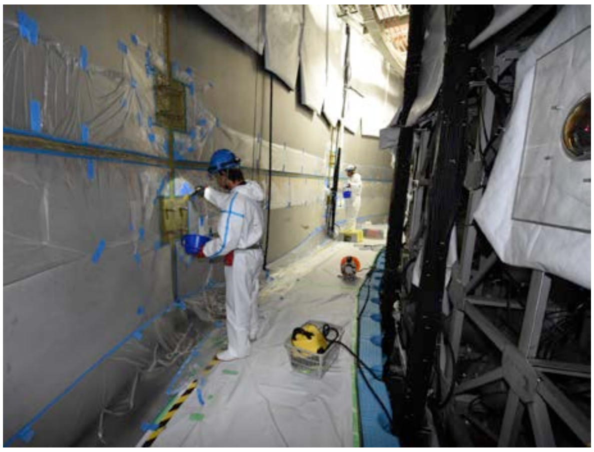

Fig.4 Tank refurbishment work in 2018

For the first run period with Gd, 13 tons of gadolinium sulfate octahydrate ($Gd_2(SO_4)_3 \cdot 8H_2O$) have been introduced into the SK tank. This corresponds to a 0.026% concentration of $Gd_2(SO_4)_3 \cdot 8H_2O$ by weight dissolved in 50,000 tons of pure water, which is equivalent to a 0.01% concentration of Gd by weight. In order to preserve Super-Kamiokande's ability to make precise measurements of solar neutrinos the gadolinium sulfate was developed in collaboration with Nippon Yttrium Co., Ltd. to have extremely low levels of radioactive impurities.

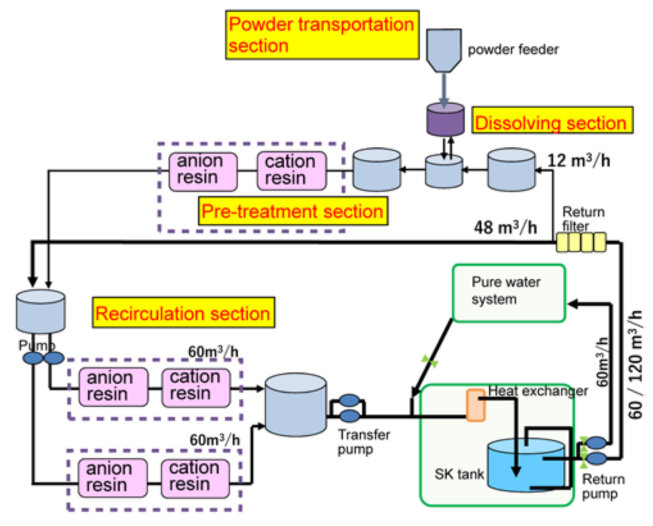

Fig.5 Gadolinium water system

Gadolinium is loaded into SK using the system shown schematically in Figure 5. A photo of the actual system is shown in Figure 6. Pure water is sent from the SK tank to the Gd-loading system at a flow rate of 60 tons/hour. The flow is separated into two streams, one for pure water, which operates at 48 tons/ hour, and another flowing at 12 tons/hour in which $Gd_2(SO_4)_3 \cdot 8H_2O$ is dissolved. The gadolinium compound is a white powdery substance (Figure 7), which is measured by the powder feeder (Figure 8 left) before being sent to the cavitation pump for dissolution (Figure 8 right). The compound is dissolved while circulating at high speed within the dissolution tank. This results in a 0.13% $Gd_2(SO_4)_3 \cdot 8H_2O$ solution, which is then purified in the "pre-treatment" section of the system. The ion exchange resin described above is the most important element in the pretreatment section.

Fig.6　Gadolinium water system

The 0.13% $Gd_2(SO_4)_3 \cdot 8H_2O$ solution is then merged with the 48 tons/hour pure water stream to make a 0.026% $Gd_2(SO_4)_3 \cdot 8H_2O$ solution, which is then sent to the SK tank using the "recirculation" section. The recirculation section continuously recirculates the SK water after the Gd loading is completed. This system's elements are the same as those in the pre-treatment section but are greater in number to handle the increased water flow.

Fig.7　Gadolinium sulfate octahydrate ($Gd_2(SO_4)_3 \cdot 8H_2O$)

Fig.8　Powder feeder (left) and cavitation pump for dissolution (right)

Gadolinium loading started on July 14th, 2020. As shown in Figure 9, pure water was sent from the top of the SK tank to the Gd-loading system and water containing dissolved Gd was sent to the bottom of the tank. Prior to initiating the Gd loading, the SK water temperature was raised by about 0.3℃ using the pure-water recirculation system. When supplying Gd water, however, its water temperature was kept about 0.3℃ lower than that of the tank water. Due to this temperature difference Gd-loaded water gradually fills the tank from the bottom as shown in Figure 9 and allows Gd to be completely loaded in about one 35-day recirculation cycle.

