The Super-Kamiokande Gadolinium experiment

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1 Introduction

Super-Kamiokande (Super-K) is a water Cherenkov detector (see Figure 1) located in a mine at Kamioka-cho at 1000 m (2700 m water equivalent) below the top of Mt. Ikenoyama in Gifu prefecture, Japan. Super-K has been in operation since April 1996, and is currently in its fifth data-taking period (see Table 1). It has produced major physics results among which the discovery of the atmospheric neutrino oscillations [2] after two years of data taking, for which Takaaki Kajita was awarded the Nobel Prize in physics in 2015. Super-K covers a wide range of neutrino physics such as solar neutrinos [3], searches for proton decay [4], dark matter-like particles [5] and supernova relic neutrinos [11] etc. Recently, the discovery of gravitational waves has sparked significant interest in looking for the neutrinos emitted by compact object mergers[6]. The up to date list of publications is available online [7]. In spite of the large success of the experiment, some analyses are still limited by statistical uncertainty, and would benefit from increasing exposure. Other analyses suffer from background contamination, as in the case of the supernova relic neutrino search, and would benefit more from the development of new background suppression techniques. The proposed introduction of gadolinium (Gd) ions into the water tank of Super-K, results ultimately in higher than 90% efficiency of free neutrons capturing on the Gd, giving a handle on antineutrinos acting via inverse beta decay, and possibly a method of background reduction for many studies. Hence, in the coming years, the physics potential of Super-K with Gd is thus expected to be largely improved with respect to the current situation.

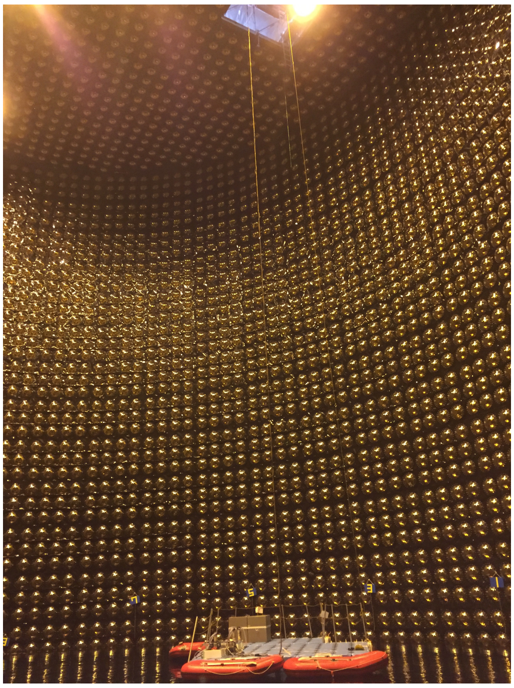

Figure 1: The inner detector of Super-K during the tank open work in July 2018.

2 Super-Kamiokande detector

Super-Kamiokande [8] is so far the largest pure water Cherenkov detector ever built. It consists of a cylindrical stainless tank structure containing 50 kilotons of ultra pure water. The water tank is 39 m in diameter and 42 m high and is divided into two regions by the detector structure: the inner detector (ID) corresponding to a cylinder with a diameter of 33.8 m which contains 32 kilotons of water (for 22.5 kilotons fiducial), and the outer detector (OD) separated by the detector structure supporting photomultiplier tubes (PMTs). The ID serves as the target of interactions and is instrumented by 11129 inward-facing 20-inch PMTs (see Figure 1) while the OD is used to veto external cosmic ray muons and is equipped with 1885 outward-facing 8-inch PMTs. On the inner surface of the support structure, spaces between PMTs are covered with black-colored PET sheets to suppress reflection of Cherenkov light created by charged particles interacting with the water. 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 and hence the ID and the OD just define two optically separated regions. The different phases of the Super-K experiment are summarized in Table 1. The detector was upgraded with improved electronics in the summer of 2008. The period after this upgrade is referred to as SK-IV and ended in May 2018 to refurbish the detector toward the next project of Super-K (SK-Gd) which is planned to start in early 2020. This refurbishment work, which lasted eight months, allowed to replace broken PMTs in both ID and OD, to install the water piping line of the new water system for SK-Gd, and to stop water leak from the tank by sealing the stainless steel wall. The on-going phase, SK-V, which followed the refurbishment work, recovers the same level of water transparency as before (i.e more than 100 m). The next phase, scheduled late 2019 or early 2020, will be doping the water with a water-soluble chemical compound of Gadolinium [$Gd_2(SO_4)_3$ simply referred as Gd in this document]. The Super-K collaboration took that decision after the good results (no loss of water transparency etc.) obtained with EGADS[1], a small SK-GD demonstrator with a water tank volume of 200 m^3 doped with 0.2% Gd, built in 2013, and tested successfully these last years. As a first step, 0.02% of Gd (10 tons) will be dissolved in the Super-K tank in 2020 and under this condition, the performance of the detector will be evaluated and the background level estimated. The current schedule estimates that Super-K will be stable and ready to take physics data in late 2020. In a second step, not yet scheduled, up to 0.2% (100 tons) is expected to be dissolved.

