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Status of GADZOOKS!: Neutron Tagging in Super-Kamiokande

P. Fernández for the Super-Kamiokande collaboration

Department of Theoretical Physics, University Autonoma Madrid, 28049 Madrid, Spain

Abstract

The GADZOOKS! project pursues the upgrade of the Super-Kamiokande detector as a way to efficiently detect thermal neutrons. Inverse beta decay reactions, as well as charged current quasi-elastic (CCQE) scattering of low energy anti-neutrinos (up to a few hundreds of MeV) in SK, produce one positron and one neutron in the final state. Being able to observe the final state neutron in coincidence with the prompt positron would mean that SK could identify these reactions as genuine with very high confidence.

GADZOOKS! will open to Super-Kamiokande - and water Cherenkov detectors in general - a wealth of physics currently inaccessible due to background limitations. The most important is observing for the first time the diffuse supernova neutrino background: Super-Kamiokande enriched with gadolinium will discover it after few years of running.

The main R&D program towards GADZOOKS! is EGADS: a 200 ton fully instrumented tank built in a new cavern in the Kamioka mine. EGADS incorporates all the necessary subsystems to make GADZOOKS! a reality. In this contribution we will describe EGADS, we will present its current status and discuss the main results and conclusions arrived at so far. In addition, we will analyze other issues specific to the running of GADZOOKS!.

Keywords: astrophysics, neutrino, neutron tagging, water Cherenkov detector

1. Introduction

Super Kamiokande (SK) is a 50,000 ton water Cherenkov detector located in the Kamioka mine under 1000 m of rock, which began the data taking in 1996. The detector is divided into inner and outer detector, the former is used for physics measurements and instrumented with 11146 PMTs of 20 inches, while the latter is used as a veto to reduce background and is instrumented with 1885 PMTs of 8 inches. The typical volume used for physics measurements is 22,500 tons, 2 m away from the inner detector wall.

The major achievements of SK are the discovery of the massive character of neutrinos through atmospheric neutrino oscillations [1], explanation of the solar neutrino problem [2] [3], the first indication of terrestrial matter effects through the day/night asymmetry in the solar neutrino flux [4]. As long baseline far detector it has confirmed the atmospheric neutrino results (KEK) [5] [6] and first detected the ν_e appearance (T2K) [7]. It also puts the best proton decay bounds [8] and the most stringent limits on Diffuse Supernova Neutrino Background (DSNB) [9] [10].

2. GADZOOKS!

The scientific capabilities of SK would improve dramatically if it is able to identify anti-neutrino interactions.

GADZOOKS! (Gadolinium Antineutrino Detector Zealously Outperform Old Kamiokande Super!) [11] is the project for upgrading the SK detector by dissolving gadolinium (Gd) in its water. Gd has the largest thermal neutron cross-section of all stable nuclei, of about 49000 barn, so Gd will capture the majority of final state

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neutrons produced in the interactions after they have thermalised. In addition, after the neutron has been captured, the Gd de-excites emitting a γ ray cascade with a total energy of 8MeV. As a result, by adding 0.2 % by mass of Gd as $Gd_2(SO_4)_3$, SK could achieve a very high efficiency for detecting the neutrons produced by the interacting neutrino.

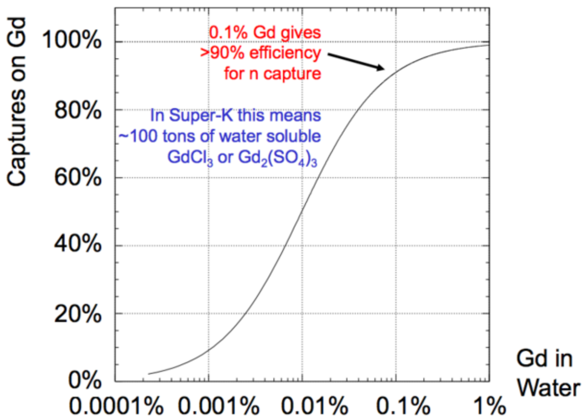

Figure 1: Neutron captures on Gd as a function of the concentration of gadolinium dissolved in water.

