INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS

J. Phys. G: Nucl. Part. Phys. **29** (2003) 2543–2567 PII: S0954-3899(03)68150-8

Science from detection of neutrinos from supernovae

R N Boyd[1], **G C McLaughlin**[2], **A St J Murphy**[3] **and P F Smith**[4,5]

[1] Department of Physics, Department of Astronomy, Ohio State University, Columbus, OH 43210, USA

[2] Department of Physics and Astronomy, North Carolina State University, Raleigh, NC 27695, USA

[3] School of Physics, University of Edinburgh, Edinburgh, EH9 3JZ, UK

[4] Rutherford Appleton Laboratory, Chilton, Oxfordshire, OX11 OQX, UK

[5] Department of Physics and Astronomy, University of California at Los Angeles, Los Angeles, CA 90095, USA

Received 26 August 2003
Published 14 October 2003
Online at stacks.iop.org/JPhysG/29/2543

Abstract

The neutrinos emitted from supernovae contain information about the physics of stellar collapse and of the nature of the neutrinos themselves. Several large detectors exist that will be capable of observing some subset of those neutrinos. In addition, we have designed OMNIS, the Observatory for Multiflavour NeutrInos from Supernovae. OMNIS will detect the neutrinos from (a) neutral-current interactions from ν_e, ν_μ, $\bar{\nu}_\mu$, ν_τ and $\bar{\nu}_\tau$, and (b) charged-current interactions from high-momentum ν_e, with lead nuclei. It will utilize two types of detectors: (1) lead slabs alternating with vertical planes of neutron detectors, in which neutrons produced by neutrino–lead interactions will be detected, and (2) lead perchlorate, in which both the resulting neutrons and Cerenkov light will be detected. OMNIS will measure neutrino masses below 100 eV, provide new information on MSW or vacuum oscillations from ν_μ/ν_τ to ν_e, especially to Θ_{13}, and possibly diagnose the process of collapse to a black hole. It will observe the late-time evolution of the neutrino distributions, and possibly see predicted late-time effects, e.g. a phase transition from neutron-star matter to kaon-condensed matter or quark matter. OMNIS is also sensitive to some modes of nucleon decay that should make it possible to improve significantly on present limits for those modes. Of crucial importance to OMNIS is an experiment, using neutrinos from a stopped pion beam, to determine the flavour and energy-dependent response of lead to neutrinos. This will provide important input into cross section calculations for which few data currently exist. We plan to perform this experiment using one of the lead perchlorate detector modules from OMNIS.

1. Introduction

A massive star evolves by consuming, through nuclear reactions, the nuclear fuels that comprise its different burning zones (Arnett 1996, Boyd 1999). After each fuel in its core is consumed the core compresses, raising its temperature to a level that ignites its next fuel. The core stabilizes while the next fuel burns, until it reaches a temperature of several billion K and has been converted into iron and nickel. At this point it cannot be stabilized by burning another fuel so, if its mass is sufficiently large, it collapses to a neutron star. The prodigious amount of energy contained in the stellar core (Burrows 1990), $\sim 10^{53}$ erg, is released in the seconds after the star's collapse. A small fraction, $\sim 1\%$, goes into the shock wave that explodes the star, and $\sim 0.01\%$ into the light that identifies it as a supernova (SN). Most of the energy, 99%, is emitted in neutrinos. The time distribution of neutrinos *as they are emitted from the core of the star* is thought to first exhibit a spike when the shock wave passes through the ν_e neutrinosphere, followed by an extended hump, extending for several seconds, expected to contain comparable numbers and mean energies of ν_μ, $\bar{\nu}_\mu$, ν_τ, and $\bar{\nu}_\tau$ ($=\nu_x$). The total energies contained in each of the distributions are thought to be the same, but the ν_e are expected to have a lower mean energy than the $\bar{\nu}_e$, which in turn have a lower mean energy than the ν_x. However, oscillations are expected to change the flavour/energy mix considerably by the time the neutrinos arrive at the Earth, as discussed below.

To date, a large burst of neutrinos from a SN has never been observed. The events seen from SN 1987A (Hirata *et al* 1987, Bionta *et al* 1987), shown in figure 1, were insufficient to allow more than a qualitative comparison of data and theory, but they did indicate that the standard model of stellar collapse is essentially correct. More definitive statements, however, are limited both by the statistically poor sample of events and the fact that essentially only $\bar{\nu}_e$-initiated events were observed.

