

## New ideas in neutrino detection

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**Abstract.** What is new in the field of neutrino detection? In addition to new projects probing both the low and high ends of the neutrino energy scale, an inexpensive, effective technique is being developed to allow tagging of antineutrinos in water Cherenkov (WC) detectors via the addition to water of a solute with a large neutron cross-section and energetic  $\gamma$  daughters. Gadolinium is an excellent candidate since in recent years it has become very inexpensive, now less than \$8 per kilogram in the form of commercially available gadolinium trichloride. This non-toxic, non-reactive substance is highly soluble in water. Neutron capture on gadolinium yields an 8.0 MeV gamma cascade easily seen in detectors like Super-Kamiokande. The uses of  $\text{GdCl}_3$  as a possible upgrade for the Super-Kamiokande detector – with a view toward improving its performance as an antineutrino detector for supernova neutrinos and reactor neutrinos – are discussed, as are the ongoing R&D efforts which aim to make this dream a reality within the next two years.

**Keywords.** Neutrino; antineutrino; supernova; reactor; Super-Kamiokande; gadolinium; gadzooks.

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### 1. New projects

There are a number of interesting new projects under construction around the world which will extend our understanding of neutrinos. Some of these will be probing very low neutrino energies, while others will look at the very highest energy neutrinos.

Table 1 contains a list of some of these new neutrino experiments. It is not a complete list of every new or proposed project, but rather indicates some of the interesting new developments in neutrino detection which we can expect to see in the next few years. Note that these detectors are sensitive to some *fifteen orders of magnitude* in neutrino energies!

### 2. I need patience, and I need it now!

The new projects mentioned in the last section will collect neutrinos from our Sun, our galaxy, and possibly from extragalactic sources as well. However, none of

**Table 1.** Some new neutrino projects.

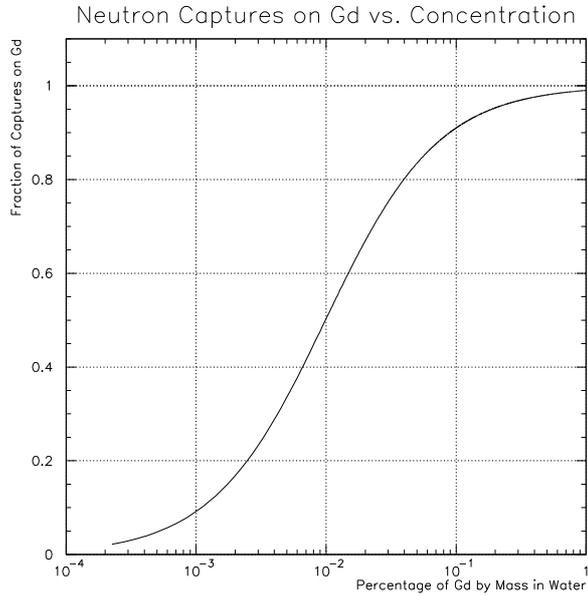
Detector	Neutrino source	Typical $\nu$ energy	Likely turn on date
IceCube	Extragalactic	PeV	2006
ANITA	GZK	EeV	2006
Borexino	Solar ${}^7\text{Be}$	0.8 MeV	2007
KamLAND-II	Solar ${}^7\text{Be}$	0.8 MeV	2007
Mini-CLEAN	R&D for Solar $pp$	0.3 MeV	~2007
ANTARES	Astrophysical	TeV	~2007
NESTOR	Astrophysical	TeV	~2007
SNO++	Solar ${}^7\text{Be}$	0.8 MeV	~2008
XMASS	Solar ${}^7\text{Be}$ and $pp$	0.3 MeV	~2009

them will be very good at observing some of the most interesting neutrinos – those produced in supernova explosions. But who has the patience to wait for the next nearby supernova?

Theorists and experimentalists alike wonder how we can get more neutrino data like SN1987A provided, as nearby supernovas are fairly rare events. On the other hand, supernovas themselves are *not* rare at all; on average, there is one supernova explosion somewhere in our Universe every second. Consequently, all the neutrinos which have ever been emitted by every supernova since the onset of stellar formation suffuse the Universe. These constitute the diffuse supernova neutrino background (DSNB), also known as the ‘relic’ supernova neutrinos. If observable, the DSNB could provide a steady stream of information about not only stellar collapse and nucleosynthesis but also the evolving size, speed, and nature of the Universe itself. What is more, these relic supernova neutrinos travel, on average, six *billion* light-years before reaching the Earth – certainly the ultimate long baseline for studies of neutrino decay and the like.