With this concentration, the time elapsed after the prompt signal (neutrino corresponding charged lepton) is about 35 μs ($\sim$ 10 μs for neutron thermalisation and $\sim$ 20 μs for the neutron to be absorbed by Gd).
The main interaction of neutrinos in SK especially at low energies (up to hundreds of MeV) are:

$$\nu_\alpha + n \rightarrow l_\alpha + p \quad , \quad \bar{\nu}_\alpha + p \rightarrow \bar{l}_\alpha + n \qquad (1)$$

Meaning that in this energy range, an efficient neutron tagging technique, such as Gd neutron capture, is able to distinguish between neutrinos and antineutrinos.

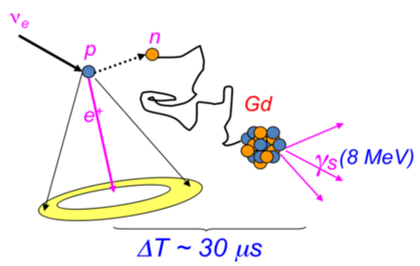

Figure 2: Inverse beta decay in GADZOOKS!

This neutron tagging method is around 5 times more efficient than the current technique, which tags some of the final state neutrons by detecting the 2.2 MeV photon emitted by the deuteron produced when a neutron is captured by the hydrogen present in the water. The weakness of the emitted photon and the larger elapsed time after the prompt signal ($\sim$ 200 μs) makes this method much less efficient.

2.1. Main physics outcomes

Next we go through some of the new physics research paradigms and the improvement of current measurements that GADZOOKS! will be able to do.

- Diffuse Supernova Neutrino Background (DSNB): One of our main goals for this upgrade is to be able to first detect DSNB. This is the neutrino background from all the supernovae that have occurred during along the history of the universe. This measurement will provide very important information, like the mean energy spectrum core collapse supernovae and the star formation rate of the universe.
  At present, this measurement is largely affected by backgrounds, spallation and solar neutrinos as shown in Fig. 3, that can be excluded effectively with neutron tagging.

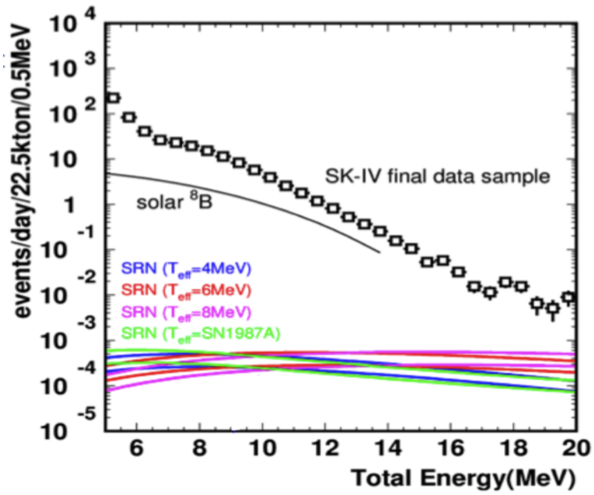

Figure 3: Different theoretical model predictions compared with current SK neutrino final sample, whose main source is the spallation events which still remain after the current spallation cut.

For the time being, SK can only put upper limits which are 2 to 4 times larger than the theoretical predictions [9], as shown in Fig. 4.

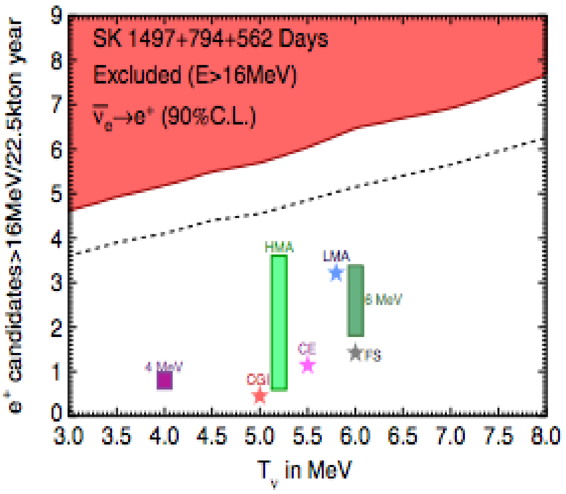

Figure 4: KamLAND and SK with and without hydrogen neutron tagging limits for DSNB