Several large detectors exist around the world that will observe neutrinos when those from the next galactic SN arrive at Earth. Super-Kamiokande (Super-K) will detect of order 10^4 events from a SN at the galactic centre, induced by $\bar{\nu}_e$ interacting with the protons and oxygen nuclei in its water. It will measure the energy distribution of the $\bar{\nu}_e$. Super-K will also detect some ν_x, but the threshold for their detection is sufficiently high that their number will be considerably less than that of the $\bar{\nu}_e$. The actual number is uncertain, especially since the neutrino distributions are expected to vary from a zero-chemical-potential Fermi–Dirac form, particularly on their tails.

The Sudbury Neutrino Observatory (SNO) is expected to produce around 1000 events from a SN near the galactic centre. While this is considerably less than that expected from Super-K, it will contain a fair fraction, roughly 25%, of ν_x-induced events. SNO operates both with ordinary water and heavy water; the ordinary water will be most sensitive to $\bar{\nu}_e$, but the heavy water will produce sensitivity to the ν_x, and also to the ν_e via charged-current (CC) interactions. Another detector with interesting sensitivities to SN neutrinos is KamLAND. Its detection medium is liquid scintillator, its protons are sensitive to $\bar{\nu}_e$ and the carbon to ν_x. KamLAND would be expected to produce roughly half as many SN-neutrino-induced events as SNO, but with about 35% being ν_x-induced. The SNO, Super-K and KamLAND yields are given in table 1, although it should be noted that they are all for the no-oscillation case. They would be expected to increase from those values when oscillations are included.

However, as discussed below, it is important to obtain a large number of events induced by neutrinos and antineutrinos of all flavours, but specifically by the ν_e. With detectors that are currently, or soon to be, on line, by far the most events will be detected in the $\bar{\nu}_e$ channel. Thus, to obtain a large signal from all other neutrino flavours, we are proposing to build OMNIS, the Observatory for Multiflavour NeutrInos from Supernovae (see list of collaborators in the

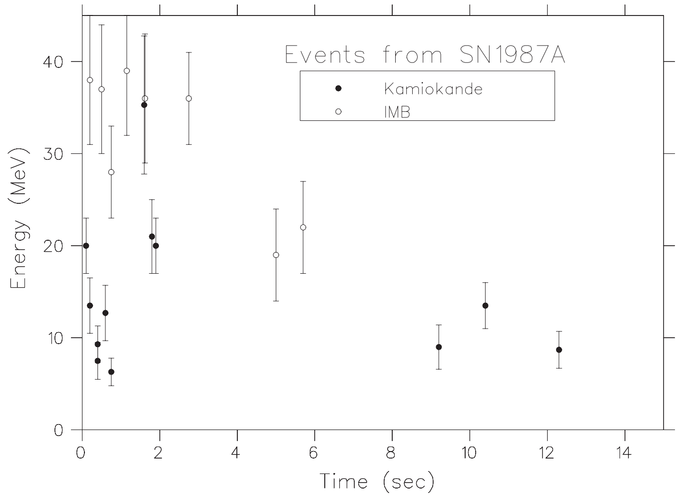

Figure 1. The energies and arrival times of the neutrino events from SN 1987A detected in the IMB and Kamiokande detectors.

Table 1. Yields of events from an 8 kpc distant SN. A single neutron detection efficiency of 50% was assumed for the LS (lead slab) modules, and 100% for the LPC (lead perchlorate, assumed mixed with 20% water) modules. In the oscillation scenario assumed, the total yield from OMNIS, obtained by summing the '$\nu_{\mu,\tau}$ osc' rows for LS and for LPC, would be about 2000 events. However, as explained in the text, if θ_{13} is sufficiently large, that ν_e column yields would increase considerably. Note that the yields for Super-K, SNO, and KamLAND are given for the no-oscillation scenario.