In 2003, the Super-Kamiokande Collaboration published the results of a search for these supernova relic neutrinos [1]. Unfortunately, this study was strongly background limited, especially by the many low-energy events below 19 MeV which swamped any possible DSNB signal in that most likely energy range. Consequently, this study could see no statistically significant excess of events and therefore was only able to set upper limits on the DSNB flux.

If it were possible to look for coincident signals from these inverse beta events, i.e., for a positron’s Cherenkov light followed shortly and in the same spot by the gamma cascade of a captured neutron, then these troublesome backgrounds could be greatly reduced. DSNB models vary, but in principle Super-K should then clearly see a few of these events every year. A much larger, future detector like the proposed Hyper-Kamiokande [2] would, with coincident neutron detection, collect a sample of relic supernova neutrino events equal to what was seen seventeen years ago from SN1987A *every month or so*.



**Figure 1.** How the concentration of gadolinium affects detectable neutron absorption.

But how can neutron detection be made to work in very large water Cherenkov detectors such as these?

### 3. A modest proposal

John Beacom and I are proposing to introduce non-toxic, water soluble gadolinium (tri)chloride,  $GdCl_3$ , into the rebuilt Super-Kamiokande-III detector. As neutron capture on gadolinium produces an 8.0 MeV gamma cascade, the inverse beta decay reaction,



in such a modified Super-K will yield coincident positron and neutron capture signals. This will allow a large reduction in backgrounds and greatly enhance the detector's response to both supernova neutrinos (galactic and relic) and reactor antineutrinos.

The gadolinium must compete with the hydrogen in the water for the neutrons, as neutron capture on hydrogen yields a 2.2 MeV gamma, which is essentially invisible in Super-K. The neutron stopping power of Gd in solution can be seen in figure 1.

So, by using 100 t of  $GdCl_3$  we would have 0.1% Gd by mass in the SK tank, and just over 90% of the inverse beta neutrons would be visibly caught by gadolinium. Due to recent decline in the price of gadolinium as a result of new large-scale production facilities opening up in Inner Mongolia, adding this much  $GdCl_3$  to Super-K

would cost no more than \$500,000 today, though it would have cost \$400,000,000 back when SK was first designed.

We propose calling this new project ‘GADZOOKS!’ In addition to being an expression of surprise, here’s what it stands for: Gadolinium Antineutrino Detector Zealously Outperforming Old Kamiokande, Super!

This proposal is detailed in our recent article [3]. Note that this is the only method of detecting neutrons which can be extended to the tens-of-kilotons scale and beyond, and at reasonable expense – adding no more than 1% to the capital cost of detector construction – as well.

#### 4. Galactic supernova neutrinos

Naturally, if we can do relics, we can do a great job with galactic supernovas, too. With 0.1% gadolinium in the Super-K tank, the copious inverse betas get individually tagged, allowing us to study their spectrum and subtract them away from the directional elastic scatters, which will double our pointing accuracy. The  $^{16}\text{O}$  NC events no longer sit on a large background and are hence individually identified, and the  $O(\nu_e, e^-)F$  events’ backwards scatter can be clearly seen, providing a measure of burst temperature and oscillation angle.

In addition, based on event timing alone, Super-K with  $\text{GdCl}_3$  will be able to immediately identify a neutrino burst as a genuine supernova. This is due to the fact that the average timing separation between subsequent neutrino interactions would be much longer than the timing separation between coincident events (except for a *very* close supernova, but in that case see the ‘SN early warning’ section). Even a modest number of these coincident inverse beta events would be a clear signature of a burst and could not be faked by mine blasting, spallation, or dropped wrenches.

These same distinctive inverse beta signatures will allow SK to look for black hole formation (and other interesting things) out to extremely long times after the burst. Above 6 MeV, coincident inverse beta background events, primarily due to the many nuclear power reactors in Japan, will occur on the level of less than one a day. This is to be compared with about 150 single events a day in our final low-energy sample. Therefore, the presence of Gd in the SK water will mean that signals from a supernova will take much longer to drop below the background level, making late neutrino observations of the cooling SN remnant possible for the first time.

#### 5. SN early warning

Inspired in part by our GADZOOKS! preprint, another group of scientists has recently pointed out the possibility of being able to tell that a wave of SN neutrinos was about to pass through the Earth [4].

