Current status of SK-Gd project and EGADS

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Abstract. Supernova Relic Neutrino (SRN) has not been observed yet because of its low event rate and high background. By adding gadolinium into water Cherenkov detector, inverse beta decay will have two signals, the prompt one is positron signal and the delayed one is a ∼8 MeV gamma cascade from neutron capture on gadolinium. By this way, background for SRN can be largely reduced by detecting prompt and delayed signals coincidently, and Super-K will also have the ability to distinguish neutrino and anti-neutrino. SK-Gd is a R&D project proposed to dissolve gadolinium into Super-K. As a part of it, EGADS, a 200ton water Cherenkov detector was built in Kamioka mine. Current status of SK-Gd project and the physics work being performed in EGADS will be presented here.

1. Introduction
1.1. Super-Kamiokande
Super-Kamiokande is a 50 kton water Cherenkov detector which is located in Kamioka mine in Gifu Prefecture of Japan. It has 11,129 20-inch diameter photomultipliers (PMTs) in its inner detector and 1,885 8-inch-diameter PMTs in its outer detector [1]. The purpose of the Super-K is various neutrinos physics and the measurement of proton life time. It observed solar neutrinos [2], atmospheric neutrinos [3] as well as accelerator neutrinos [4], and several evidences for neutrino oscillations were found. Super-K detector started to take data from April 1996 and now it is running its fourth phase. Super-K has been collecting data for nearly twenty years and it is still the largest neutrino detector in the world.

1.2. SRN search and SK-Gd project
As 99% of the energy is released by neutrino flux in supernova process, it is an important way to study supernova models by neutrinos. It is considered that supernova occurs two or three times within one century in our galaxy. Although there is no supernova observed from SN1987A, supernova is always occurring in the 15 billion years history of the universe. These neutrinos from past supernovae are called Supernova Relic Neutrinos (SRN), or known as another name as Diffuse Supernova Neutrino Background (DSNB).

Predicted spectrum of SRN is shown in Figure 1. Solar and reactor neutrinos are dominant below 10 MeV, and atmospheric neutrinos become dominant above 30 MeV. The event rate of SRN between 10 MeV and 30 MeV is expected to be about 1.3-6.7 events/year/22.5 kton in Super-K. The reason for why SRN has not been observed is high background and low event rate. In SRN detection, inverse beta decay (IBD, \( \nu_e + p \rightarrow e^+ + n \)) plays an important role, because its cross section is two orders of magnitude larger than \( \nu_e \) elastic scattering with electron, which is the second most visible interaction of SRN in Super-K. Currently, IBD only has a Cherenkov
signal produced by positron, and the neutron can be captured by free protons, with a result of 2.2 MeV gamma ray emission. The coincidence detection of positron and neutron can effectively reduce the background, however it is very difficult to detect 2.2 MeV gamma rays and the method of tagging neutrons by 2.2 MeV gamma ray has a very low efficiency. Adding gadolinium into Super-K was proposed [6]. The cross section of thermal neutron capture on natural gadolinium is 49000 barn, while 0.3 barn on free protons. And neutron capture on $^{155}$Gd and $^{157}$Gd can emit 8.5 MeV and 7.9 MeV gamma rays respectively. It will make neutron tagging much easier and more efficient than 2.2 MeV gamma. Now a lot of R&D works are ongoing and the project of adding gadolinium into SK is called SK-Gd project.

2. Evaluating Gadoliniums Action on Detector System (EGADS)

2.1. Construction

Evaluating Gadoliniums Action on Detector System (EGADS) is an experiment funded in 2009, which is proposed to test gadolinium effect on Super-K. A 200 m$^3$ stainless steel tank was designed and built inside Kamioka mine in 2010, several tens of meters from SK tank. 240 20-inch PMTs were installed into EGADS tank and its own data acquisition system has been developed. A few of these PMTs are prototypes which will be tested for Hyper-K while the others are the same with Super-K PMTs. And also, some of the Super-K PMTs are installed with acrylic vessels and some of them are bare ones.