Detector	Target material	Fiducial mass (ton)	Target element	Yield (ν_e)	Yield ($\bar{\nu}_e$)	Yield (ν_x)
Super-K	H_2O	32 000	p, e, O	280	13 000	9
SNO	H_2O	1 600	p, e, O	25	800	9
SNO	D_2O	1 000	d, e, O	300	280	470
KamLAND	Liquid scintillator	1 000	C	80	600	400
				Yield: ν_e, CC	Yield: $\bar{\nu}_e$	Yield: NC all species
OMNIS	LS	2 000	Pb			
No-osc				100	–	270
Allowed MSW osc				1120–1460	–	270
OMNIS	LPC	1 000	Pb, H			
No-osc				60	40	120
Allowed MSW osc				440–560	80–100	120

appendix). It will consist of

(a) 2000 tons of lead slab (denoted as LS) planes interleaved with neutron-detecting slabs.
(b) 1000 tons of lead perchlorate (denoted as LPC) modules which will convert neutrinos to radiation that can be detected: Cerenkov light and/or neutrons.

The LPC modules will provide the ratio of charged-current (CC) to neutral-current (NC) interactions in lead, while the LS modules will produce a large number of both types of events at a low cost. Both types of detectors will detect the neutrinos within 0.1 ms after they interact with a lead nucleus. OMNIS will observe at least 2000 neutrino-induced events from a SN at 8 kpc, the distance to the galactic centre, estimated with the recent neutrino mixing results from Super-K (Fukuda *et al* 2001) and SNO (Ahmad *et al* 2001, 2002). This number reflects an MSW transition in the SN atmosphere to convert some of the high-momentum ν_μ and/or ν_τ into ν_e of the same momentum, with a corresponding number of ν_e converted into low-momentum ν_μ or ν_τ. If it were possible to have no mixing at all (indicated as the 'No-osc' rows in table 1) there would be a large NC production of neutrons from nuclear excitation; a 2000 ton LS target would produce about 400 one- or two-neutron events, primarily from the ν_x. In this hypothetical no-mixing scenario, OMNIS would have little sensitivity to the (lower momentum) ν_e because of the threshold and E^2 dependence of the excitation cross section. With the mixing expected, however, the high-momentum ν_e will enhance the CC signal that provides a much larger number of both one-neutron and two-neutron events. For OMNIS, this will produce 2000–2500 events (see table 1), depending on the precise values of the oscillation parameters. However, merely detecting these events is insufficient to obtain the physics information that we hope to gain from OMNIS; it is also essential to determine how many NC and CC events were observed, and to measure the spectrum of the CC events. It is these functions that the LPC will perform.

For a SN at the far side of the galaxy, a distance of ~20 kpc, OMNIS' yield would be smaller than indicated above, but might still be ~360 events. Even that total would enable much of the physics we hope to do with OMNIS. Of course, a close SN would produce a huge number of events. For example, Betelgeuse is a massive red giant that is only ~150 pc from Earth. The final stages of stellar burning proceed so quickly that the red giant phase is often the last one that the periphery of a star exhibits before the star becomes a SN. When Betelgeuse becomes a SN it will produce millions of events in OMNIS. This would represent an extraordinary scientific opportunity.

Table 1 compares the yields from various detectors, showing that OMNIS complements the others, especially with its sensitivity to ν_e. As is discussed below, it is important to observe large numbers of all the neutrino flavours; the sensitivity of Super-K and SNO to $\bar{\nu}_e$ and ν_x, and of OMNIS to ν_e and ν_x will do so. Only in this way will it be possible to observe many of the phenomena in stellar astrophysics and neutrino physics that are of interest.

One very important feature of SN neutrinos in the context of stellar collapse is their energy distributions. OMNIS' LPC modules will measure the ν_e energy distribution directly from the Cerenkov radiation produced by electrons from the Pb(ν_e, e^-) reaction and identification of the residual states to which the reaction proceeded (identified by the number of neutrons emitted, as explained below). Since the high-energy ν_e that OMNIS can detect will have been produced as (high mean energy) ν_x, OMNIS will thereby measure the distribution of the ν_x as they were emitted from the SN core. In addition, OMNIS will impose two energy thresholds, the one- and two-neutron emission thresholds, on the NC interactions, so will provide a consistency test of the distribution of the high mean energy ν_x. The important thing to note is that virtually all of the events from OMNIS will reflect the energy distribution of the ν_x as they are emitted from the core of the star.