Let us suppose that a relatively large, rather close star, like Betelgeuse, is about to explode as a supernova. Carbon burning takes about 300 years, then neon and oxygen burning each power the star for half a year or so. Finally, silicon ignites,

forming an inert iron core. After about two days of Si burning, the star explodes as a supernova.

But during silicon burning the star is hot enough ( $T > 10^9$  K) that the pair annihilation process

$$e^+ + e^- \rightarrow \nu_x + \bar{\nu}_x \quad (2)$$

starts to produce large numbers of  $\bar{\nu}_e$ s with an average energy of 1.87 MeV. This is coincidentally *just* above the inverse beta threshold of 1.8 MeV.

Therefore, if Super-K has GdCl<sub>3</sub> in it when this happens, we would expect to see  $\sim 1000$  inverse beta neutron capture singles (the positron is not above Cherenkov threshold) a day. This is *seven times* the current low-energy singles rate in SK, and could not be missed. No other detector on Earth would know that the main burst was about to arrive – only SK with Gd could do this! Surely the astronomical and neutrino communities, not to mention our gravity-wave colleagues, would appreciate knowing that a nearby star was about to explode.

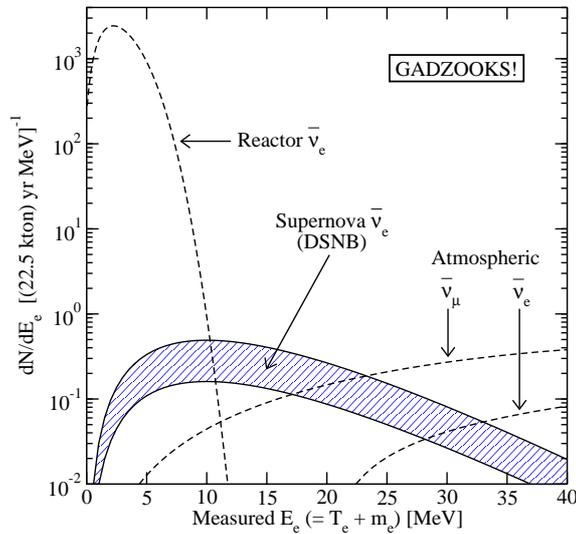
Now, it is granted that the supernova has to be pretty close. This trick will only work well out to about 1 kiloparsec in Super-K or 5 kpc in Hyper-K. On the other hand, these are the most valuable bursts and we would have the most to lose if we missed one due to calibration or scheduled detector downtime. Such downtime could be postponed a few days in the event of a sudden rise in the neutron capture rate. So, I like to think of this as a supernova insurance policy.

## 6. Reactor antineutrinos

It does not have anything to do with the detection of supernova neutrinos, but if we were to introduce a 0.1% solution of gadolinium into Super-Kamiokande, we could collect enough reactor antineutrino data to reproduce KamLAND's first published results [5] in just *three days* of operation. Their entire planned six-year data-taking run could be reproduced by Super-K with GdCl<sub>3</sub> in seven weeks, while Hyper-K with GdCl<sub>3</sub> could collect six KamLAND-years of  $\bar{\nu}_e$  data in just one day.

Super-K would collect enough reactor  $\bar{\nu}_e$ s every day to enable it to monitor, in real time, the total reactor  $\bar{\nu}_e$  flux. This means that, unlike KamLAND, it would not be dependent on the power companies which operate the reactors accurately reporting their day-to-day power output. Note that these plentiful reactor  $\bar{\nu}_e$  events would not be confused with the comparatively rare relic supernova  $\bar{\nu}_e$ s because of the widely differing antineutrino energy ranges and spectra of the two processes. Figure 2 shows the expected coincident signals in a gadolinium-enhanced Super-K.

Also inspired by our GADZOOKS! preprint, another set of scientists has calculated the effect such reactor antineutrino measurements would have on the precision of the solar neutrino mixing parameters [6]. They find that after just three years of data-taking Super-K with gadolinium could reduce the error on  $\Delta m_{12}^2$  from the current value of  $\pm 10\%$  to just over  $\pm 1\%$  at the 99% confidence level. This would constitute the first precision determination of one of the fundamental neutrino parameters. The corresponding improvement on the precision of  $\sin^2 \theta_{12}$ , while not as dramatic as that for  $\Delta m_{12}^2$ , would nevertheless be significant in its own right.