Gadolinium sulfate ($\text{Gd}_2(\text{SO}_4)_3$) was chosen for our candidate. The work of filling gadolinium into EGADS tank started from November 2014. Soaking tests for chemical effect of gadolinium sulfate on several materials were conducted at Okayama University previously. The filling work was finished by April 2015 and 0.2% gadolinium sulfate has been dissolved. A 90% efficiency of neutron capture is expected under this concentration.

As it is essential to remove the impurities and keep the water quality at a good level, circulation system for gadolinium loaded water was developed at University of California, Irvine (UCI). Gadolinium loaded water pumped out from EGADS tank will go through ultra-filter, two nano-filters, deionizers, UV lights and micro-filters. Gadolinium or particles of about the size of gadolinium will be gathered into a collection buffer tank, and then be mixed with purified water and return into the tank.

2.2. Water transparency monitoring

In order to monitor the water transparency change in the tank, a water transparency measurement device called Underground Device Evaluating Attenuation Length (UDEAL) was developed at UCI. UDEAL can take water samples automatically from three positions (top,
center, bottom) of the tank, and measure the samples with laser by seven different wavelengths (337 nm, 375 nm, 405 nm, 445 nm, 473 nm, 532 nm and 595 nm). These wavelengths cover the main range of Cherenkov light signals in Super-K. By using the measurement results of UDEAL, water transparency is evaluated as the intensity of Cherenkov light left at a distance of 15 m (LL_{15m}). Time-related change of water transparency is shown in Figure 2. Gadolinium sulfate was injected into the tank by four times, after the injection transparency got down suddenly, and then recovered as a result of circulation. Measurement with spectrophotometer and other studies are also being performed.

![Figure 2. Water transparency change measured by UDEAL](image)

### 3. Calibration work

#### 3.1. PMT calibration

In PMT calibration, Quantum Efficiency (QE) and gain are two important factors. Here, QE also includes the correction efficiency of photoelectrons onto the first dynode of the PMT. Gain is the conversion factor from the number of collected photoelectrons to output charge (in units of pC). Low energy events like SRN signals usually consist of single photoelectron (pe) hits so their analysis heavily depends on QE calibration, while high energy events depend more on gain calibration.

First of all, we need to determine the high voltage value for all the PMTs. We use Xe flash lamp as a light source. Light from the lamp passes through a UV filter and then be injected into the tank through optical fiber, finally arrive at a scintillator ball placed in the center of the tank. The scintillator ball is an acrylic ball containing 15 ppm POPOP as a wavelength shifter and 2000 ppm MgO as a diffuser to make the light emission from the ball as uniform as possible [7]. Output charge of the PMTs can be adjusted by changing the high voltage applied on them. PMTs with the same geometry are divided into one group. After high voltage adjustment, the PMTs in the same group are expected to have the same value of output charge. Figure 3 shows that difference between every PMT and the average value of its group is less than 1%, with 0.003% RMS.

Relative QE of each PMT is measured by Ni-Cf source. Neutrons are provided by $^{252}$Cf, then 9 MeV gamma rays are emitted isotropically by neutron capture on $^{58}$Ni. Ni-Cf source was placed at the center of the tank, and more than 99% of observed signals are due to single pe. Relative QE can be calculated by counting event rate of each PMT, and MC simulation is used to cancel the geometry differences. The dispersion of relative QE is 5.7% of RMS.

PMTs gains are measured with laser diode. Here we need two measurements. In the first one we emit high intensity flashed from the center of the tank to make each PMT can get a suitable number of photons, and then calculate the average charge of each PMT. In the second
measurement, we emit low intensity flashed to make sure that every event only hit a few PMTs so that almost all of these signals are single pe. By taking the ratio of the average charge in the first measurement and the hit rate in the second measurement, relative gain of each PMT can be estimated and the dispersion is 6.8% of RMS.

All of these calibration works were carried out when EGADS tank were filled with pure water. And other works such as timing corrections and Rayleigh scattering measurement were also performed.

3.2. Using Xe flash lamp as a long term monitor

After basic calibration works, it is also important to monitor the long term performance of the PMTs. So we installed the Xe flash lamp with scintillator ball into a side hole of the tank, which is about 2 m from the center hole. The time-related change of the PMTs are termly checked.