Phase	**SK-I**	**SK-II**	**SK-III**	**SK-IV**	**SK-V**	**SK-Gd**
Period	Apr 1996-Jul 2001	Oct 2002-Oct 2005	Jul 2006-Aug 2008	Sept 2008-May 2018	Jan 2019-?	2020?-?
Photo coverage	40%	19%	40%	40%	40%	40%
Electronics	ATM	ATM	ATM	QBEE	QBEE	QBEE
Live days	1489.2	798.6	518.1	3244.4	on-going	?

Table 1: The different data taking periods of Super-Kamiokande experiment.

3 Physics potential with Gadolinium

3.1 Improved neutron tagging efficiency

Many analyses in Super-K involve the Inverse Beta Decay (IBD) channel $\bar{\nu}_e + p \rightarrow e^+ + n$ (either as signal or as background), producing in the final state a positron and a neutron. Super-K does not have the ability to distinguish an electron from a positron, and hence, the distinction between IBD and beta decay only relies on the detection of the neutron in coincidence with the emission of the Cherenkov light produced by the positron/electron. Currently, the neutron is captured mainly by free protons, which result in the emission of a 2.2MeV gamma ray 200 microseconds later. This large delay between the capture and the signal as well as the low energy of the associated gamma rays makes this process particularly difficult to detect and hence, the currently neutron tagging efficiency in Super-Kamiokande is less than 20%. Therefore, J. F. Beacom and M. R. Vagins suggested in [12] to dope the water with Gadolinium whose cross section for thermal neutron capture is 49000 barn, versus 0.3 barn for free protons. In addition, after the absorption of the neutron, a cascade of gamma rays is emitted with total energy of about 8 MeV, well above SK's energy threshold making the detection easier. The coincident detection of a positron's Cherenkov light, followed shortly thereafter in roughly the same place by a shower of gamma rays (the delay between the Cherenkov light and the gamma cascade is on average

[1]EGADS stands for Evaluating Gadolinium's Action on Detector Systems.

30 μs, the two vertices being spaced by less 50 cm, within the vertices position resolution of Super-K) will serve to positively identify $\bar{\nu}_e$ from IBD in the detector. With a concentration of 0.02% (in mass) corresponding to the first phase of the SK-GD program, the neutron will be captured by Gd in 50% of the case while with the final target of a 0.2% concentration, the capture efficiency raises to 90%. Assuming the detection efficiency of the photons from Gd to be 90%, an overall neutron tagging efficiency of 80% is then expected. These numbers have been checked experimentally in EGADS using a neutron source of Am/Be where with a concentration of 0.2% of Gd, the neutron capture efficiency was measured to be (85.3 ± 0.3)%[13].

3.2 Search for Supernova Relic Neutrinos

In February of 1987, the Kamiokande detector (with IMB and Baksan detectors) were the first experiments to detect neutrinos from a supernova burst. Since then, no supernova explosion has occurred in or near our galaxy. Supernova explosions provide a huge source of neutrino flux, neutrinos carrying about 99% of the binding energy released during the collapse of the star. Even if in our galaxy, they may be fairly rare (current estimation is about three per century), it is estimated that about 10^{17} supernova explosions have occurred over the entire history of the universe, yielding about one supernova explosion every second somewhere in the universe. The low energy neutrinos (typically below 100 MeV) emitted from these past and present events have suffused the universe, with a flux estimation of about few tens/cm^2/sec [9]. This so-far unobserved neutrinos flux is usually referred as the Supernova Relic Neutrinos (SRN) also known as the Diffuse Supernova Neutrino Background (DSNB). Its detection would provide important insights into cosmology, the history of star formation, nucleosynthesis, and stellar evolution. Furthermore, the study of supernova bursts, which produce and disperse elements heavier than Helium, is vital to understand many aspects of the present Universe. Detection of the SRN would also be the first detection of neutrinos from significant redshifts $z > 1$, and the second detection of supernova neutrinos. The SRN flux is proportional to the rate of all core-collapse supernovae, including optically dark "failed" supernovae that collapse to form black holes, a phenomenon that has not been observed yet. The SRN spectrum shape would also provide a crucial calibration for numerical supernova models.