Moreover, the short detection time associated with events seen by OMNIS, $<100\ \mu$s for diffusion and capture of the neutrons, will allow it to observe short-time phenomena in the neutrino luminosities associated with stellar collapse, e.g., collapse to a black hole. OMNIS' size will also allow direct measurement of neutrino masses down to 10–20 eV if the collapse did not go to a black hole, and its size plus its fast timing capability might give masses to a few eV if it did. Finally, the special sensitivity of lead to the energy of the ν_e makes it capable of observing flavour oscillations of some types, e.g., $\nu_e \leftrightarrow \nu_\tau$, that would be difficult to observe with any other detectors.

OMNIS will also be designed to have very low backgrounds. It will be located at a depth of at least 2000 mwe, at which the ambient muon-related neutron background in the target is expected (Smith 2001) to be much smaller than the rate of neutrons produced by SN neutrinos even at times tens of seconds after the start of the burst. The neutron flux from U or Th in the cavern walls will be similarly low. This, together with the size of OMNIS, will allow it to observe SN neutrinos for tens of seconds after their onset. Given the sensitivity of lead to ν_e energy, this will test the predictions of the evolution of neutrino energy and luminosity from stellar-collapse models. It might also allow observation of other possible late-time phenomena, such as the neutrino signal that might accompany a phase transition in the neutron star from neutrons to kaon-condensed or quark matter.

One natural spin-off from the large SN neutrino detectors is that they serve also as detectors of nucleon decay. Indeed, the most stringent limits that have been determined at present have come from Super-K. For example, the limit for the $p \rightarrow \pi^o e^+$ decay mode is 5×10^{33} years (Smy 2001). These limits are as strong as they are because of the ease of observing Cerenkov radiation in large water detectors, as these decay modes ultimately produce relativistic charged leptons, which produce the Cerenkov radiation sought. However, another predicted mode, that of $n \rightarrow \nu\bar{\nu}\nu$, cannot be observed in the same way; it has a lower limit of around 5×10^{26} years (Particle Data Group 2000). However, OMNIS will have the capability to observe such nucleon decay processes with greatly improved sensitivity.

2. Astrophysics from observation of supernova neutrinos

2.1. Stellar collapse diagnosis

The observation of neutrinos from supernovae (SNe) provides a unique opportunity to understand the core-collapse process and the subsequent explosion of a massive star (Burrows 1990). The different flavour neutrinos are likely to contain different types of information. Specifically, the ν_e should exhibit a 'neutronization spike', produced as the outgoing SN shock wave passes through the ν_e neutrinosphere that first signals the core collapse, shortly after the protoneutron star has formed, from

$$p + e^- \rightarrow n + \nu_e. \tag{1}$$

The collapse that precedes the neutronization spike is thought (Burrows 1990) to trap the neutrinos produced, keeping their energy within the collapsing core so as to increase the temperature to the maximum extent possible. This requires, because of large coherence effects on the cross sections for neutrinos on nuclei, that pre-existing nuclei not be destroyed until the maximum density of the core has been reached. Then, following the neutronization spike, neutrinos of all flavours are thought to be created in tens of milliseconds deep within the core of the star (Burrows 1990, Langanke and Martinez-Pinedo 2003), their trapping stretching the time scale over which they are emitted to seconds. These features are illustrated in figure 2. The gross feature of the predicted time structure for the $\bar{\nu}_e$ following the neutronization spike was confirmed by the observations of SN 1987A (Hirata *et al* 1987, Bionta *et al* 1987), shown in figure 1.

Neutrinos and antineutrinos of all flavours are produced in the hot core by the processes

$$e^+ + e^- \rightarrow \nu_j + \bar{\nu}_j, \tag{2}$$

$$A^* \rightarrow A + \nu_j + \bar{\nu}_j, \tag{3}$$

where $j = e$, μ and τ. These reactions and subsequent neutrino scattering produce the neutrino distributions that, when they are fit to Fermi–Dirac distributions with an effective chemical

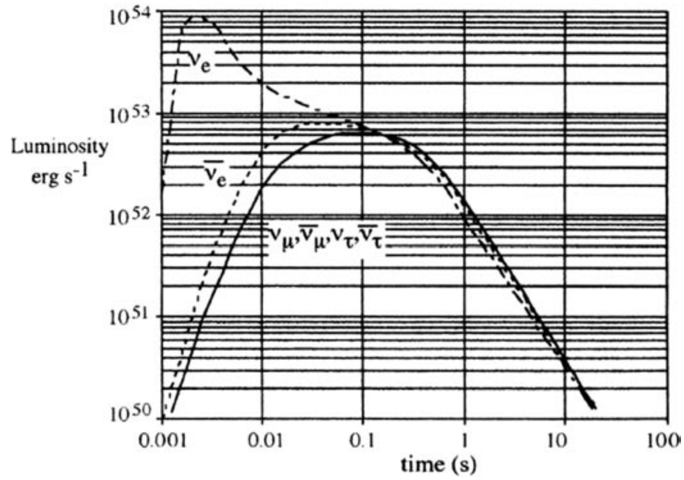

Figure 2. Predicted luminosities for a SN neutrino burst for the different flavour neutrinos (Raffelt 1996).