This monitor can also be used to make a cross check for the water quality change in the tank. We choose the farest and nearest PMTs from the scintillator ball and take the ratio of their charges. The long period change of the ratio is shown in Figure 4, it has the same trend with the water transparency measurement of UDEAL—transparency decreased suddenly when gadolinium sulfate was injected, and then recovered after circulation system started running.

![Figure 3. Ratio of farest PMT and nearest PMT charge. The first point is set to 0 as reference.](image_url)

4. Estimation of neutron capture efficiency

4.1. Experiment setup

The most important point of SK-Gd project is the detection of 8 MeV gamma from neutron capture on gadolinium. In order to estimate the neutron capture efficiency of gadolinium in EGADS, Am/Be are chosen as a neutron source, $^{241}$Am decays to $^{237}$Np by giving out a $\alpha$, then $\alpha$ reacts with $^4$He and finally a neutron and a 4.43 MeV de-excitation gamma ray are produced.

In SRN detection, events are expected to have two signals, the prompt one is the Cherenkov light made by positron, and the delayed one is the gamma ray made by neutron capture. To make similar events as SRN, Am/Be source is placed on the top of BGO crystal, and the 4.43 MeV gamma from Am/Be source can hit on BGO and make scintillation light. The scintillation light made by 4.43 MeV gamma has a large number of PMT hits and can be easily separated from neutron capture gamma. By such setting, the scintillation events can be considered as the prompt signal while the neutron capture gamma is the delayed signal, and neutron capture efficiency can be estimated by coincidence detection of these two.

4.2. Data analysis of neutron capture gamma

Neutron capture gamma rays are analysed by comparison with Monte Carlo simulation. Reconstructed energy and the time difference between prompt signal and the corresponding
delayed signal is shown in Figure 5 and Figure 6. The average capture time is 29.89±0.33 micro-second in 0.2% concentration, while M.C. simulation is 30.03±0.77 micro-second. Backgrounds have been removed and the data and M.C. have good agreement in both distributions.

![Figure 4. Time difference between prompt and delayed signals.](image1)

![Figure 5. Reconstructed energy of delayed signals.](image2)

Neutron capture efficiency of gadolinium finally turns to be 84.36±1.79% while MC simulation is about 84.51±0.33%. Detection efficiency is included and more details about the uncertainty of this analysis is still in progress.

Data taken by other sources is also being analysed.

5. Summary and prospect

0.2% gadolinium sulfate has been successfully dissolved into EGADS tank. Water system and transparency measurement device are running as expected. Basic calibration work was finished in pure water condition, and neutron capture efficiency of gadolinium was measured at 0.2% concentration. Based on the success of EGADS, SK-Gd project has already been approved by SK collaboration, with the precise timeline yet to be determined.

The electronics in EGADS is using Analog Timing Module (ATM), which was also used in the first, second and third phase of Super-K. Super-K fourth phase is using different modules called QTC-Based Electronics with Ethernet (QBEE), and EGADS electronics will also be replaced with QBEE in the future.

There is also some other remaining work, such as improving the radiopurity of our Gd sulfate. Once all of these are finished, we will be completely prepared to add gadolinium into Super-K.

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References

[1] Fukuda Y et al (Super-Kamiokande Collaboration) 2003 Nuclear Instruments and Methods in Physics Research Section A 501 418
[2] Fukuda S et al (Super-Kamiokande Collaboration) 2002 Phys. Lett. B 539 179
[3] Fukuda Y et al (Super-Kamiokande Collaboration) 1998 Phys. Rev. Lett. 81 1562
[4] Abe K et al (T2K Collaboration) 2011 Phys. Rev. Lett. 107 041801
[5] Horiiuchi S, Beacom J and Dwek E 2009 Phys. Rev. D 79 083013
[6] Beacom J and Vagins M, 2004 Phys. Rev. Lett. 93 171101
[7] Abe K et al (Super-Kamiokande Collaboration) 2014 Nuclear Instruments and Methods in Physics Research Section A 737 253