PROCEEDINGS OF SCIENCE

Status of the Gadolinium project for Super-Kamiokande

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EGADS (Evaluating Gadolinium's Action on Detector Systems) is a test facility for a new neutrino detection method with a Gd-loaded water Cherenkov detector. In this method, anti-neutrino events with the charged-current interactions on protons are identified by the coincidental detections of the prompt positron signal from the inverse beta decay and the delayed gamma-ray signal from the neutron capture on Gd sulfate which is dissolved in the water. Introducing this method to a large water Cherenkov detector, Super-Kamiokande, we will achieve the first detection of the supernova relic neutrinos and improved ongoing physics studies with the capability of anti-neutrino identification and high precision measurement with reduced background.
EGADS consists of the stainless tank holding 200 ton Gd solutions with two hundred forty 20-inch PMTs and special water circulation system for filtration and gadolinium recovery. It is designed to evaluate the effect of dissolving Gd sulfate to water transparency and detectors. In 2011 and 2012, we tested the performance of water circulation system with the 15 ton buffer tank. At autumn 2012, we will install the PMTs to 200 ton tank and start detector commissioning with our DAQ. The current status of EGADS is presented.

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1. SRN Search with Super-Kamiokande

Throughout the 15 billion years history of the universe, numerous supernovae have exploded. We have observed these supernovae by the eyes and telescopes. The neutrino detectors are also counted as the important monitors for supernovae, by successful detection of neutrinos from the supernova SN1987A by Kamiokande. Each core collapse supernova releases 99% of its energy, the order of 10^{46} J, as neutrinos. These neutrinos from the past supernovae, which is called as the supernova relic neutrino (SRN), are still in existence and waiting for our discovery. SRN signal has never seen, though several neutrino experiments have searched the signal.

Super-Kamiokande is the world largest water Cherenkov detector. It has measured the proton lifetime upper limit and also observed atmospheric, solar and accelerator neutrino oscillations [1][2][3][4][5]. SK also has searched the SRN signal primarily through the antineutrino charged-current interaction on free proton, so called inverse beta decay (IBD, $\bar{\nu}_e$+p$\rightarrow$e$^+$+n). The second most visible mode for SRN search is less frequent by about 2 orders of magnitude. Current approach of SK on SRN search is to eliminate as many backgrounds as possible to detect the positron from IBD and the spectrum of SRN on the backgrounds. Super-Kamiokande set the world best limit between 2.8 and 3.0 $\bar{\nu}_e$ cm^{-2}s^{-1} for $>$17.3 MeV E_ν (90% C.L.) with this approach [6].

2. Gadolinium Loaded Super-Kamokande

The idea to add gadolinium to Super-Kamiokande, so called GADZOOKS!, was proposed first by J. Beacom and M. Vagins [7]. The SRN signals could be studied if anti-neutrinos were tagged by the detection of neutrons following IBD, as the coincidence detection greatly reduces backgrounds from radioactivities and other neutrino reactions. In this idea, gadolinium is doped for the detection of neutrons using the neutron capture on gadolinium nuclei. ^{157}Gd has the largest thermal neutron capture cross section, 254000 barn, among all stable nuclei. ^{156}Gd has also a large cross section, 60700 barn. Natural gadolinium contains 15.7% of ^{157}Gd and 14.5% of ^{156}Gd and they play main role in the neutron capture. In total, the cross section for the thermal neutron capture on natural gadolinium is 49000 barn, compared to 0.3 barn on free protons of hydrogen. The highlight of gadolinium is that Gd^{155} and Gd^{157} emit γ-ray cascade with the total energy of 8.5 MeV and 7.9 MeV in their neutron captures, respectively. These 8 MeV γ-ray emissions make it easy to tag the neutron capture on gadolinium and to reconstruct the capture position, time and energy, comparing to the case of free proton and its 2.2 MeV γ-ray emission.