potential, comprise the *standard model* of SN neutrino production, as was assumed to produce the numbers in table 1. This model predicts that the ν_x would have considerably higher mean energies ($\approx$25 MeV) than would the ν_e ($\approx$11 MeV) and $\bar{\nu}_e$ ($\approx$16 MeV) (Qian *et al* 1993), since the ν_x interact with the nucleons in the stellar environment only through the NC interaction, whereas the ν_e and $\bar{\nu}_e$ interact also through the CC interaction, trapping the latter species in the cooler regions further from the centre of the star.

However, these are only the features of the neutrinos as they are *emitted from their neutrinospheres*. Recent solar neutrino results from Super-K (Fukuda *et al* 2001) and SNO (Ahmad *et al* 2001, Ahmad *et al* 2002) point to the large mixing angle solution of solar neutrinos between ν_e and ν_μ, and Super-K (Fukuda *et al* 1999), Soudan 2 (Mann 2000), and MACRO (Barish 2000) have observed $\nu_\mu \leftrightarrow \nu_\tau$ oscillations in atmospheric neutrinos, also with a large mixing angle. Thus we based our estimated yields on this solution (with $\sin^2 2\theta = 0.8$). Such MSW transitions would mix the ν_e with ν_μ and ν_τ distributions, producing some high-energy ν_e and some low-energy ν_x. These effects are discussed further below.

Recent studies, though, have focused on possible reactions that affect both the numbers and the energies of the emitted neutrinos. Neutrino bremsstrahlung (Hannestad and Raffelt 1998, Raffelt 2001)

$$n + n \rightarrow n + n + \nu_i + \bar{\nu}_i \tag{4}$$

could be important, but would probably only affect the numbers of low-energy neutrinos, while the 'inelastic scattering process' (Hannestad and Raffelt 1998, Janka *et al* 1996, Raffelt 2001)

$$\nu + n + n \rightarrow \nu + n + n \tag{5}$$

would affect their energies. The energy distributions of the neutrinos can also indicate whether those energies are distorted from a Fermi–Dirac zero-chemical-potential distribution to one that is 'pinched' at both the low- and high-energy ends by neutrino scattering (Totani *et al* 1998, Raffelt 2001) in the dense stellar core. Since this depends on the energy dependence of the neutrino cross sections, some deviation from the zero-chemical-potential Fermi–Dirac distribution appears to be inevitable, as emphasized by Dighe and Smirnov (2000). The ratio of OMNIS' two-neutron to one-neutron yields will be extremely sensitive to this effect.

The effect on OMNIS' energy distribution measurements will be less dramatic, but it may be observed there too. Both measurements will receive important confirmation from Super-K's NC yield. The combined time and energy distributions are important for assessing the validity of the description of the region outside the protoneutron star, and they might well indicate the presence of convection and rotation (Burrows 1990, Mezzacappa *et al* 1998, Totani *et al* 1998). Convection in particular could dominate the other processes that would affect the neutrino distributions; it has been speculated that the thermal energy it would bring up to near the surface would increase the luminosity and harden the neutrino spectra. The result would be an increase in OMNIS' yield, especially for two-neutron events.

2.2. Late-time effects

One feature by which existing and future models of neutron star formation may be tested involves the mechanics and time scales by which they cool. These predictions are complicated; a recent study (Pons *et al* 1999) suggests that the mean neutrino energies increase, as the nascent neutron star coalesces, up to 10 s or so, then begin to decrease. The rate of decrease depends sensitively on the details of the nuclear equation of state, especially on the existence of metastable stars, i.e., those with hyperons that are unstable to collapse upon deleptonization, over several tens of seconds. The two- to one-neutron event ratio in the LS modules would be especially sensitive to changes in the mean neutrino energies, while the changes in distribution with time would also be measured in the LPC modules while the luminosity remained sufficiently high. This effect would be difficult to measure for ν_μ or ν_τ in any other way. This emphasizes the importance of designing OMNIS with a sufficiently low background rate that it can observe the neutrino luminosities from a SN over the time scale over which these changes would be expected.

