# RELIC SUPERNOVA NEUTRINOS

M.R. VAGINS
*University of California, Irvine*
*Department of Physics & Astronomy*
*4129 Reines Hall*
*Irvine, CA 92697, USA*

Relic supernova neutrino detection is discussed, with particular emphasis on the Super–Kamiokande experiment. Presently under intensive study and discussion, a novel proposed modification to existing and future water Cherenkov detectors is presented. Enabling such detectors to identify neutrons will significantly enhance their capabilities for relic supernova neutrino detection as well as for a wide variety of other physics topics.

## 1 Introduction

On February 23rd of this year we celebrated a big anniversary — it has been twenty years since the observation of neutrinos from supernova SN1987A. But nearby supernovas are fairly rare events, occurring approximately once every few decades within our own galaxy. Consequently, the handful of neutrinos seen in 1987 remain the only neutrinos ever observed which originated from somewhere more distant than our own Sun.

However, there are many galaxies, and so on average one supernova explodes somewhere in our universe every second. All of the neutrinos which have ever been emitted by every supernova since the onset of stellar formation suffuse the universe. As a result, we are continuously bombarded with diffuse supernova neutrino background (DSNB) radiation. In fact, about 100,000 of these so-called "relic" supernova neutrinos pass through each one of us every second.

These neutrinos, if observable, could provide a steady stream of information about not only stellar collapse and nucleosynthesis but also on the evolving size, speed, and nature of the universe itself. This goal, until recently a distant dream of both theorists and experimentalists, may now be achievable within the next few years. The work which could make this possible, along with its far-reaching implications for other types of neutrino physics, will be the focus of this paper.

## 2 Know Your Limits

Super–Kamiokande (Super–K, SK) is the world's largest underground water Cherenkov detector. With a total mass of 50 kilotons and a fiducial mass of 22.5 kilotons, it is located some 250 km west of Tokyo in an old zinc mine deep in the Japanese Alps. The detector is described in detail elsewhere [1].

In 2003 the Super–Kamiokande Collaboration conducted a search for supernova relic neutrinos [2] based on the first five years of data from Super–K. Unfortunately, this study was strongly background limited, especially by the many low energy events below 18 MeV which swamped any possible DSNB signal in that most likely energy range. Consequently, this search could see no statistically significant excess of events and therefore was only able to set upper limits on the DSNB flux. These limits, which at 18 MeV were about one event per 22.5 kton per year per MeV, are just a bit higher than modern theoretical predictions of the flux. However, as a background-limited search a convincing DSNB signal would require at least another twenty years of Super–K data. Not a very encouraging situation!

But what if the DSNB events could be uniquely identified in SK, freeing the analysis from background complications?

## 3 How Can One Identify the DSNB Events?

In what began in 2002 as a search for a new method of extracting the relic supernova neutrino signal without background issues, theorist John Beacom and I have been tossing around ideas regarding modifying the Super–K detector. We finally decided to tackle the DSNB problem once and for all, with the admittedly ambitious goal of extracting a clear, positive signal within the next few years. It has proven to be a very fruitful partnership: in 2004 we published a *Physical Review Letters* article [3] outlining our proposal, upon which this paper is largely based.

### *3.1 The Goal*

All of the events in the present DSNB analysis are singles in both time and space. This singles rate is actually quite low in Super–K, only three events per fiducial ton per year. Therefore, if it were possible to look for coincident signals, 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 background singles could be eliminated.

"Wouldn't it be great if we could tag *every* supernova relic neutrino," we thought. Well, the reaction we are looking for is:

$$\overline{\nu}_e + p \rightarrow e^+ + n \tag{1}$$

So the real question is, how can we reliably identify the neutron?

### *3.2 The Challenge*

Of course, it is well known that free neutrons in water get captured by free protons and emit 2.2 MeV gammas, far below Super–K's normal trigger threshold. However, if we could manage to see these we'd be in business! Maybe we could just lower the Super–K threshold briefly after each regular trigger...

This would be possible, and no SK change except a new trigger board would be required. Such a board has actually been built and tested in Super–K, but its efficiency for neutron detection is very low. As DSNB interactions within Super–K are rare, above 10 MeV just a handful per year, what we really want is to get *all* of this signal.

Hence, we need something in the water which will compete with the hydrogen in capturing neutrons.

### *3.3 The 0.1% Solution*

We finally turned to the best neutron capture nucleus known: gadolinium. It has a nice 8.0 MeV gamma cascade, easily visible in Super–K. Unlike metallic Gd, the compound gadolinium (tri)chloride, $GdCl_3$, is highly water soluble.

We found that in order to collect 50% of the neutrons on gadolinium and 50% on hydrogen you'd need to put just 9 tons of $GdCl_3$ in Super–K. That's exactly two cubic meters. No problem!

Even better, to collect >90% of the neutrons on gadolinium you'd only need to put 100 tons of $GdCl_3$ in Super–K. That's about twenty cubic meters, or a 0.1% concentration of Gd in the tank, and with it we can tag almost all of the relic events.

Models vary, but with this solute in the water Super–K should see about five DSNB events each year with virtually no background at all. Now imagine a future, megaton-scale water Cherenkov detector like Hyper–Kamiokande (Hyper–K) observing 100+ supernova relic neutrinos every year...

### *3.4 The Price of Gd in China*

From a physics standpoint it certainly seems like $GdCl_3$ is a nice compound to use for tagging neutrons, but can we afford 100 tons or more of it? As it turns out, there has been a dramatic revolution in the price of gadolinium over the past two decades. The opening of new mineral fields in the Gobi desert and the scaling up of rare earth refining and purification technologies have caused the price to plummet *three orders of magnitude* in recent years.