Supernova bursts generate all types of neutrinos, however, because of their larger cross section with water, electron anti-neutrinos are the most copiously detected neutrinos in a water Cherenkov detector like Super-K. About 88% of the detectable supernova neutrino events are IBD and thus the search for SRN will clearly benefit from the SK-Gd phase. Super-K has previously carried out searches for SRN from the expected positrons detection (through the emission of the Cherenkov light) without requiring the detection of a delayed neutron and only a integral flux upper limit was set (current best limit) for neutrinos energy threshold $E_{\bar{\nu}_e} > 17.3$ MeV [10]. Since the detector couldn't directly differentiate electrons from positrons, these searches suffered from background of electrons and positrons explaining such a large threshold. However, the current limit of flux is 2 to 4 times larger than the theoretical predictions [14] making realistic the discovery of SRN in the next years if we manage to suppress some backgrounds, as expected with the detection of both the positron and the neutron in coincidence.

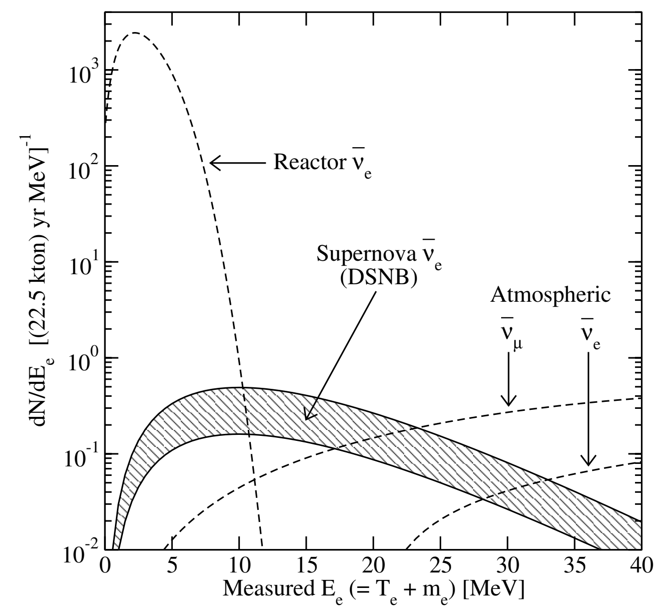

Figure 2: Spectra of low energy $\bar{\nu}_e + p \rightarrow e^+ + n$ coincident signals in Super-K. From [12].

A first attempt was made in Super-K in which the neutron was tagged by its capture on hydrogen [11] but it did not improve the SRN limit because it suffers from a low tagging efficiency of about 18% leading to poor statistics. Figure 2, shows the energy spectra expected in Super-K for the main reactions producing in coincidence a positron and a neutron [12]. The SRN signal would be visible in the positron energy range about 10 to 30 MeV. In this energy range, the largest backgrounds comes from the decay of invisible muons, i.e., nonrelativistic muons produced from atmospheric ν_μ and $\bar{\nu}_\mu$ and the decays of spallation products of cosmic-ray muons. With the SK-Gd phase, decays of invisible muon would be reduced (suppressing the contribution from ν_μ) and spallation products not producing neutrons can be strongly reduced, reasonably opening up the energy range between 10 MeV and 30 MeV for SRN search. According to the various existing models, SK loaded with Gd would measure 3 to 5 SRN antineutrino events per year [15]. Figure 3 shows the expected number of events after 10 years of data-taking in SK-Gd. The SRN signal (several models are shown) is clearly seen above the background in the energy range 10-30 GeV. Hence, the world's first observation of the SRN by Super-K is expected in the next decade. Note however, that a non-detection would require novel stellar or neutrino physics, for example, a change in the equation of state, extremely fast rotation, invisible neutrino decays on cosmological scales, or the effect of hypothetical particles on the emission model of supernovae [14]. SRN search will thus ce a "no-lose" analysis.

3.3 Other physics analyses

Even if the observation of the SRN is the main motivation for Gd-loading, the neutron tagging will lead to other analyses improvements.

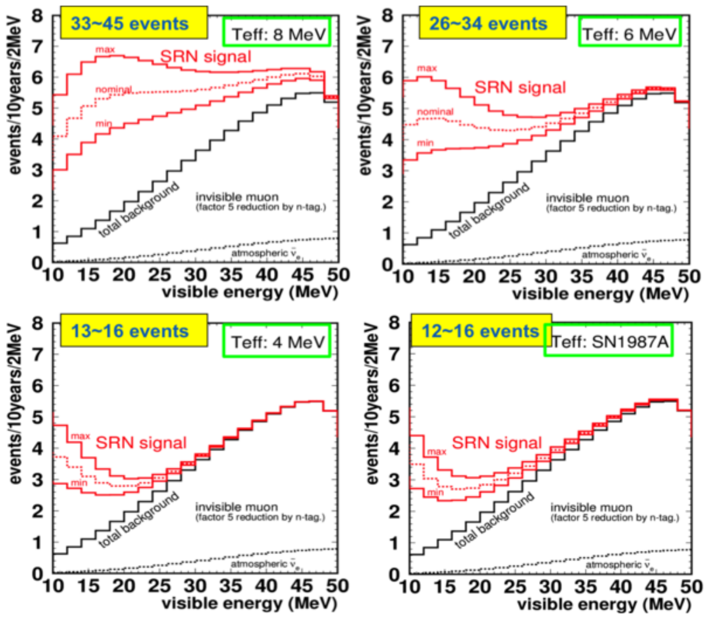

Figure 3: Expected number of events and energy spectrum for SRN assuming different effective neutrino temperatures (Teff) after 10 years of SK-Gd data taking. From [15].