An additional point of interest drives the capability for late-time counting, that of the possibility of observing signatures for a phase transition from the neutron star to a kaon-condensed or quark-matter star. Recent work (Reddy *et al* 2001) has suggested that such a phase transition could produce a mixed-phase region. The neutrinos would scatter from droplets in the mixed-phase region, producing a pulse some tens of seconds after the core bounce, the result of a sudden burst of energy released in neutrinos from the core from the phase transition. The estimated energy release would be expected to produce only a few events in OMNIS from a SN at the galactic centre, but that would be well above the background rate of less than 1 Hz at late times, so might be observable.

2.3. Collapse to a black hole

Observation of SN neutrinos would also allow observation of the formation of a black hole should such an event result from stellar collapse. If the collapse were delayed by even a fraction of a second from the time the first neutrinos were emitted, it would produce an abrupt termination of the neutrino luminosities (Burrows 1990), although not necessarily at the same instant for all the luminosities (Baumgarte *et al* 1996). Since the ν_x interact differently with matter than do the ν_e and $\bar{\nu}_e$, their neutrinospheres would probably not be at the same distance from the centre of the collapsing star. The termination time difference would be expected to be $\sim$1 ms (Beacom *et al* 2000, Baumgarte *et al* 1996), so observing this difference requires timing capability of the level that OMNIS and Super-K will achieve. Measurement of the differences in sizes of the neutrinospheres would only be possible for a close SN (because of statistics), but the possibility of such an event must be considered in building a SN neutrino observatory. In addition, a late-time collapse to a black hole might provide a timing signal that could be used in measuring neutrino masses.

2.4. ν- and r-process diagnosis

The ν-process of nucleosynthesis has been shown (Woosley *et al* 1990, Wallerstein *et al* 1997, Boyd 1999) to describe the synthesis of some nuclides that had previously evaded theoretical understanding, including ^{180}Ta, ^{138}La, ^{19}F, ^{11}B and ^{7}Li. It does this via neutrino-induced reactions on pre-existing nuclides in the hot neutrino wind from a SN. While agreement between the observed abundances of these nuclides and those predicted by ν-process production does appear to be qualitatively good, a detailed comparison between theory and observation requires a better understanding of the energy distribution of the neutrinos that cause the reactions (Myra and Burrows 1990). OMNIS will provide a much better definition of the energy distributions of the ν_e, hence of the ν_x, than can be obtained with any other detector, so will provide the means for a much more stringent test of the ν-process model.

Another manifestation of the neutrino spectra is found in the r-process. The neutrinos set the electron fraction in the neutrino driven wind environment, which determines whether the r-process can even occur (Qian *et al* 1993, Meyer *et al* 1998). The spectra are crucial for determining the neutron-to-proton ratio, and OMNIS will provide this information.

Another effect is 'neutrino post-processing' that has been observed (Haxton *et al* 1997, Qian *et al* 1997) in the aftermath of the r-process. Studies have shown that the abundances of the nuclides just below the r-process peaks at 130 and 195 u could be attributed to nuclear reactions on the r-process peak nuclides with the hot neutrinos, primarily ν_x, that would be emanating from the core of the star just after the r-process had completed its nucleosynthesis. The description of this process apparently depended only on the 'fluence', or integrated neutrino flux, but the energy distribution would also be important in determining its capability for producing these nuclides.

2.5. Frequency of supernova and black hole formation

An important aspect of SN neutrino detection is the frequency with which galactic core-collapse SNe occur. Uncertainties arise because the observational record reflects only those SNe that were close enough to Earth that they were not obscured by dust in the galaxy. It has been suggested that the rate inferred from various astrophysical arguments (typically 3 per century: Van den Bergh (1993), Tammann *et al* (1994)) is too low, at least for our galaxy. A number of recent papers have discussed the observational record in our galaxy (Dragicevich *et al* 1999, Totsuka 1990, Hatano *et al* 1997, Strom 1994). Along with one recently discovered SN (Aschenbach 1998), this suggests roughly eight core collapse SNe in the past 2000 years out to an efficiently observable distance of 4 kpc, representing the local $\sim$7% of the galaxy, and leads to an estimate of about 6 ± 1 per century for the whole galaxy. Another estimate (Bahcall and Piran 1983), using a different approach, has yielded a galactic SN event rate as high as 10 per century. Regardless of the actual rate, the OMNIS components must be designed for long life.