Therefore, with an efficient neutron tagging as the one with Gd, we expect to be able to reduce most of the backgrounds and be sensitive to DSNB. According to the various existing models, SK loaded with Gd would measure 3 to 5 DSNB antineutrino events per year, interacting via inverse β decay (IBD) in the detector.

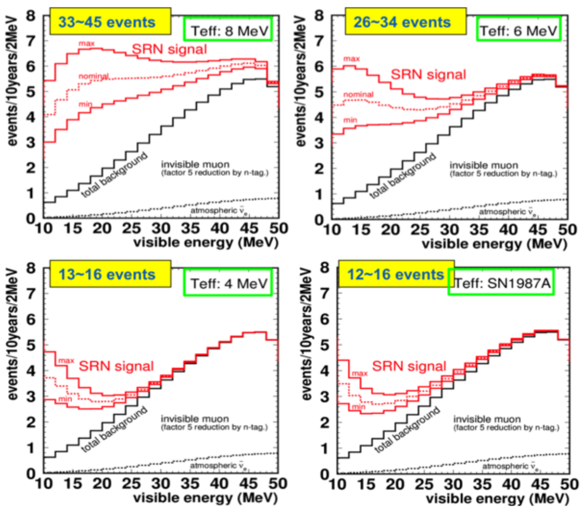

Figure 5: Expected number of events and energy spectrum for DSNB assuming different effective neutrino temperatures (T_{eff}) for 10 years of SKGd data taking.

- Galactic Supernova Burst: When a massive star at the end of its life collapses to a neutron star, it radiates almost all of its binding energy in the form of neutrinos, most of which have energies in the range 10 to 30 MeV, and are emitted over a timescale of several tens of seconds.
These neutrinos are released just after core collapse, whereas the photon signal may take hours or days to emerge from the stellar envelope.
SK will acquire a huge number of neutrino events if the supernova is close enough (namely in our galaxy), providing much information about early stages of the core-collapse process, its spectrum and time profile.

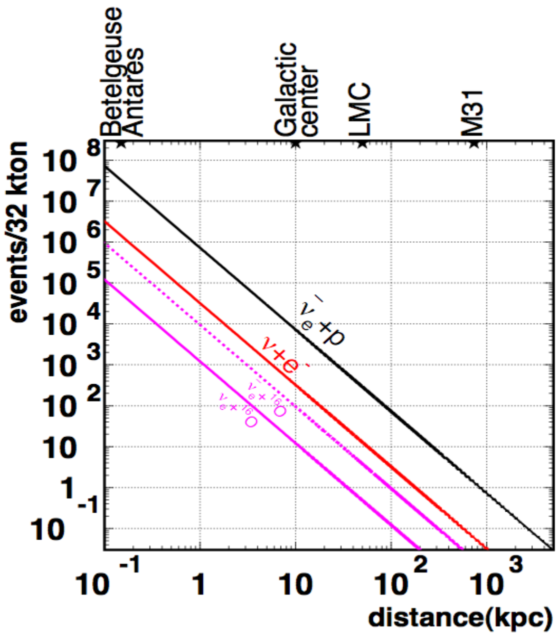

Figure 6: Number of events detectable in SK fiducial volume as function of the distance to the supernova with 5 MeV energy threshold.

But supernovae emit both, neutrinos and antineutrinos, with different energies and at different stages of core-collapse, therefore being able to improve discrimination between neutrino-electron scatterings (dominated by ν_e) and inverse beta reactions by adding Gd, would yield to a more detailed picture of the whole core-collapse process, extracting the ν_e and $\overline{\nu}_e$ spectra independently.