Because of the large cross section, 0.1% by mass of dissolved gadolinium in the water target is sufficient to achieve above 90% of thermal neutron captures on gadolinium, instead of hydrogen. This allows event-by event correlation test with previous positron-like events' timing and position information. Adding gadolinium to Super-Kamiokande will reduce the low energy background by the factor of 2×10^{-4} and extend the SRN search window lower, down to 10 MeV, where more SRN signals expected[8]. With the 10 - 30 MeV search window, we expect 0.8 - 5.0 SRN events per year.

3. Evaluating Gadolinium's Action on Detector System (EGADS)

Evaluating Gadolinium's Action on Detector System, EGADS, was proposed for R&D of gadolinium loaded Super-Kamiokande. Adding gadolinium in the water is naturally expected to affect on its transparency, which is the essential factor of water Cherenkov detector. The chemical effect of gadolinium sulfate ($Gd_2(SO_4)_3$) on the detector material is also concerned. $Gd_2(SO_4)_3$ is the our best candidate, after soaking tests on several materials at Okayama University. The detection efficiency of this coincidence method and the neutron background from the detector environment are also important issues to be studied. EGADS is carefully designed for these R&D.

The EGADS facility is located in the Kamioka Mine in Japan, several tens of meters far from from SK detector. In the facility, EGADS water circulation system and 200 ton water Cherenkov detector tank are located. The facility environments provides similar cosmic and natural backgrounds to SK. The detector is built to evaluate the chemical effect on SK materials. The 200 ton water Cherenkov detector tank is made of stainless steel and two hundred forty 20-inch Hamamtsu PMTs will be installed inside it. The material of 200 ton tank and the PMTs are the same as the SK and its inner detector PMTs. Some of the PMTs will be installed with the fiberglass enclosure and acrylic pressure vessels, as those installed in SK today. All PMTs are connected to a functional DAQ system including the same front-end electronics as SK before 2008. The EGADS water circulation system is newly designed for purifying gadolinium loaded water and keeping its high water transparency without losing gadolinium. EGADS also has a special water transparency measurement device, so called UDEAL (Underground Device Evaluating Attenuation Length), which is developed by University of California, Irvine (UCI) for studying the water purification and watching the transparency. These details are described in the next section. The gadolinium pre-treatment system and recovery system are also the main equipments of EGADS. The pre-treatment system was built to dissolve gadolinium sulfate into water and remove the uranium which might be contained in it, before injecting the concentrated solution into the water system. The gadolinium recovery system is being developed at UCI to retrieve gadolinium from Gd-loaded water. Currently, tanks filled with ion exchange resin is used to retrieve gadolinium instead of the recovery system.

3.1 EGADS Water Circulation System

It is essential to keep high transparency for water Cherenkov detector, for its higher energy resolution, position resolution and detection capability at lower energy. It is also important to remove the radioactive impurities for the lower background measurement. The EGADS water circulation system (Fig. 3.1)is the bland-new water circulation and purification system for gadolinium loaded water. To filter the water of impurities without unacceptable losses or concentration variation of gadolinium solute in the process, "selective band-pass" filtration method is developed at UCI and applied. In this filtration process, gadolinium and similar-sized particles are divided from the larger and smaller particles and concentrated. First, the water from 200 ton tank is filtered with ultra-filter, which removes impurities larger than Gd. Then the product goes to two nano-filters, which filter out particles of about the size of gadolinium. At this stage, gadolinium concentrated water is taken as the reject of the filters and lead to a collection buffer tank. The product of the nano-filters are treated with reverse osmosis membranes (RO) to remove smaller impurities. Finally, the RO product is mixed with the gadolinium concentrated water in the collection tank and returned to 200 ton tank after degas process. Deionizers, UV lights and micro-filters are also installed in the water system to remove anions of about the size of gadolinium and organic carbons.