The ratio of black hole to neutron star formation has been estimated to be as low as 1:4 (Bahcall and Piran 1983) to about 1:1 (Brown and Bethe 1998, Bethe and Brown 1995) to as high as 9:1 (Qian *et al* 1998). Despite the wide range, the values do suggest that black hole formation is at least not a much rarer event than neutron star formation.

3. Neutrino physics and related phenomena

Another type of information that might be obtained from SN neutrinos concerns the properties of the neutrinos themselves: their masses and transformations between them. Although the recent results from Super-K (Fukuda *et al* 2001) and SNO (Ahmad *et al* 2001, 2002) confirm that at least some neutrinos have non-zero mass, the new results do not give the mass values directly, nor do they determine all possible combinations of neutrinos involved in the transformations. Thus any measurements of neutrino masses via their time of flight from the SN to Earth, or of additional oscillation modes, would be of fundamental significance. OMNIS would provide the first direct measurements of ν_μ and ν_τ masses down to the cosmologically significant 10–100 eV region (improving the existing limits by a factor for 10^4 for the ν_μ and 10^6 for the ν_τ). Furthermore, this could provide a direct demonstration (rather than indirect, via neutrino oscillations) that none of the neutrinos has sufficient mass (>10–20 eV) to constitute a significant fraction of the dark matter in the galaxy. In addition, possible sterile neutrino states have not been completely ruled out; their existence would have profound implications.

3.1. Direct neutrino mass measurements

Neutrinos will arrive at the Earth in mass eigenstates. The difference in arrival time of two neutrinos, one of small mass and the other with a much larger mass, is

$$\Delta t(s) = 1.6[R/8\,\mathrm{kpc}][m(\nu)/50\,\mathrm{eV}]^2[25\,\mathrm{MeV}/E(\nu)]^2 \qquad (6)$$

where $m(\nu)$ is the rest mass energy of the more massive neutrino in eV/c^2 and $E(\nu)$ is its energy in MeV. Thus a light neutrino and one with a mass of 50 eV/c^2, assuming they were emitted simultaneously from a SN 8 kpc distant from earth, would be separated in time by 2 s (after travelling for 25 000 years!).

However, both neutrinos would have energy distributions, which results in the overall time profile being 'stretched', with more energetic neutrinos for all plausible mass values undergoing a relatively small time shift with respect to each other (see figure 3). The distributions could provide relative masses of the different neutrinos, while an absolute arrival time can be determined by correcting for the energies of the ν_e measured in OMNIS' LPC modules, and of the $\bar{\nu}_e$ in the water Cerenkov detectors (Beacom *et al* 2000). This simplified analysis can be extended to take into account neutrino mixing. It is necessary to correct for the transit time of the neutrinos between OMNIS' two sites, a few ms (which would require information about the SN direction (Beacom and Vogel 1996)). If there were a significant mass difference, either good statistics would be necessary to separate the peaks, or one would require some way to discriminate between the neutrino flavours (determined by comparing OMNIS' NC and CC event times with the times at which the events began to be seen in other SN neutrino observatories, transmitted via the Supernova Neutrino Early Warning System (SNEWS) (Murphy 1999)). Given the recent solar and atmospheric data, in a normal hierarchy the heaviest eigenstate is ν_3, which is composed primarily of ν_μ and ν_τ, and is therefore detectable only via NC interactions. The leading edges of the distributions appear to give the best chance of providing (Beacom 2000), depending on the statistics, a timing signal at the several ms level. In this way, OMNIS could provide a mass measurement to $\sim$20 eV/c^2. However, in the event of collapse to a black hole, (Beacom *et al* 2000) OMNIS might allow a mass measurement to as low as 3 eV/c^2.