**Figure 2.** The expected coincident signals in Super-K with 100 t GdCl<sub>3</sub>. Detector energy resolution is properly taken into account. The upper supernova curve is the current SK relic limit, while the lower curve is the theoretical lower bound.

## 7. Gadolinium R&D

But John and I never wanted to merely propose a new technique – we wanted to make it work!

In September 2003 and again in 2005, I received Advanced Detector Research Program grants from the U.S. Department of Energy for the study of GdCl<sub>3</sub>'s properties and possible effects on Super-Kamiokande. These grants cover three main topics:

- (1) Explore the chemistry, stability, and optical properties of GdCl<sub>3</sub> in detail.
- (2) Understand any changes needed in the SK water system in order to recirculate clean water but not remove the GdCl<sub>3</sub> solute.
- (3) Soak samples of all materials which comprise the Super-K detector in water containing GdCl<sub>3</sub> over a period of greater than one year and then look for any GdCl<sub>3</sub>-induced damage.

A scaled-down version of the Super-K water filtration system was built at the University of California, Irvine. We are currently using this system to test out new water filtration technologies in order to maintain the desired GdCl<sub>3</sub> concentration in the otherwise pure water. Gadolinium retention rates of over 99.9% per pass have been achieved. Meanwhile, at Louisiana State University materials aging studies are underway. After a GdCl<sub>3</sub> exposure equal to 30 years at the proposed concentration in Super-K we see no significant damage to the aged detector components. Preliminary measurements of the optical properties of GdCl<sub>3</sub> were conducted in Japan during the spring of 2004, with very promising results.

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After two years of these bench tests, I was allowed to use the K2K experiment's one kiloton (KT) water Cherenkov tank, a 2% working scale model of Super-Kamiokande at KEK, for large-scale Gd studies. This was possible only after K2K's long-baseline neutrino beam turned off for good in early 2005 and final post-calibration runs were completed. In November 2005 I introduced 200 kg of  $\text{GdCl}_3$  into the KT.

The good news is that adding gadolinium chloride itself did not hurt the water transparency in the KT tank, and the water filtering system developed at UCI worked perfectly. The bad news is that the chlorine attached to the gadolinium to make it dissolve in water attacked some old rust in the KT tank, which is made of painted iron, and lifted it into solution. This then made the water transparency go down and the water change color. Finally, at the end of March 2006, we removed  $\text{GdCl}_3$  and drained the KT so we could look inside and be sure of what was happening.

This inspection of the inside of the KT tank showed large areas (about 20% of the total inner surface area) which had not been properly painted back in 1998 – these were very rusty. It is not believed that the  $\text{GdCl}_3$  itself caused the rust. This has been checked with tabletop tests involving clean and pre-rusted iron samples soaked in  $\text{GdCl}_3$  solutions. As Super-K is made of stainless steel, not (badly) painted iron, we still expect this idea will work in Super-K, though more studies are clearly needed.

It has been decided that the next step in the gadolinium R&D will be to build a custom-made tank out of stainless steel, and make it as similar to Super-K as possible. In April, 2006, Lawrence Livermore National Lab agreed to fund the construction and operation of a stainless steel Gd-testing tank in the US. Construction will most likely begin sometime in July 2006.

We learned a number of important things in the kiloton detector:

- (1)  $\text{GdCl}_3$  is easy to dissolve in water.
- (2)  $\text{GdCl}_3$  itself (i.e., in the absence of old rust) does not significantly affect the light collection.
- (3) Choice of detector materials is critical with  $\text{GdCl}_3$ .
- (4) The 20-inch Super-K PMTs operate well in conductive water.
- (5) Our Gd filtration system works as designed at 3.6 t/h and can easily be scaled up to higher (Super-K level) flows.

All of these findings are of course applicable to putting  $\text{GdCl}_3$  into Super-Kamiokande someday. Since Super-K is made of good quality stainless steel, not iron, we do not expect such rust trouble there. Even so, we should (and will) make things work with gadolinium in a stainless steel test tank first.

After discussions at the most recent Super-Kamiokande Collaboration meeting in May 2006, it now appears quite likely that the decision will be made to put gadolinium into Super-K sometime in the next two years. The University of Tokyo is beginning to assign some of their young people to focus on the project, and we now have a gadolinium working group within the Super-K Collaboration and this is extremely encouraging!

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