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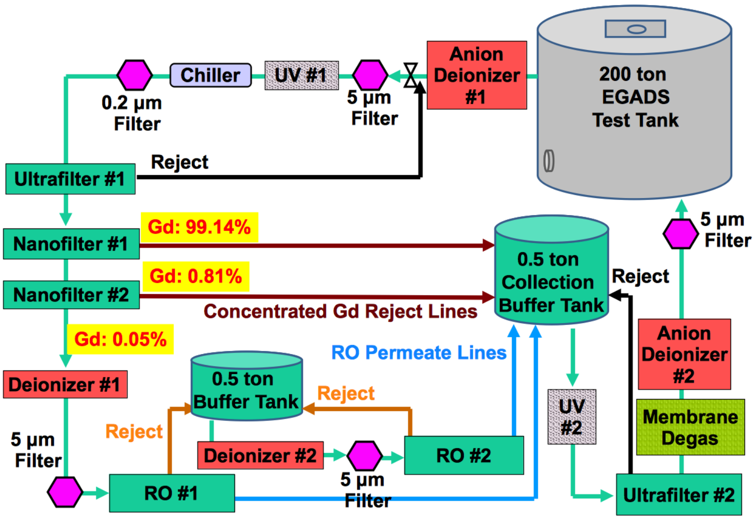

Figure 1: The schematic of EGADS water circulation system at July 2012.

3.2 Water Transparency Measurement Devices

The R&D of water circulation system and achievement of the high water quality with gadolinium are the dominant purposes of EGADS. UDEAL, the water transparency measurement device, is developed by UCI for monitoring the water quality. It measures the water transparency in real time with laser at 7 wavelengths, 337 nm, 375 nm, 405 nm, 445 nm, 473 nm , 532 nm and 595 nm, covering the main range of Cherenkov light seen at SK. The precision is very high even on ultra-pure water, about 1% of the attenuation length above 100 m. We evaluate the transparency of our pure and Gd-loaded water using the amount of Cherenkov light to be detected after 15 m in the water (Cherenkov light left at 15 m, LL15). The length of 15 m is determined from the average path length between the position where Cherenkov light is generated and the position where the light is detected by PMT in SK. Not only the attenuation between 15 m, but also Cherenkov light spectrum and the quantum efficiency of 20-inch PMT are considered for the calculation of LL15. A spectrophotometer JASCO V-550 is also used to measure the attenuation spectrum between 200 nm and 800 nm. The spectrophotometer is much less sensitive than UDEAL, but the results are complementary to find out unexpected impurities and to evaluate the effect of the gadolinium absorption below 337 nm on Cherenkov light detection.

3.3 Water Circulation Test

EGADS water circulation system has been operational since 2011. From March to June 2011, pure water was circulated through the water circulation system and 200 ton detector tank and kept being purified. During the test, we achieved high water transparency and water attenuation length above 100 m between 375 and 445 nm. This value is comparable with the pure water of Super-Kamiokande water circulation system. For the Gd-loaded water circulation test, we moved to 15 ton tank of our pre-treatment system from the 200 ton tank. The smaller tank provides much quicker response of water transparency to changing the configure of the circulation system. After successful circulation of pure water with 15 ton tank, 0.2% by mass of $Gd_2(SO_4)_3$, which is equivalent to

0.1% by mass of gadolinium, was dissolved into the water at August 2011. The stable circulation of Gd-loaded water and its high water transparency was attained from January to March 2012. The attenuation length was above 80 m between 405 and 445 nm. The selective filtration and water purification were successfully applied to the Gd-loaded water and above 99.9% of gadolinium was recovered per turn. The LL15 of our Gd-loaded water was stable at 70% during the period, while LL15 of SK pure water is 75% to 80%. So we achieved the high transparency of the Gd-loaded water, where 85% of Cherenkov lights comparing to SK.

