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Status of the Super-Kamiokande gadolinium project

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ABSTRACT

The diffuse flux of neutrinos released from all past supernova explosions in the universe is known as the supernova relic neutrinos (SRN). Super-Kamiokande (SK) has conducted searches for these SRN events via their inverse beta decay interactions in the detector, in the process establishing the world's best limits on this still unobserved flux. These limits are within about a factor of two of the theoretically predicted fluxes. But these searches are background limited, and without some major improvement further progress will be difficult. The addition of gadolinium (Gd) compound into the SK detector was proposed to reduce background. Gd has the largest thermal neutron capture cross-section among all stable nuclei and emits an 8 MeV γ cascade following the capture. By coincidental tagging of positrons with the γ rays from Gd neutron capture, we can identify the dominant SRN signal in SK: inverse beta decay. This Gd-loading technique should allow SK to make the world's first observation of a SRN signal. We will demonstrate the principle of a Gd-doped water Cherenkov detector (transparency of the Gd-doped water, Gd-doped water circulation method, neutron capture efficiency, etc) with a dedicated test facility named EGADS. EGADS consists of a 200 ton water Cherenkov detector, a Gd dissolving pre-treatment device, a Gd-capable water circulation system, and a custom-built water transparency measurement device. We have evaluated Gd-doped water circulation using the main EGADS water system since 2012. The evaluation of the overall performance of EGADS will start in 2013 after PMT installation.

1. Introduction to the Gd-doped water Cherenkov detector

On the 23rd of February 1987, the Kamiokande II detector observed a neutrino burst from SN1987A [1]. This was the first detection of a supernova's neutrino burst and it introduced a new method of investigation: neutrino astronomy. Since the beginning of the universe, enormous numbers of supernovae have exploded. The neutrinos emitted from all such supernova explosions constitute the diffuse Supernova Relic Neutrino (SRN) flux. Measuring the overall flux and energy spectrum of the SRN will enable us to investigate the history of past supernovae. For example, the flux of SRN would provide information on the star formation rate and supernova rate in galaxies.

The world's best limit on the SRN flux comes from Super-Kamiokande (SK) [2], a large water Cherenkov detector located in the Kamioka mine in Japan. SK searches for SRN events via a positron signal produced by the inverse beta decay interaction ($\overline{\nu_e} + p \to e^+ + n$), since its cross-section is by far the largest of the possible supernova neutrino interactions with water [3].

While SK does have the world's best limit, its current search for SRN is strongly constrained by background; the search region for SRN electron anti-neutrinos has been confined to 16–30 MeV. The most important backgrounds are atmospheric ν_μ and ν_e charged current interactions and γ rays produced by neutral current ν–^{16}O interactions.

GADZOOKS! [Gadolinium Anti-neutrino Detector Zealously Outperforming Old Kamiokande, Super!], a gadolinium-doped water Cherenkov detector, has been proposed [4]. The addition of 0.1% gadolinium (Gd) to the SK water is the key to reducing SRN backgrounds, which should allow the first detection of the SRN signal. Neutrons produced by inverse beta decays are quickly thermalized and captured by the Gd. With its large thermal neutron capture cross-section (49000 barn), 0.1% Gd in solution gives about 90% efficiency for neutron capture; the remaining 10% are captured invisibly by protons in the water ($p + n \to d + 2.2$ MeVγ). Neutron capture on Gd emits about 3–4 γ rays with a total energy of 8 MeV. The coincident detection of the prompt positron and the delayed γ cascade makes it possible to uniquely identify anti-neutrino events and to lower the energy threshold for the SRN search down to 10 MeV, where many more SRN events are expected (see Fig. 1). Given the predicted rates, this widening of the energy window should lead us to the first observation of a SRN signal in SK. We had

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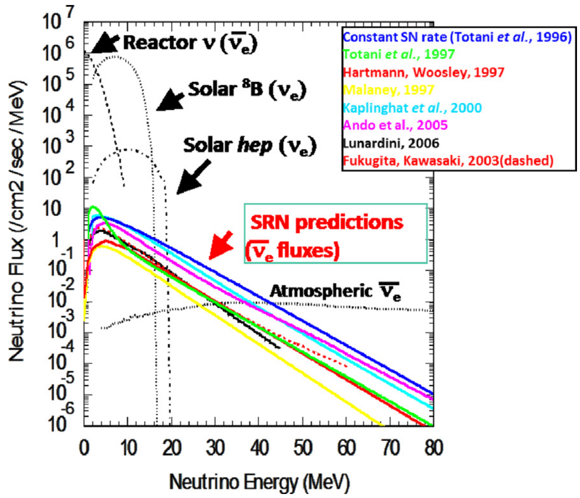

Fig. 1. Solid lines show predicted SRN spectrum for different models. Black dotted lines represent the spectra of solar neutrinos, atmospheric neutrinos, and reactor neutrinos, some of the potential backgrounds to the SRN search. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

to determine first which was the best Gd compound to dissolve in the SK water. To become a good candidate for full scale R&D, the compound had to be water soluble, relatively transparent to Cherenkov light, and not be too difficult to handle in large quantities, as around 100 tons (roughly half of which is gadolinium) would be required for a 50 kton detector. We considered three easily dissolved candidate Gd compounds, $GdCl_3$, $Gd(NO_3)_3$, $Gd_2(SO_4)_3$. But we discovered that the chlorine in $GdCl_3$ could cause unwanted corrosion, and strong light absorption by nitrate was evident below 350 nm, cutting off a significant part of the Cherenkov light spectrum. Consequently, $Gd_2(SO_4)_3$ is the best candidate we have thus far identified.

