Gd for Super-Kamiokande and ANNIE

Lluís Martí Magro

Kavli IPMU (WPI), UTIAS, The University of Tokyo, Kashiwa, Chiba 277-8583, Japan
E-mail: martillu@suketto.icrr.u-tokyo.ac.jp
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From detectors like IMB, Kamiokande to SNO and Super-Kamiokande: The history of water Cherenkov detectors is long and successful. Initially designed for proton decay searches they were used to detect neutrinos and became soon famous for the observation of those from the supernova SN1987a. In light water Cherenkov detectors, each neutron capture produces a 2.2 MeV gamma which is too low for an efficient detection. Neutron-absorbing doping agents such as sodium chloride or gadolinium have been proposed as they produce a gamma cascade of about 8 and 8.5 MeV. They were first proposed for monitoring nuclear explosions. However, because gadolinium has the largest thermal neutron capture cross section GADZOOKS! was soon proposed to dope large water Cherenkov detectors with it. By just loading with 0.2% gadolinium sulfate in mass into the ultra-pure water 90% of the neutron captures will be on gadolinium. Here, I summarise the current status of two proposed future projects related to the gadolinium loading technique: ANNIE and SuperK-Gd.

KEYWORDS: neutrino, Cherenkov, detector, gadolinium, supernova.

1. Introduction

Nothing travels faster than light in vacuum but when a charged particle exceeds the speed of light in a given medium the equivalent of a sonic boom for light happens and Cherenkov radiation is emitted. The light is emitted on a cone. In water Cherenkov detectors this light is then detected by photo-multipliers (PMTs) that are sensitive to single-photons. The timing and charge recorded from all the PMTs is used to reconstruct position, direction and energy of the charged particles in water Cherenkov detectors like Super-Kamiokande (SuperK). Neutral particles can be seen only if they decay or interact with other particles in the detector in such a way that charged particles above Cherenkov threshold are produced.

One example are neutrons. At SuperK, they are currently captured by protons producing a single 2.2 MeV gamma. The resulting Compton-scattered electron is above but too close to its Cherenkov energy threshold (0.768 MeV) and thus, the detection efficiency is low (about 20% [1]). For some searches this low efficiency represents a drawback when large backgrounds are present. One example of this is the search for supernova relic neutrinos (SRN): the neutrinos from all the past core collapse supernovae (ccSNe) in the history of the universe. The main detection channel here is the inverse beta decay (IBD): $\bar{\nu}_e + p \rightarrow e^+ + n$, where currently only positrons are efficiently detected. As a consequence, IBD and backgrounds like electrons from the decay of invisible muons (muons below Cherenkov energy threshold) cannot be distinguished.

Other advantages related to neutron tagging would come from searches where no neutrons are expected. Proton decay (PD) studies are a good example because in most of the proposed decay modes there is no accompanying neutron. In these searches, the main background comes from atmospheric neutrinos. The interaction of these neutrinos usually produce at least one neutron at SuperK, see figure 1. Therefore, if a PD candidate event is found, the fact that no neutron was found would increase the confidence in that event.
In order to be able to tag neutrons in large water Cherenkov detectors a new technique was proposed [3]. Among all the elements in the periodic table, gadolinium (Gd) has the largest thermal neutron capture cross section (49000 barns to be compared to the 0.33 barns for hydrogen and 0.0002 barns for Oxygen). The idea is to dope the ultra-pure water of SuperK (or any other large water Cherenkov detector with large photo-coverage) with 0.2% of Gd (SO$_4$)$_3$ in mass. Because of the large Gd thermal neutron capture cross section about 90% of the captures would be on Gd. When a neutron is created it quickly thermalizes and is captured on Gd (~30 µs to be compared to ~200 µs for ultra-pure water). The neutron capture on Gd is efficiently detected since it produces a gamma cascade of about 8 MeV shared among 3-4 photons.

In the next section, I will briefly introduce and discuss the proposed Gd loaded water Cherenkov detector (ANNIE) that will measure neutron multiplicity yields in interactions of neutrinos in the GeV energy range. Next, I will describe and give an update of SuperK-Gd, the project that will enhance neutron tagging capabilities at SuperK by dissolving Gd in its otherwise ultra-pure water.

2. ANNIE

The proposed Gd loaded water Cherenkov detector ANNIE (Atmospheric Neutrino Neutron Interaction Experiment) is being designed to measure the neutron yield in neutrino interactions with Gd loaded water [4]. One of the main motivations for that is the fact that atmospheric neutrino interactions in water represent the largest background in PD searches. Atmospheric neutrino interactions almost always produce one neutron or more. Therefore, if a PD event is found, the fact that no neutron is found would increase the confidence in the event being a real PD event. However, if we want to calculate an exact confidence for PD discovery we need to know the neutron yield in neutrino interactions.