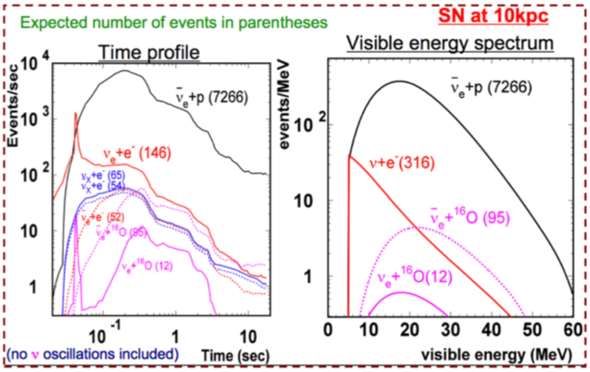

Figure 7: Supernova neutrino energy spectrum and time profile.

- Pre-supernova: These are stars which are at the onset of their collapse, just after carbon ignition, and release most of its energy through neutrinos. During the silicon burning stage, the neutrino luminosity is eight orders of magnitude less than in the peak at core-collapse, but while the later lasts just a few seconds, the Si burning phase takes several days. During the Si burning phase ~1% of the total energy of core-collapse are emitted through pre-supernova neutrinos with a monotonically increasing rate [12].

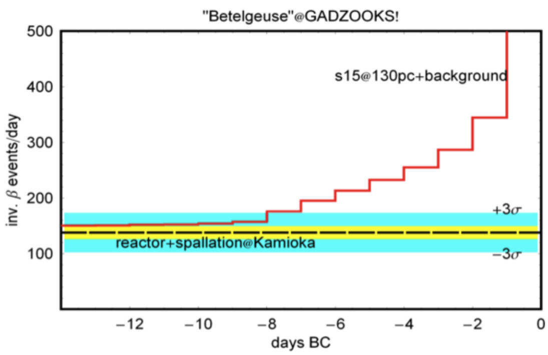

Figure 8: Monotonically increase of neutrino flux emission from pre-supernova candidate Betelgeuse [12].

Antineutrinos from Si burning stage have an average energy of 1.85 MeV, much less than the typical 10-20 MeV of supernova neutrinos. This means that SK cannot detect most of the e$^+$ from the antineutrinos interacting IBD, but in GADZOOKS!, the low energy backgrounds for antineutrinos are reduced and the energy threshold can be lowered, allowing the detection of a larger number of events.

The next table compares the expected number of events by SK and GADZOOKS! for Betelgeuse assuming it is 0.13 kpc away.

Detector	Target mass	Min. pre-collapse	Ev. 24-0h pre-collapse	Ev. 3-0h pre-collapse
Super-K	32 kt	5 MeV	173	158
GADZOOKS!	22.5 kt	3.8(1.8) MeV	442(1883)	345(1130)

Table 1: Estimate of the numbers of detectable events by SK and GADZOOKS! from pre-supernova candidate Betelgeuse, assuming it is 0.13 kpc away [12].

- Reactor Neutrinos: GADZOOKS! will be able to get rid off most of the backgrounds for reactor antineutrinos below 10 MeV. This opens the possibility to do a second analysis for the neutrino oscillation parameters of the solar sector, improving their current accuracy. Although the future of japanese nuclear reactors is not clear yet, GADZOOKS! will achieve the detection of similar reactor antineutrino rate as KamLAND when all the japanese reactors were on.

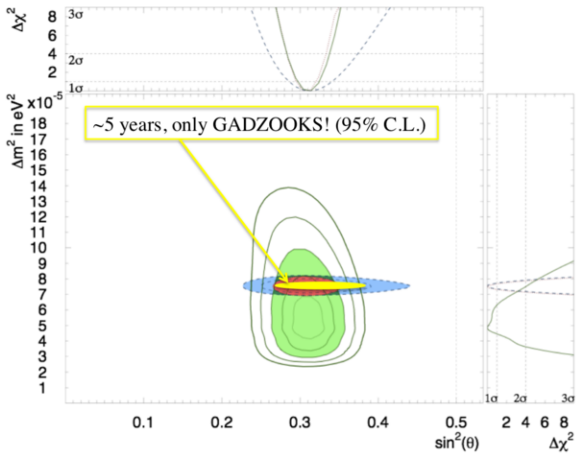

Figure 9: Sensitivity contours for solar oscillation parameters: prediction for 5 years of reactor antineutrino data in GADZOOKS! (yellow), compared to the current solar (green), KamLAND (blue) and solar+KamLAND (red) data.

