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EGADS Progress

LLUÍS MARTÍ MAGRO[1] FOR THE SUPER-KAMIOKANDE COLLABORATION.

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Abstract: As proposed by GADZOOKS!, the Super-Kamiokande (SK) experiment has been developing an extensive R&D program that will allow neutron tagging in water Cherenkov detectors. Because of the very large thermal neutron capture cross section of gadolinium (Gd), adding Gd into ultra pure water would result in a high efficiency for free neutron detection. Thus, electron antineutrinos interacting through inverse beta decay could be uniquely detected by the coincident detection of the prompt positron signal and the delayed 8 MeV gamma cascade from the neutron capture on Gd. Among other advantages, we expect to be able to detect the diffuse supernova neutrino background at SK.
EGADS (Evaluating Gadolinium's Action on Detector Systems) is a test facility in the Kamioka mine that is currently evaluating all the effects of adding a Gd compound (0.2% by mass of Gd sulfate) into a large water Cherenkov detector like SK. It currently features a 200 ton tank and a water filtration system that removes all impurities but keeps Gd. A DAQ system has been prepared and in summer 2013, 240 PMTs will be installed.

Keywords: Super-Kamiokande, neutron tagging, Cherenkov detector, supernova, gadolinium.

1 Motivation and strategy

Core-collapse supernovae (ccSNe) are among the most energetic phenomena in the universe, releasing on the order of 10^{46} J each. Of this, about 99% of the energy is released as neutrinos, implying a huge neutrino flux. To date, the only ccSN whose neutrinos have been detected is SN1987A. The neutrinos were detected at Kamiokande II [1] in Japan, IMB [2] in the US, and Baksan [3] in Russia; they constitute a very valuable piece of information regarding core-collapse supernovae. The rather low rate of ccSN (about three per century in our galaxy) provides a prime motivation to study the Diffuse Supernova Neutrino Background (DSNB), the neutrinos from all the past supernovae in the history of the universe. The observation at SK of the DSNB is currently limited by two irreducible backgrounds: at low energies by sub-Cherenkov muons decaying into electrons and at higher energies by atmospheric neutrinos. Because of these two backgrounds, while SK has been able to set the best limit on the DSNB flux [4] the DSNB remain undetected.

At SK the main mode to detect DSNB is through inverse beta decay (IBD): $\bar{\nu}_e + p \rightarrow e^+ + n$, as shown in Figure 1. Without efficient neutron tagging we cannot distinguish between electrons from muon decays and true DSNB IBD events.

In the ultra-pure water of SK, the neutron is usually captured by hydrogen and produces a 2.2 MeV gamma, which is difficult to detect (about 20% efficiency). This difficulty was addressed by John Beacom and Mark Vagins when they proposed GADZOOKS! [5]. The strategy proposed in GADZOOKS! is to add a soluble compound of gadolinium (Gd) to the water of SK. With a thermal neutron capture cross section of 49000 barns, neutron capture on Gd (as compared to hydrogen with 0.33 barns) yields a 8 MeV gamma cascade (shared among 3-4 gammas). Therefore, by requiring coincident detection of the prompt positron and the delayed neutron capture ($\sim$30 μs and vertices within $\sim$50 cm) we will be able to significantly reduce backgrounds.

Given its large neutron capture cross section, adding 0.1% by mass of gadolinium would be enough to achieve 90% of neutron captures on Gd. Reducing backgrounds will allow us to lower the energy threshold for DSNB studies (from 16 MeV for the current SK limit). In case of a galactic SN, the identification of the dominant IBD would improve the study of the other reactions. Of special interest is the ν_x elastic scattering: $\nu_x + e^+ \rightarrow \nu_x + e^+$ because the recoiled electron retains directional information of the original neutrino and thus to the SN.