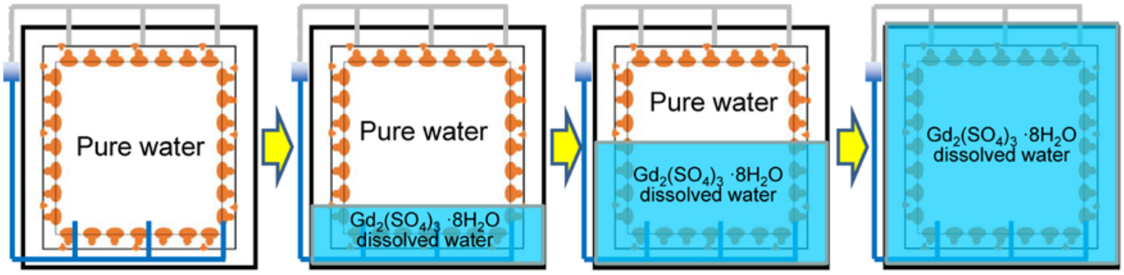

Fig.9　Gd-loading scheme

Figure 10 shows the cumulative amount of $Gd_2(SO_4)_3 \cdot 8H_2O$ added over time. The straight line indicates that the loading has been very stable during the loading period. On August 17th the Gd loading was completed. Figure 11 shows how the Gd concentration in the tank changed daily, indicating that the Gd filled the tank gradually from the bottom to the top of SK, as expected.

【Future plans】

The first stage of Gd loading described here resulted in a Gd concentration of 0.01% and a neutron capture efficiency of 50%.　Over the next few years the Gd concentration will be increased, enabling the first ever observation of supernova relic neutrinos within seven or eight years.

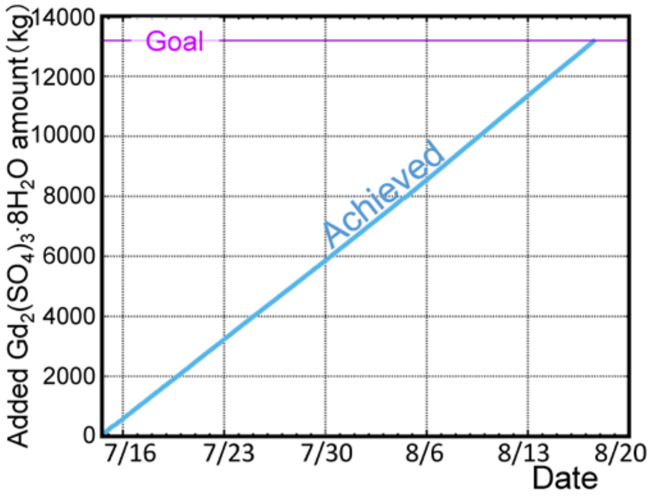

Fig.10 Cumulative amount of $Gd_2(SO_4)_3$·$8H_2O$ added over time

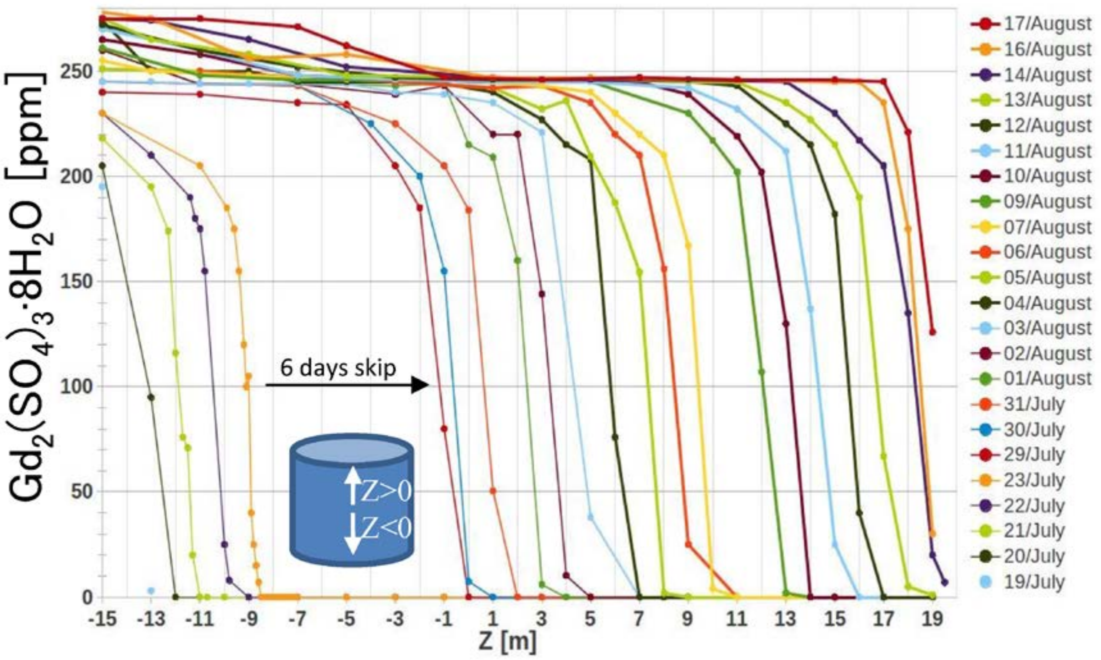

Fig.11 $Gd_2(SO_4)_3$·$8H_2O$ concentration in the tank changed daily