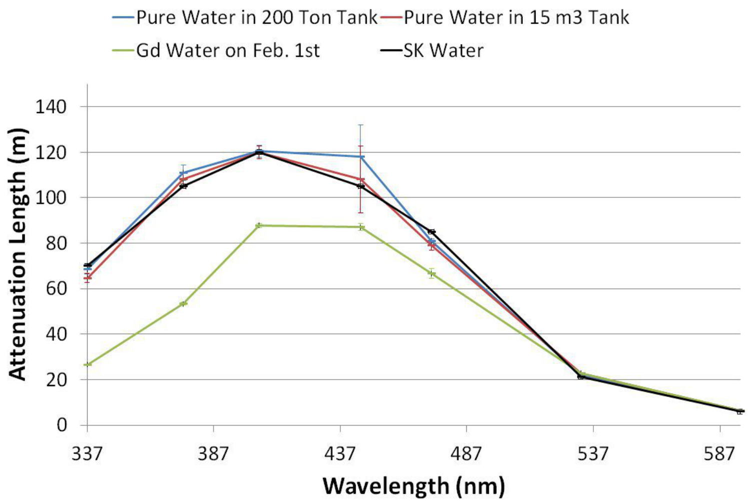

Figure 2: The attenuation length of water measured by UDEAL at each period of water circulation test. The results of pure water circulated with 200 ton and 15 ton tanks are comparable to that of SK pure water.

4. Status and Future Plan

EGADS water circulation system has been operational since January 2011. The 200 ton detector tank was also ready, though PMTs are not installed into it yet. The circulation of pure water was successfully finished with 200 ton tank and the circulation of 0.2% $Gd_2(SO_4)_3$ solution was also achieved with 15 ton tank of the pre-treatment system in early 2012. After the Gd-loaded water circulation test, the study for the filter replacement to maintain the water circulation has been done from March to December 2012. At December 2012, the circulation test was moved back to 200 ton tank again. After the pure water circulation test, we will start the Gd-loaded water circulation with 200 ton tank soon. The installation of 240 PMTs into the detector tank is planned at April 2013. Then the pure and Gd-loaded water circulation will be tested with 200t tank and PMTs. Finally, the detection efficiency of IBD using the double tagging with neutron and positron will be measured with a neutron source.

5. Summary

EGADS, the R&D project for gadolinium loaded water Cherenkov detector, is now being performed. The new ability to detect neutrons using the neutron capture reaction on gadolinium would

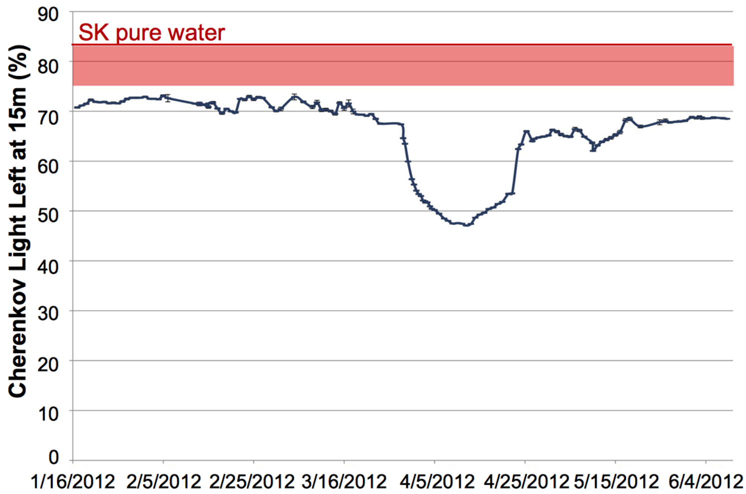

Figure 3: The history of Cherenkov Light Left at 15m (LL15) during the water circulation test in early 2012. The LL15 reached to above 70% and was stable between January and March 2012. The LL15 of typical SK pure water is also shown by the red band. At end of March, we began filter replacement study and the transparency was dropped as the result.

greatly improve the identification of anti-neutrino reactions ($\bar{\nu}_e$+p→e$^+$+n) from the backgrounds. The improvements will lead us to the first detection of supernova relic neutrino and also allow us to start new studies in anti-neutrino spectroscopy. The EGADS project already achieved the stable circulation and purification of 0.2 percent weight gadolinium sulfate solution with 15 ton tank. The transparency of the solution was high to keep the 70% of Cherenkov light left at 15 m, so far which corresponds to 85% of Super-Kamiokande pure water case. The circulation test of gadolinium solution with 200 ton tank, PMT installation and the detection efficiency measurement is planned for 2013. Once this R&D project is completed, we will push the plan to add gadolinium into SK forward and make a great improvements of neutrino physics.

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