SK-Gd will improve supernova burst analyses: First, ν and $\bar{\nu}$ fluxes will be measured independently constraining the supernova models. Secondly, neutrino elastic scatterings $\nu + e^- \rightarrow \nu + e^-$ allow us to determine the direction in the sky where the neutrinos came from and hence the ability to point our optical telescopes towards the SN before it is optically visible. Therefore, being able to identify the much larger IBD background events (which does not have directional information) to this reaction will improve by a factor 2 the pointing accuracy (down to 3° for a supernova at 10 kpc). Thirdly, during the Si-burning phase, massive stars emits low energy $\nu - \bar{\nu}$ pairs (about 2 MeV) to balance the energy production. Even if, in this phase, the neutrino luminosity is eight orders of magnitude less than in the peak at core-collapse, while the later lasts just a few seconds, the Si burning phase takes several days and radiates about 1% of the total energy of core-collapse [16]. While the neutrinos are not possible to detect due to their low energy, anti-neutrinos could be detected through IBD. Although the positron would still be below the Cherenkov threshold, the neutron could still be detected in SK-Gd. The rise in trigger rates from neutron captures would be a signal of a forthcoming supernova event several hours/days before the neutrino burst.

Searches for neutrinos with higher energy (GeV range), can also benefit from Gd loading. For long baseline neutrinos (T2K), a very high statistics measurement of the electron anti-neutrino flux and spectrum from Japan nuclear power reactors, would allow to improve the determination of the mixing parameters connecting the first two generations of neutrinos. Even neutrino-neutron elastic scattering will become a new significant neutral-current channel in accelerator studies. In addition to the better discrimination $\nu/\bar{\nu}$, SK-Gd improves the atmospheric neutrino oscillation analysis [15] thanks to the neutron multiplicity determination which allows to distinguish the neutral current, charged current deep inelastic scattering and the charged current electron neutrino interactions used by the analysis. Moreover, neutrino energy estimates are more accurate when the energy transfert to the nucleus is taken into account, as high energy neutrinos lead to more final state neutrons (this effect also improves the T2K oscillation analysis).

Overall, the atmospheric oscillation in SK-Gd would improve significantly the sensitivity to the CP violation phase and the mass hierarchy. As an illustration, Figure 4 shows the χ^2 distribution for rejecting the value $\delta_{CP} = 0$ with (pink curve) and without (black) the Gd in absence of systematics errors. The normal hierarchy is assumed.

Neutron tagging provides also an improvement on the sensitivity of proton decay searches. For instance, in the $p \rightarrow e^+\pi^0$ decay mode, the neutron multiplicity in the proton decay sample gives an handle to reduce the background (by one order of magnitude). It also helps in the study of bound-nucleon decay in which a neutron is ejected.

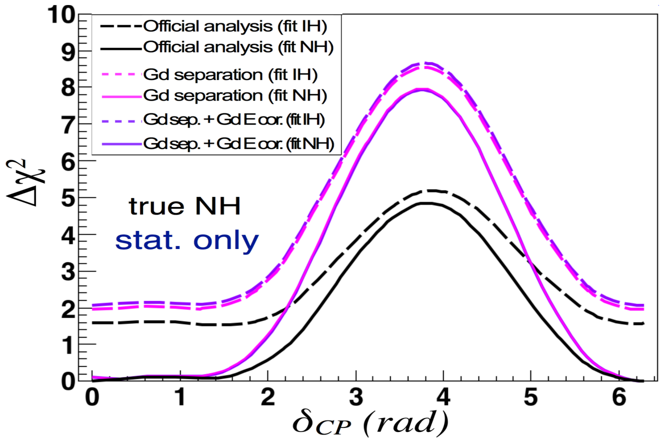

Figure 4: χ^2 distribution assuming $\delta_{CP} = 0$. No systematics included. The statistics correspond to 2300 days. From [15].

In conclusion, SK-Gd project is now very well advanced after the refurbishment work of the detector and the positive results of EGADS demonstrator. Neutron tagging, thanks to the addition of Gadolinium in the tank of Super-Kamiokande, will be a major improvement in neutrino physics and will impact both low energy and high energy physics for the next decade.

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