- Others:
  - Improve the knowledge about atmospheric and accelerator neutrino interactions and final states.
  - Neutron tagging can also help in the separation of neutrino and antineutrino at the GeV scale.

- Neutron tagging reduces background in proton decay searches since it requires no neutrons to appear in the final state.

3. EGADS

EGADS (Evaluating Gadoliniums Action on Detector Systems) is a R&D project for testing the feasibility of adding Gd in water Cherenkov detectors. It consists of a 200-ton tank instrumented with 240 PMT's of 20" (like those in SK), a selective filtration system specially designed and developed to deal with Gd-doped water, a pretreatment system for purifying and dissolving $Gd_2(SO_4)_3$, a water transparency monitoring system, a device for measuring uniformity of the concentration and a system for removing the Gd from the water.

3.1. Latest results

The most relevant results from this test facility are presented.

- Water transparency measurement with UDEAL (Underground Device Evaluating Attenuation Length): This device measures the transparency of light through the water in the different parts (top, middle, bottom) of the 200-ton tank and for seven different wavelengths.

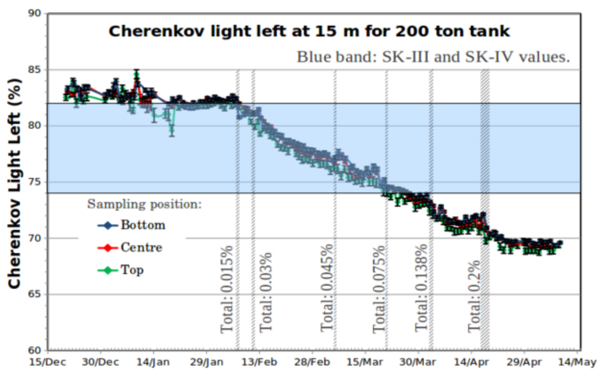

Figure 10: Water transparency measurement by UDEAL when EGADS was not instrumented, showing the effect of Gd.

For the non-PMT-instrumented EGADS the water attenuation length was very stable and good quality, showing very good behavior when introducing Gd, droping the water transparency less than 15%. Once EGADS was instrumented, the water transparency was not so good for pure water and became worse during the procedure of adding Gd, when changing the water level. After investigation, it was found that a type of wire became rusty, which has been replaced, and EGADS will soon resume its normal activity.

- Gd concentration measurement with AAS (Atomic Absorption Spectrometer): The water is periodically sampled from three points of the detector (top, middle, bottom) in order to measure the concentration of Gd and check the uniformity of the $Gd_2(SO_4)_3$ throughout the tank.
  For non-PMT-instrumented EGADS, the concentration becomes rapidly uniform along the whole volume of the detector after each Gd insertion and $Gd_2(SO_4)_3$ remains homogeneously dissolved.

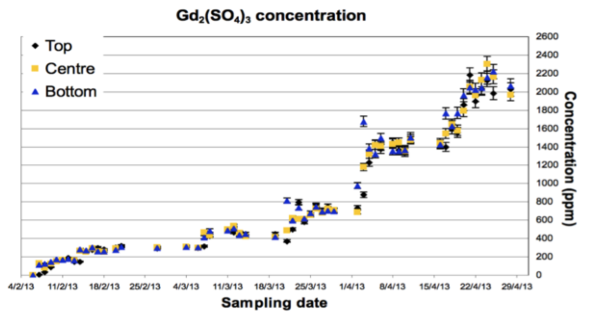

Figure 11: $Gd_2(SO_4)_3$ concentration at non-PMT-instrumented EGADS.