Soak tests for all component materials of the SK detector were conducted to evaluate any potential corrosion and/or deterioration. Each sample piece was placed into a polypropylene bottle filled either with 0.1% Gd solution or pure water and stored at a variety of controlled temperatures. The transparencies of the aged solutions were investigated by measuring them with a JASCO V-550 spectrophotometer. This study showed that the effect of Gd-loading on the SK detector materials can be expected to be negligible and water transparency will remain high if water temperature is kept at 15°C, the temperature of the surrounding rock at the underground SK site.

2. Overview of the EGADS experiment

We decided to excavate a new experimental hall near the SK detector in the Kamioka mine and construct a dedicated R&D facility in order to demonstrate the principle of GADZOOKS! [5]. This facility is named EGADS [Evaluation Gadolinium's Action on Detector Systems]. As shown in Fig. 2, the EGADS facility consists of a 200 ton water Cherenkov detector, a Gd dissolving pre-treatment system with its own 15 ton tank, a main Gd-capable water circulation system, and a water transparency measurement device. Two hundred forty 20-in. PMTs will be installed in the 200 ton detector once transparency studies with circulated Gd-doped water are completed. The following items are being tested with this facility:

1. Transparency of the Gd-doped water. As in SK, it is important to keep the transparency high to enable various physics analyses.

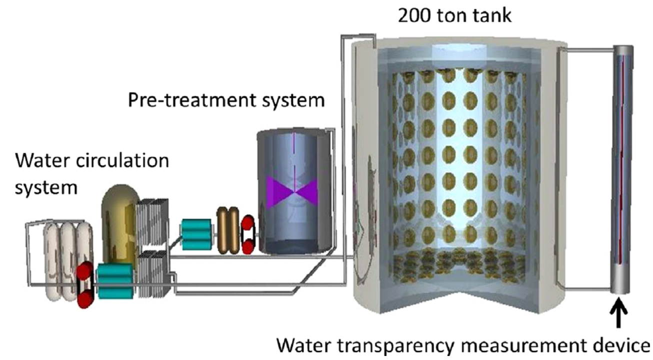

Fig. 2. The dedicated Gd test facility named EGADS.

2. Gd-doped water purification system. Since the current SK water system removes ions, it must be modified to purify without removing the Gd compound.
3. Effect of Gd on detector materials. We will look for any Gd-related corrosion and/or deterioration of SK materials. The 200-ton EGADS water Cherenkov detector was constructed with the same materials as used in SK detector including 20-in. PMTs.
4. Behavior and handling of the Gd in the water. The Gd should be uniformly distributed in the detector, and be able to be removed quickly, economically, and completely whenever desired.
5. Ambient neutron level in the tank. We need to check how Gd gamma events from non-IBD neutrons could affect the solar neutrino measurement in the SK detector.
6. Neutron capture efficiency. The detection efficiency of Gd γ signals should be studied to evaluate the eventual performance of a Gd-doped SK detector. This measurement will be conducted using the 200-ton Cherenkov detector.

2.1. Water systems

The EGADS water systems consist of a pre-treatment system and a main circulation system.

We first dissolve the $Gd_2(SO_4)_3$ powder into water in the 15-ton pre-treatment tank to make a 0.2% gadolinium sulfate solution. The built-in stirrer in the 15-ton tank helps dissolve the $Gd_2(SO_4)_3$ powder completely and quickly. The pre-treatment system is equipped with microfilters, a UV lamp to kill bacteria, and a special resin which passes gadolinium but removes uranium and thorium with more than 99% efficiency. The water is then injected from the pre-treatment system into the main circulation system.

The water at EGADS must be kept ultra pure without removing $Gd_2(SO_4)_3$. Consequently, the main EGADS water system is named "selective filtration" [6], because multivalent ions such as Gd^{3+} and $(SO_4)^{2-}$ are selected out. A schematic view of this system is shown in Fig. 3. The membrane pore size of nanofilters (NF) is smaller than Gd and SO_4 ions, so such multivalent ions are selected out at the NF. The Gd-rejected water is then sent through reverse osmosis (RO), where only H_2O molecules can pass through the membrane. The pure water and $Gd_2(SO_4)_3$ are reunited in the collection buffer tank and sent back to the 200-ton detector. Details of this water system are described in [6,7].

Ion exchange resin is used in the Gd removal system currently installed in the EGADS experimental hall. The Gd is removed by this system with an efficiency of more than 99%. In the near future, a more economical removal system, likely employing a mechanical filter press and/or cascade filtration, will be installed. This new