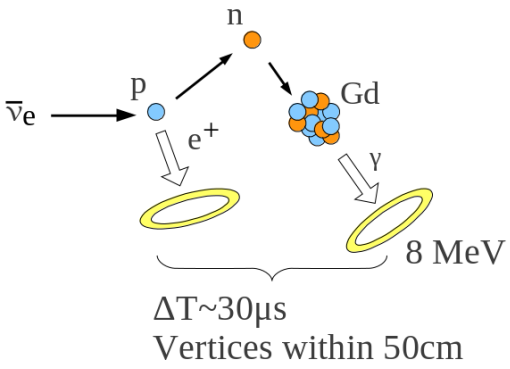

Figure 1: For DSNB searches at SK, the main mode is through inverse beta decay, where currently only the electron can be detected efficiently. As a result, two irreducible backgrounds currently exist at SK: invisible muons decaying into electrons and atmospheric neutrinos. This situation would be remedied by the addition of Gd to the water.

To investigate whether the 8 MeV gamma cascade can be detected, a special apparatus was deployed at SK. An Am/Be source (which produces a 4.43 MeV gamma and a neutron) embedded inside a bismuth germanium oxide (BGO) scintillation cube was immersed inside an acrylic cylindrical vessel filled with 2.4 litres of a 0.2% $GdCl_3$ solution. The 4.43 MeV gamma induces the BGO to scintillate light and constitutes the primary (prompt) trigger. The neutron moves through the Gd loaded water inside the acrylic

vessel until it is captured. The results [6] demonstrate that the delayed neutron capture on Gd can easily be detected by SK.

2 Evaluating Gadolinium's Action on Detector Systems: EGADS

Soon after GADZOOKS! was born, an R&D program was begun. Metallic Gd is hardly soluble in water. However, there are many Gd salts that are very soluble. Thus far three candidates compounds have been studied: $GdCl_3$, $Gd(NO_3)_3$ and $Gd_2(SO_4)_3$. $GdCl_3$ is very easy to dissolve in water and it is transparent to Cherenkov light, but the chlorine has unwanted effects on detector components. $Gd(NO_3)_3$ is also easy to dissolve and does not corrode detector components. However, the nitrate is opaque in the UV region (which represents a large fraction of the detected Cherenkov light). Finally, $Gd_2(SO_4)_3$ is also easy to dissolve in cold water and has good optical properties. Soak tests in Japan using the 31 materials present at SK have been performed, as well as additional studies on stainless steel by the company which constructed SK's 50-kton tank; they all show that gadolinium sulfate is a good candidate in regard to material compatibility.

In order to maintain good water transparency at SK, the water is continuously cleaned and recirculated. Similarly, after loading water with Gd continuous filtration would be needed. However, the current method for pure water filtration cannot be used with Gd-loaded water because the Gd would be quickly removed. An intense research program on Gd-loaded water filtration was carried out in the US; this resulted in a new kind of water system (selective band pass filtration) that would clean the Gd-loaded water while simultaneously maintaining a constant level of dissolved Gd [7].

In 2009 the R&D project EGADS was funded in Japan [8] and a new experimental hall in the Kamioka mine near SK was excavated. The purpose of the project is to give the final answer to all the remaining challenges and questions that loading water with Gd for Cherenkov detectors poses. At EGADS the selective water purification system will show that it can retain the Gd while keeping the water transparency high. We will study the effects on detector components by using the same materials that are present at SK (including a 200-ton stainless steel tank and 50-cm PMTs). We will also study the necessary methods and techniques adding and removing Gd in a efficient and economical way. Since neutron backgrounds will be visible, we will also investigate how to reduce the neutron backgrounds from all sources (spallation, uranium and thorium fission chains, etc).

Some of the main EGADS components are: a 15-ton plastic tank equipped with a stirrer to dissolve Gd into water, a pre-treatment system with micro-filters to remove the largest contaminants dissolved along with the Gd and special resin (AJ4400) tanks to remove uranium, a selective band pass filtration system (hereafter main water system), UDEAL (Underground Device Evaluating Attenuation Length) to measure the water attenuation length [9], a 200-ton stainless steel (same as SK) tank that will be equipped with 240 PMTs, and an SK-like data acquisition system (DAQ).