When Gd was added after the PMT installation, no major effect was seen in uniformity and stability of Gd.

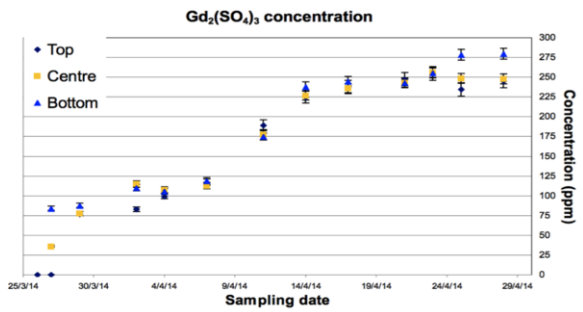

Figure 12: $Gd_2(SO_4)_3$ concentration at instrumented EGADS.

- Calibrations: Various calibrations are done in order to know the response and performance of the detector.
  - 1 photo-electron peak to measure the response of the PMTs.

- Relative timing calibration of the PMTs.
- PMT relative gain calibration.
- auto-Xe lamp connected to a scintillation ball monitors the gain variations.
- Am/Be source is used to test the detector performance and check the Gd neutron capture efficiency. It is based in the decay of ^{241}Am emitting an α particle captured by ^{9}Be which decays to ^{12}C emitting a 4.4 MeV photon (prompt signal) and a neutron.
  Since the delay of the neutron capture depends on the Gd concentration, this calibration is also used to check the amount of Gd in the water. The results agree well with the Monte Carlo simulations.

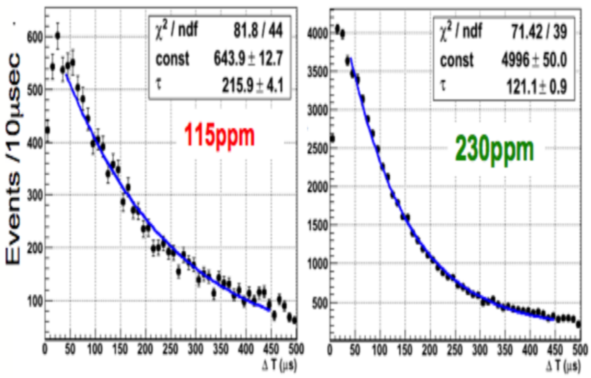

Figure 13: Preliminary results for the neutron capture delayed time for different Gd concentrations in water measured at EGADS.

$Gd_2(SO_4)_3$	data (μs)	MC (μs)
115 ppm	215.6 ± 4.1	221.8 ± 2.3
230 ppm	121.1 ± 0.9	124.8 ± 2.1

Table 2: Preliminary comparison between data and Monte Carlo of neutron capture time given two $Gd_2(SO_4)_3$ concentrations in parts per million.

4. Inverse β reconstruction

The success of GADZOOKS! will depend very much on how efficient we can identify low energy antineutrinos via their inverse-β reaction (IBD).
For that, Monte Carlo studies are done simulating the detector's response to the prompt and delayed signal. In addition to that, we must take care of the effect of the Gd compound on the light transmission, which decreases about 15 % compared to the pure water value. The two most extreme causes of the attenuation length loss are considered for this study, either absorption or Rayleigh scattering. This IBD efficiency study is done using the Monte Carlo and reconstruction tools of SK, and analysed with multivariate likelihood method.

	$e^+ + \gamma$s			e^- only		
	SKwater	Ray	Abs	SKwater	Ray	Abs
e reconstruction	99.6%	99.6%	99.7%	99.6%	99.5%	99.7%
γs Volume cut	89.4%	87.5%	80.3%	25.8%	25.7%	25.8%
Likelihood	96.5%	94.8%	91.7%	<0.001%	<0.001%	<0.001%
Total eff.	85.95%	82.64%	73.46%	$< 4\cdot10^{-4}$ %	$< 4\cdot10^{-4}$ %	$< 4\cdot10^{-4}$ %
	efficiencies			in-purities		

Figure 14: IBD reconstruction efficiency by relating the prompt (e^+) and delayed (γ cascade from neutron capture on Gd) signals, for three types of water transparency loss, pure-water-like, scattering-like and absorption-like.