This can be achieved by using the Booster Neutrino Beam (BNB) at the Fermi National Accelerator Laboratory and it is foreseen to be installed in the existing (and currently unused) hall of the SciBooNE experiment. The energy of the neutrinos from the BNB is similar to those of atmospheric neutrinos, see right figure 2. When running in neutrino mode the beam is ~93% $\nu_\mu$ and its peak is at ~700 MeV. The expected number of charge current interactions is ~7000 events per ton per 10$^{20}$ protons-on-target (POT) while the beam runs at 7.5 kHz with 4·10$^{12}$ POT.
An interesting feature that has been foreseen is the use of early prototypes of Large Area Picoseconds Photo-Detectors (LAPPDs), figure 3a. It should demonstrate the capabilities and feasibility of LAPPDs in water and Gd loaded water Cherenkov detectors. In particular, a timing resolution below 100 picoseconds and a spatial resolution of 3 mm for single photons. This should allow a better track and vertex reconstruction as compared to traditional PMTs of the order of a few centimetres [5]. These features of LAPPDs are mandatory for such a small detector where photon drift times for direct light are below 10 nanoseconds (just similar to those of a traditional PMT resolution).

The size of the detector will be similar to that of SciBooNE: a cylindrical shape of ~3.8 m and ~2.3 m in diameter, see figure 3b. Apart from the LAPPDs, it will be instrumented with about 60-100 8-inch PMTs from the old IMB experiment. The muon range detector (an iron-scintillation sandwich detector) from SciBooNE can be recycled for ANNIE. It can reconstruct muon momentum and energies up to 1.2 GeV. Dirt neutrons from neutrino interactions with materials upstream will be removed with the front anti-coincidence counter while ambient neutrons from cosmic rays and sky shine neutrons from the beam dump and long lived isotopes will be removed by time cuts around the beam time window.

In conclusion, ANNIE represents an exceptional opportunity to improve the final-state neutron abundance from neutrino interactions as a function of their momentum transfer. One direct benefit of this measurement will be the improvement in the sensitivity of PD searches in water Cherenkov detectors. On the other hand, the development and test of the LAPPDs at ANNIE may represent an important technological milestone for water Cherenkov detectors.

3. SuperK-Gd

The main motivation to employ a new technique based on Gd loaded water in large water Cherenkov detectors came from SRNs. Soon after GADOOKS! [3] was proposed an R&D program at SuperK started: Evaluating Gadolinium’s Action on Detector Systems (EGADS). In 2009 a new hall near SuperK was excavated in the Kamioka mine. The project had five clear goals: it demonstrated that the filtration system can achieve and maintain a good water quality while keeping the Gd in water constant, it showed that Gd sulfate has no adverse effects on the SuperK detector components, it has
shown that we can add/remove Gd in a efficient and economical way, it showed it will not affect other SuperK analyses and finally, how to reduce the now visible neutron background (from spallation, U/Th fission chains from impurities in the Gd sulfate and ambient neutrons, etc).

It features a 200-ton tank made of the same stainless steel as the SuperK tank, a pre-treatment system (for Gd sulfate dilution and first stage cleaning before injection into the 200-ton tank), a newly developed water filtration system (able to clean all impurities, including all ions except Gd), a device to measure water transparency (Underground Device Evaluating Attenuation Length, UDEAL) and an atomic absorption spectrometer (AAS) to measure Gd concentrations in water. After several Gd loading tests were carried out at EGADS [6] (including a full 0.2% Gd sulfate load in the empty 200-ton tank), 240 photo-detectors were installed in summer 2013. The photo-coverage in EGADS is similar to SuperK (about 40 %). Opaque black polyethylene terephthalate sheets were installed too. A DAQ system with similar front-end electronics to SuperK before 2008 was also installed.

The last loading of our detector started towards end of 2014. Gd loading is done in several steps until the final target concentration of 0.2% in Gd sulfate is achieved. The water transparency is being constantly monitored. Figure 4 shows the Cherenkov light left after propagating 15 m in EGADS water as a function of time for three sampling positions in the 200-ton tank at top, centre and bottom positions. The Gd loadings are indicated by vertical hatched lines and theirs widths indicate the loading duration. After each Gd loading the water transparency decreases first and then recovers. Note that other drops are due to temporary operational disruptions in our water purification system. This figure clearly shows that after the full loading is achieved and enough recovery time, the water transparency is still within typical SK-III and SK-IV water transparency values (blue band).