The EGADS project follows five stages: first we circulated pure water through the 200-ton tank (no PMT mounted) with the main water system to confirm that it works before Gd is added. Second, circulate 0.2% Gd sulfate-loaded water through the 15-ton tank. Thanks to the faster recirculation rate through this smaller tank we could verify that the water system can both maintain high water quality and retain the Gd. Third, circulate Gd-loaded water through the 200-ton stainless steel tank. Fourth, mount the 240 PMTs (this summer). Finally, after a brief period of circulation and baseline calibrations with pure water, circulate Gd-loaded water through the fully equipped 200 ton tank for the full realization of the EGADS project.

2.1 EGADS first steps

In a first stage and after installing all the new equipment, it was mandatory to test its performance without gadolinium sulfate (hereafter just Gd if not stated differently). In the first half of 2011, we circulated pure water through the 200-ton tank. The water transparency was frequently monitored by UDEAL in three different positions of the tank: bottom, centre, and top. Soon after the main water system started to run the water quality improved, reaching SK water transparency levels [10].

The next step was to load the pure water with Gd. For this test, the 15-ton tank usually used to dissolve the Gd before injection into the 200-ton tank was used. Its advantage is its much smaller volume that allows faster recirculation, and therefore any change in the water quality was easier and faster to observe than if we had used the 200-ton tank. This test started in the second half of 2011 and lasted until end of 2012. The Gd sulfate concentration was measured with an Atomic Absorption Spectrometer (AAS) and as before, the water transparency was monitored with UDEAL. The lessons we extracted from this test have proven essential for the next steps and will be summarized briefly here:

We learned how to properly prepare the filter membranes before installation in their housings. Good membrane conditioning - far in excess of the manufacturer's recommendations for normal use - is paramount to ensure that no contaminants degrade the water transparency. After upgrading our membrane flushing system no water transparency drop has been seen after installing new membranes in the main system.

Gadolinium sulfate is better dissolved in cold water, preventing filter membranes from slowly clogging. This clogging results in a slow decrease in flow rate and eventually new membranes need to be installed.

The resin AJ4400 in the pre-treatment system, that was originally installed because it removes uranium, also improves the water transparency and after an initial conditioning period does not remove Gd.

After about a year and a half of tests with Gd in the 15-ton tank we achieved good water quality, a constant Gd concentration for long periods, and mastered a proper membrane maintenance and installation procedure. Only then were we prepared for the next step: circulating Gd-loaded water through the 200-ton stainless steel tank.

2.2 Current status

In 2013, from February 6th to April 20th, the 200-ton tank was stepwise loaded with Gd until the final 0.2% concentration was reached. The process began with single batches of 30 kg each; later, approximately double-sized batches were employed. During this process, the concentration was periodically measured with an AAS, as shown in Figure 2. Each batch was dumped into the water-filled 15-ton tank and then stirred until completely dissolved. Next, the loaded

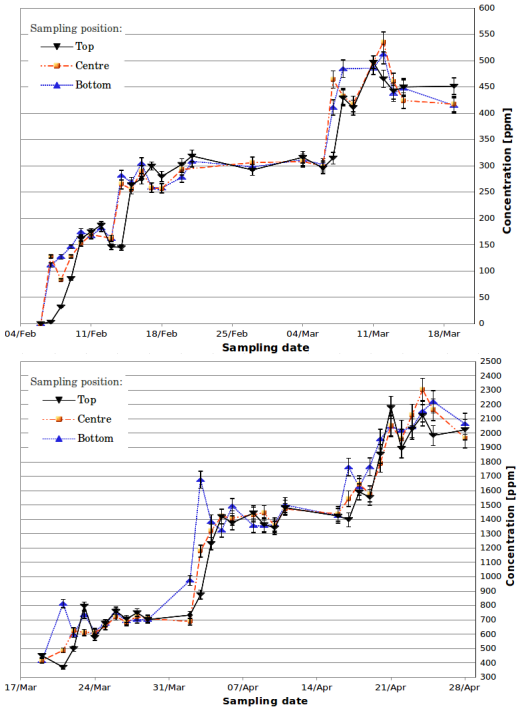

Figure 2: Gadolinium sulfate ($Gd(SO_4)_3 + n \cdot H_2O$) concentration during Gd loading from three sample points: top, centre, and bottom of the 200-ton tank. The top figure shows single batch loadings while the bottom shows double batches.

water was circulated through the pre-treatment system's 3 μm and 0.2 μm filters to remove dust and other impurities mainly coming from the gadolinium sulfate salt itself. Finally, the Gd-loaded water was injected into the 200-ton tank after being processed at least once through the main water system. The main water system injects the filtered water (in this case also Gd-loaded water) into the bottom of the 200-ton tank. The water that will be filtered in the main water system is drawn from the top of the tank.