If we had tried to use gadolinium in Super–Kamiokande from day one the raw materials alone would have added $400 million dollars (U.S.) to the cost of that $100 million project. Today, acquiring 100 tons of 99.99% pure $GdCl_3$ will cost us just under $530,000. The formerly high price of gadolinium could very well explain why no one has ever even proposed using gadolinium in very large detectors before.

## 4 What Else Can We Do With Gd?

If adding $GdCl_3$ only allowed us to clearly see the as-yet-unobserved relic supernova neutrinos it would be a significant scientific breakthrough. In just a few years, the yield of supernova neutrinos from SN1987A would be obtained and then surpassed. Furthermore, since the cost of $GdCl_3$ is low this approach, unlike all previous neutron detection technologies, is readily scalable at reasonable expense to even the largest proposed future projects. The addition of gadolinium should add less than 1% to the total capital cost of any such experiment.

As it turns out, mixing $GdCl_3$ into Super–K's water will open up a wide variety of new physics opportunities *in addition* to making possible the world's first observation of the DSNB.

### *4.1 Galactic Supernovas*

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 $^{16}$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 $GdCl_3$ 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 stuff) 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 singles 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.

### *4.2 SN Early Warning*

Inspired in part by our *PRL* article's preprint, another group of authors has pointed out the possibility of being able to tell that a wave of SN neutrinos was about to pass through the Earth [4]:

Let's suppose that a relative 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

$$e^+ + e^- \rightarrow \nu_x + \overline{\nu}_x \tag{2}$$

starts to produce large numbers of $\overline{\nu}_e$'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 $GdCl_3$ 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, granted, the supernova has to be pretty close. This trick will only work well out to about 2 kiloparsecs in Super–K or 10 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, think of this as a supernova insurance policy.

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 $GdCl_3$ in seven weeks, while Hyper–K with $GdCl_3$ could collect *six KamLAND-years of* $\overline{\nu}_e$ *data in just one day.*

Although Super–K with $GdCl_3$ will not be able to extract spectral information over the entire energy range to which scintillator detectors are sensitive, it will have the unique ability to provide some $\overline{\nu}_e$ directional information via the emitted positrons' Cherenkov light. This should, especially given the extremely high statistics involved, allow significantly tighter constraints to be placed on the solar neutrino oscillation parameters [6] than any other method which could conceivably become operational before the close of the present decade, and possibly far beyond. We would have these data in hand within months of the decision to introduce $GdCl_3$ into Super–Kamiokande.

## 5 Gadzooks!

Since John and I were focusing on the low energy side of things, we haven't even gotten into how this solute should also allow our high energy friends to differentiate between atmospheric (or long baseline) neutrinos and antineutrinos of all species, reduce backgrounds to proton decay searches, and so on.

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!

## 6 Gadolinium R&D

But we never wanted to merely propose a new technique — we wanted to make it work!

In 2003 and again in 2005 and 2007 I received Advanced Detector Research Program grants from the U.S. Department of Energy for the study of $GdCl_3$'s properties and possible effects on Super–Kamiokande. These grants cover three main topics:

1. Explore the chemistry, stability, and optical properties of $GdCl_3$ in detail.
2. Understand any changes needed in the SK water system in order to recirculate clean water but not remove the $GdCl_3$ solute.
3. Soak samples of all materials which comprise the Super–K detector in water containing $GdCl_3$ over a period of greater than one year and then look for any $GdCl_3$-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 $GdCl_3$ concentration in otherwise pure water. Gadolinium retention rates of over 99.9% per pass have been achieved. Meanwhile, at Lawrence Livermore National Laboratory materials aging studies are underway. After a $GdCl_3$ 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 the $GdCl_3$ were conducted in Japan during the spring of 2004, with very promising results.

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 of 2005 I introduced 200 kg of $GdCl_3$ into the KT.

The good news is that adding the 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 the $GdCl_3$ 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 $GdCl_3$ itself caused the rust. This has been checked with tabletop tests involving clean and pre-rusted iron samples soaked in $GdCl_3$ 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 was decided that the next step in the gadolinium R&D should 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. That study is now reaching completion, with results expected in mid-2007.

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

1. $GdCl_3$ is easy to dissolve in water.
2. The $GdCl_3$ itself (i.e., in the absence of old rust) does not significantly affect the light collection.
3. Choice of detector materials is critical with $GdCl_3$.
4. The 20-inch Super–K PMT's operate well in conductive water.
5. Our Gd filtration system works as designed at 3.6 tons/hr and can easily be scaled up to higher (Super–K level) flows.

All of these findings are of course applicable to putting $GdCl_3$ into Super–Kamiokande someday. Since Super–K is made of good quality stainless steel, not iron, we don't expect such rust trouble there. Even so, we should (and will) make things work with gadolinium in a stainless steel test tank first.

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 Committee within the Super–K Collaboration - this is all extremely encouraging!

## References


1. Y. Fukuda *et al.*, *Nucl. Instrum. Meth.* **A501**, 418–462 (2003)
2. M. Malek *et al.*, *Phys. Rev. Lett.* **90**, 061101 (2003).
3. J.F. Beacom and M.R. Vagins, *Phys. Rev. Lett.* **93**, 171101 (2004).
4. A. Odrzywolek *et al.*, *Astropart. Phys.* **21**, 303-313 (2004).
5. K. Eguchi *et al.*, *Phys. Rev. Lett.* **90**, 021802 (2003).
6. S. Choubey and S.T. Petcov, *Phys. Lett.* **B594**, 333-346 (2004).