Studies at U. C. Irvine show that the main effect of Gd on the water transparency is scattering, meaning that the loss in water transparency will not affect too much the reconstruction efficiency.

5. Radioactive contamination of $Gd_2(SO_4)_3$

Since the Gd compound will be dissolved and uniformly distributed along the whole active volume of the experiment, keeping controlled and as low as possible its radioactive contamination is an import an issue. For this purpose an exhaustive campaign is being carried out for measuring the radioactivity of various $Gd_2(SO_4)_3$ batches from different companies and purification processes.

Chain	sub-chain	Gd-0904	Gd-1008	Gd-1208	Gd-1302	Gd-1303	Gd-1308	Gd-1307a	Gd-1307b
^{238}U	^{238}U	51± 21	< 33	292±67	74±28	242±60	71±20	47±26	73±27
	^{226}Ra	8±1	2.8±0.6	74±2	13±1	13±2	8±1	5±1	6±1
^{232}Th	^{228}Ra	11±2	270±16*	1099±12	205±6	21±3	6±1	14±2	3±1
	^{228}Th	28±3	86±5	504±6	127±3	374±6	159±3	13±1	411±5
^{235}U	^{235}U	< 32	< 32	< 112	< 25	< 25	< 32	<12	<30
	^{227}Ac	214±10	1700±20	2956±30	1423±21	175±42	295±10	<6	<18
Other	^{40}K	29±5	12±3*	101±10	60±7	18±8	3±2	3±2	8±4
	^{138}La	8±1	<	683±15	3±1	42±3	5±1	<1	<2
	^{176}Lu	80±8	21±2	566±6	12±1	8±2	30±1	1.6±0.3	<2

Figure 15: Radiopurity measurements in mBq/kg for various $Gd_2(SO_4)_3$ samples at Canfranc Underground Laboratory.

Results show that radioactive contamination in the Gd compound is not negligible given the requirements needed for the realisation of GADZOOKS!. This radioactive contamination basically affects two measurements, DSNB and solar neutrino analysis. For estimating the impact in these measurements we assume typical values of the radioactivity levels present in the various $Gd_2(SO_4)_3$.

chain	sub-chain	assumed rad. (mBq/kg)
238U	238U *(upper)*	50
	226Ra *(bottom)*	5
232Th	228Ra *(upper)*	10
	228Th *(bottom)*	100
235U	235U *(upper)*	<30
	227Ac *(bottom)*	300

Table 3: Typical values of radioactive contamination present in the Gd compound.

- DSNB: The expected signal is ~ 5 events/year/SK, similar to the radioactive background coming mainly from ^{238}U spontaneous fission. But this background can be reduced by using AJ4400 purification resin, which has already been tested and reduces this background to $< 3{\cdot}10^{-2}$ events/year/SK.
- Solar ν: The solar electron neutrino flux at SK is ~ 10 events/day/kton for the three lowest energy bins (from 3.5 MeV to 5 MeV kinematic energy), whereas the radioactive background coming mainly from the ^{208}Tl β-decay is estimated to be $\sim 5{\cdot}10^3$ events/day/kton. Several purification processes and analysis methods are being studied to reduce this background.

6. Summary

GADZOOKS! is the project to upgrade SK incorporating 0.2% by mass of $Gd_2(SO_4)_3$ into the detector's water. This leads to a very efficient (~ 80%) way of tagging the final state neutrons that allow to make the first observation of DSNB. In addition to this, neutron tagging will improve greatly the neutrino-antineutrino separation in SK and will give much more information about the final state of the neutrino-nucleus interactions. The EGADS facility is providing the complete proof-of-principle of a Gd-loaded water Cherenkov detector, and once the tests are done, it will continue its activity as instant supernova detector with all the shown advantages of neutron tagging at this energy.