Right after the first batch injection (15 tons of water) we can see that the concentration at all sampling ports is zero (also at the bottom sampling position). After this first batch injection and once the Gd in the 200-ton tank is homogeneously dissolved, the expected concentration was 150 ppm. In the second day after injection, the centre and bottom positions have concentrations larger than 100 ppm while the top still has a very low concentration (a few ppm). Over the next few days, the concentration at the top grows rapidly and all three values (top, centre and bottom) come together 5 days after injection. This is as expected in a tank with an approximately four-day turnover time and no convection.

For the second injection, the final expected concentration was 300 ppm. In this case, the water inside the 200-ton tank was already in motion from bottom to top (right before the first injection there was no circulation through the 200-ton tank) and the increase in concentration at the top is not as delayed with respect the two other sampling positions as during the first injection. However, the expected final concentration again becomes consistent and stable after about 5 days.

Five days after the second injection and before the third injection the concentration was stable at 300 ppm. This

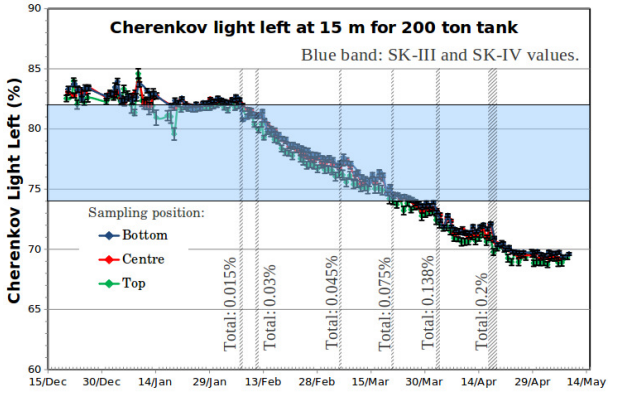

Figure 3: Water transparency in terms of percentage of Cherenkov light remaining after 15 meters of travel through the water in the 200-ton tank at three sampling positions: top, centre and bottom. Vertical hatched bands indicate Gd injections into the 200 ton tank and the horizontal blue band SK-III and SK-IV pure water values. Note the suppressed zero on the y-axis.

proves that the 60 kg of Gd sulfate dissolved homogeneously inside the tank, i.e. after two weeks the concentration at all points were the same and therefore Gd does not tend to accumulate at the bottom of the tank.

We saw similar behaviour in the next batches, all the way to the final concentration of 2000 ppm.

Figure 3 shows the water transparency in terms of percentage of Cherenkov light remaining after 15 meters of travel through the water[1] in the 200-ton tank as measured daily by UDEAL at three sampling positions: top, centre and bottom (same as for the Gd concentration). The horizontal blue band indicates SK-III and SK-IV pure water values (between 74% and 82%). The vertical hatched bands indicate when a Gd injection(s) took place. For the last two bands, two consecutive injections were performed.

The 200-ton tank was clean after the pure water circulation during the first step in the EGADS project in the first half of 2011. Before the current test with Gd we checked possible bacteria growth inside the tank. Bacteria samples at different positions inside the tank (including on the walls) showed almost no bacteria activity, indicating that the tank was in good condition. The tank was nevertheless flushed with pure water before filling it again. Therefore, before the first Gd injection, the water transparency was high, as shown in Figure 3. Cleaned water from the main water system is injected at the bottom of the tank and old water drawn from the top. For this reason, the water transparency is typically larger at the bottom than at the centre, while the smallest value usually corresponds to the top position.

Successive Gd batch injections followed (eight in total), along with a slow decrease in water transparency. Only after the fourth batch was injected did the water quality finally decrease below the SK pure water transparency band.