The Gd sulfate concentration in water was periodically measured using an AAS. These measurements were done at the same positions in the 200-ton tank as for the water transparency. The result of these measurements is shown in figure 5. The target loading for each step are shown by the horizontal lines. After each loading, the concentration increases very quickly and reaches the expected value. After almost one year since the first loading, the Gd sulfate concentration does not show any sign of Gd loss (the water transparency recoveries are thus really due to efficient water cleaning without Gd loos).

What we learn from figures 4 and 5 are two important teachings: the EGADS water purification system does remove impurities in water while it does not remove significant amounts of Gd and that Gd sulfate is basically transparent to Cherenkov light.

When disposing the Gd loaded water was needed, we tested a special resin for Gd removal. When being processed, the resin catches the Gd and the disposed water contains less than 0.5 ppb of Gd. With this rather simple method of circulating Gd loaded water through this resin, we have shown
Fig. 4. Cherenkov light left after propagating 15 m in EGADS water as a function of time for three sampling positions in the 200-ton tank at top, centre and bottom positions. The Gd loadings are indicated by vertical hatched lines and their widths indicate the loading duration. The blue band shows typical SK-III and SK-IV water transparency values.

Fig. 5. Gadolinium sulfate concentration in water as a function of time in the three sampled positions: top, centre and bottom. The final concentration of gadolinium sulfate is about 0.2% in mass. The left figure shows single loads of 30 Kg while the right figure shows the double ones of 60 Kg (note here the suppressed zero on the y-axis).

that no significant amount of Gd is being released into the environment when using this method. Our laboratory is waterproof and no uncontrolled release of Gd has ever been produced.

Finally, we have carried out several studies to check the possible negative impact in our current analyses. As expected from the very small water transparency loss with full Gd loading, these studies show that there is a very limited impact on our current analyses. This is quite impressive because in these studies the benefits of neutron tagging were not taken into account.
All the data from all tests conducted at EGADS since 2009 were compiled in a document in June 2015 and given to an internal committee set up for this purpose. The same document was also circulated to all collaborators and in the autumn SuperK collaboration meeting the SuperK-Gd project was approved. The actual schedule of the project has to be determined together with the T2K collaboration but it has been a reward for all members of the EGADS project for all the efforts done since 2009 (for some even before that with previous preliminary studies after GADZOOKS! was published in 2004).

EGADS is currently the only Gd loaded water Cherenkov detector. However, to fully exploit its unique neutron tagging capabilities we need to upgrade its front-end electronics. As mentioned above the current electronics at EGADS are similar to those at SuperK before 2008. They are based in the old SuperK ATM modules [7]. EGADS has been continuously taking data during all the Gd loading process and afterwards (including several calibration campaigns). Figure 6 shows the inside of the EGADS detector before being filled with water and the event display of an incoming muon. However, the current configuration would not be able to record a close ccSN due to the large amount of expected events even with such a small detector. To achieve this goal EGADS will upgrade its electronics with the same QBEE modules [8] that are currently being used at SuperK.

Fig. 6. Inside view of the (empty) 200-ton tank EGADS detector with its 240 photo-detectors installed and opaque black polyethylene terephthalate sheets. In the lower right corner an event display corresponding to an income muon in the detector is shown.

4. Summary

The neutron tagging capabilities will be enhanced by loading Gd, the element with largest neutron capture cross section. When Gd captures a neutron it produces a 8 MeV gamma cascade. The high efficiency in detecting this gamma cascade in a large water Cherenkov detector with large photocoverage like SuperK will enable neutron capabilities in this detector. There are many benefits related
to this new capability: identify the dominant IBD events in case of a ccSN and allow to improve the pointing accuracy of SuperK, decrease background for SRN and PD searches, etc. Very detailed studies were carried out in the EGADS project. Here, the same conditions as those in SuperK were emulated in a 200-ton detector with very good results. The project SuperK-Gd was approved and the SuperK collaboration is moving towards its next upgrade and implement this new upgrade.

An interesting project related to the Gd technology is ANNIE. It will measure the neutron multiplicity yield in the atmospheric neutrino energy range. This measurement is necessary if we want to calculate an exact confidence for PD discovery and will add very valuable information in other searches at SuperK-Gd. In addition, the new LAPPD are now under development and will be tested at ANNIE. The demonstration of LAPPD at ANNIE would signify an important technological step forward for water Cherenkov detectors in photodetection.

References