References

[1] Y. Fukuda, et al., Evidence for oscillation of atmospheric neutrinos, Phys. Rev. Lett. 81 (1998) 1562–1567. doi:10.1103/PhysRevLett.81.1562.
URL `http://link.aps.org/doi/10.1103/PhysRevLett.81.1562`

[2] S. Fukuda, et al., Solar ^8b and hep neutrino measurements from 1258 days of super-kamiokande data, Phys. Rev. Lett. 86 (2001) 5651–5655. doi:10.1103/PhysRevLett.86.5651.
URL `http://link.aps.org/doi/10.1103/PhysRevLett.86.5651`

[3] S. Fukuda, et al., Constraints on neutrino oscillations using 1258 days of super-kamiokande solar neutrino data, Phys. Rev. Lett. 86 (2001) 5656–5660. doi:10.1103/PhysRevLett.86.5656.
URL `http://link.aps.org/doi/10.1103/PhysRevLett.86.5656`

[4] A. Renshaw, et al., First indication of terrestrial matter effects on solar neutrino oscillation, Phys. Rev. Lett. 112 (2014) 091805. doi:10.1103/PhysRevLett.112.091805.
URL `http://link.aps.org/doi/10.1103/PhysRevLett.112.091805`

[5] M. H. Ahn, et al., Measurement of neutrino oscillation by the k2k experiment, Phys. Rev. D 74 (2006) 072003. doi:10.1103/PhysRevD.74.072003.
URL `http://link.aps.org/doi/10.1103/PhysRevD.74.072003`

[6] M. H. Ahn, et al., Indications of neutrino oscillation in a 250 km long-baseline experiment, Phys. Rev. Lett. 90 (2003) 041801. doi:10.1103/PhysRevLett.90.041801.
URL `http://link.aps.org/doi/10.1103/PhysRevLett.90.041801`

[7] K. Abe, et al., Evidence of electron neutrino appearance in a muon neutrino beam, Phys. Rev. D 88 (2013) 032002. doi:10.1103/PhysRevD.88.032002.
URL `http://link.aps.org/doi/10.1103/PhysRevD.88.032002`

[8] K. Abe, et al., Search for proton decay via $p \to \nu\, k^+$ using 260 kiloton · year data of super-kamiokande, Phys. Rev. D 90 (2014) 072005. doi:10.1103/PhysRevD.90.072005.
URL `http://link.aps.org/doi/10.1103/PhysRevD.90.072005`

[9] K. Bays, et al., Supernova relic neutrino search at super-kamiokande, Phys. Rev. D 85 (2012) 052007. doi:10.1103/PhysRevD.85.052007.
URL `http://link.aps.org/doi/10.1103/PhysRevD.85.052007`

[10] H. Zhang, et al., Supernova Relic Neutrino Search with Neutron Tagging at Super-Kamiokande-IV, Astropart.Phys. 60 (2014) 41–46. arXiv:1311.3738, doi:10.1016/j.astropartphys.2014.05.004.

[11] J. F. Beacom, M. R. Vagins, Antineutrino spectroscopy with large water Čerenkov detectors, Phys. Rev. Lett. 93 (2004) 171101. doi:10.1103/PhysRevLett.93.171101.
URL http://link.aps.org/doi/10.1103/PhysRevLett.93.171101

[12] A. Odrzywolek, et al., Future neutrino observations of nearby pre-supernova stars before core-collapse, AIP Conf. Proc. 944 (2007) 109.

[13] S. Horiuchi, J. F. Beacom, E. Dwek, Diffuse supernova neutrino background is detectable in super-kamiokande, Phys. Rev. D 79 (2009) 083013. doi:10.1103/PhysRevD.79.083013.
URL http://link.aps.org/doi/10.1103/PhysRevD.79.083013

[14] H. E. D. T. Totani, K. Sato, J. R. Wilson, Future detection of supernova neutrino burst and explosion mechanism, ApJ 496 (1998) 216. doi:10.1086/305364.