After the 8th injection the water transparency remained constant at about 69% of Cherenkov light left at 15 m. This is a similar value to that achieved during our tests with Gd-loaded water in the 15-ton plastic tank, which indicates that there is no transparency-damaging interaction with the stainless steel of the tank.

1. 15 m is the average Cherenkov light path length before it hits a PMT at SK

2.3 Next steps

The test with the Gd-loaded water in the 200 ton tank demonstrates that circulating Gd-loaded water through a stainless steel tank will not harm the water transparency. As a result, we have decided to move to the next stage.

Since we do not want to release Gd into the environment, to remove the Gd contained in EGADS's 200 tons of water we use a resin that is contained in large gravity-fed tanks. The water is drained through these tanks before being released into the environment. Once the resin is saturated it is safely disposed or regenerated. We have tested this resin with 1000 ppm Gd-loaded water. After being processed the water contains $<$0.5 ppb of Gd. For SK volumes, the amount of resin needed would be cumbersome; one solution would be to combine this very complete Gd-removal method with another method that remove most of the Gd before sending the remaining water and Gd to the resin for final polishing and release. We are currently studying other methods to remove Gd from large volumes which are both economical and efficient. While draining the 200-ton tank, we continuously monitored the Gd concentration coming out of the resin tanks to make sure the resin was working properly and when it became saturated we replaced the resin tanks with fresh ones.

In EGADS three types of photodetectors will be installed. Most of them, 227 in total, will be 50-cm Hamamatsu PMTs (R3600), the same type as the current SK PMTs. At EGADS we will also test 8 20-cm hybrid-photodetectors (HPD) and 5 50-cm high quantum efficiency (QE) PMTs that are currently being developed for Hyper-Kamiokande[2]. The HPD is a sensor that instead of dynodes utilizes an avalanche photodiode. The HPDs have a higher QE and higher single photon sensitivity and a much higher timing resolution as compared to the SK PMTs. The photocoverage will be similar than at SK (about 40%).

During the summer of 2011, all of the 50-cm SK-like PMTs that will be installed in the 200-ton tank were pre-calibrated along with a few extra in case we need to replace them (237 in all). In the second half of February 2013 we started the cabling work. We laid all the PMT cables from the front of the DAQ to the 200-ton tank in convenient places for later final cabling and PMT installation.

The PMT installation will be completed in July and August of 2013. As in the current SK design, some of the 50-cm SK-like PMTs in EGADS will be enclosed in pressure vessels (more properly thought of as implosion shields) made from 10 mm fibreglass (FRP) rear cases and 13 mm acrylic front covers. However, because the amount of available SK spare vessels are not enough for all the EGADS PMTs, some will be un-housed, while others will receive only an FRP case.

A fan with HEPA filters (flow: 30 m^3/hour) and O_2 and CO_2 meters will be installed inside the 200-ton tank to prevent suffocation during work inside. Once the 200-ton tank is emptied, a floating floor will be mounted inside and then the tank will be filled with pure water up to a height where the ceiling PMTs and the topmost ring of PMTs in the barrel can be mounted. Next, the tank will be drained in steps in order to mount subsequent rings in the barrel, and finally the floating floor will be removed and PMTs will be mounted on the bottom of the tank. The last eight PMTs at the top of the tank (underneath a square hatch) will be mounted from a boat inside the tank.

After PMT installation we will run again with pure water. Despite our efforts at keeping the tank interior clean during PMT installation, we expect the water quality to have worsened as compared to the previous run, and some time will be needed to recover. Near the beginning of 2014 we expect to load the 200-ton tank with gadolinium sulfate once again, the last step in the gadolinium R&D phase of the EGADS project.

In 2014 we also plan to upgrade our electronics. The current Analog-Timing-Modules (ATM) will be replaced with QTC (charge-timing-converter) Based Electronics with Ethernet (QBEE) [11]. They provide higher sensitivity for single photoelectrons, a wider charge dynamic range (about 4-5 times that of the the ATM modules) and good timing resolution for the 50-cm PMTs. With these new electronics in place EGADS will begin its new role, transforming from an R&D testbed to a working physics experiment and becoming the world's first Gd-based Cherenkov detector with full galactic supernova neutrino sensitivity [12].

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2. These numbers may change as well as the positions where they will be installed.