3.2. Neutrino transformations

Matter enhanced neutrino flavour transformations have been hypothesized to be a solution of the solar neutrino problem (Bahcall 1989). Recent atmospheric neutrino studies (Fukuda *et al* 1999, Sobel 2000, Mann 2000) and solar neutrino results from Super-K (Fukuda *et al* 2001) and SNO (Ahmad *et al* 2001, 2002) confirm this concept, and are consistent with the results from the chemical solar neutrino experiments (Cleveland *et al* 1999, Hampel *et al* 1999,

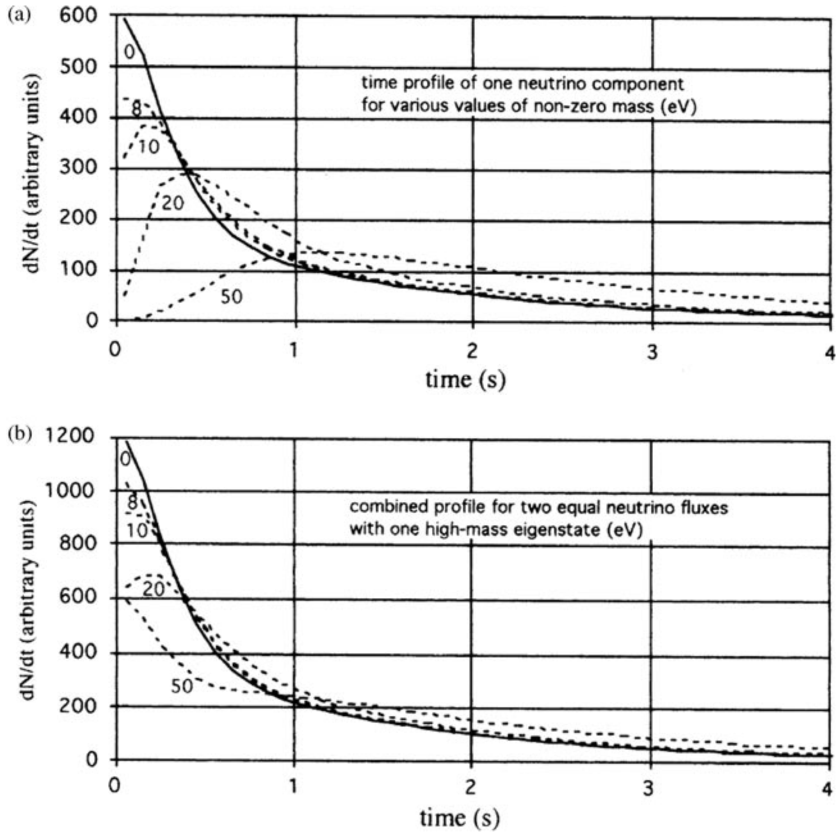

Figure 3. Typical effects of non-zero mass. (a) Effect of non-zero mass on single neutrino component. (b) Combination of (a) with equal 'zero-mass' component (Smith 2001).

Abdurashitov *et al* 1994, Altmann *et al* 2000). Terrestrial experiments (Apollonio *et al* 1999, Barish 2000, Boehm *et al* 2000), which do not span the same parameter space, generally report no transformations, with the exception of the LSND experiment (Athanassopoulos *et al* 1998). Clearly, the possibility of detecting transformations from SN neutrinos is of great interest to understanding their fundamental properties.

OMNIS' lead can provide a striking signature of neutrino flavour transformation. Events will occur in which either one or two neutrons are emitted. The latter events, because of their higher threshold, will provide a small fraction of the total if no oscillations occur. However, any mixing between ν_e and $\nu_{\mu,\tau}$ will give the ν_e spectrum a high-energy component, since the $\nu_{\mu,\tau}$ will have higher mean energy, ~20–30 MeV, than the ν_e, ~8–13 MeV. This in turn will greatly increase the neutron production in lead from CC interactions (Fuller *et al* 1999), particularly of two-neutron events. In the case of complete transformation the absolute yields would increase by a factor of 4 and the two-neutron yield by a factor of 6 compared to the no-oscillation mode (indicated as 'No-osc.' in table 1). However, some transformations are known to exist; we have adopted the oscillation parameters given by the large-mixing-angle (LMA) solution (Fukuda *et al* 2001, Ahmad *et al* 2001, 2002). In this case the ν_e will mix significantly with the other flavours, although the details may depend on the SN environment and the specifics of the neutrino mixing matrix. In any event, a measurement of a fully or partially 'hot' ν_e spectrum would provide critical information in understanding neutrino

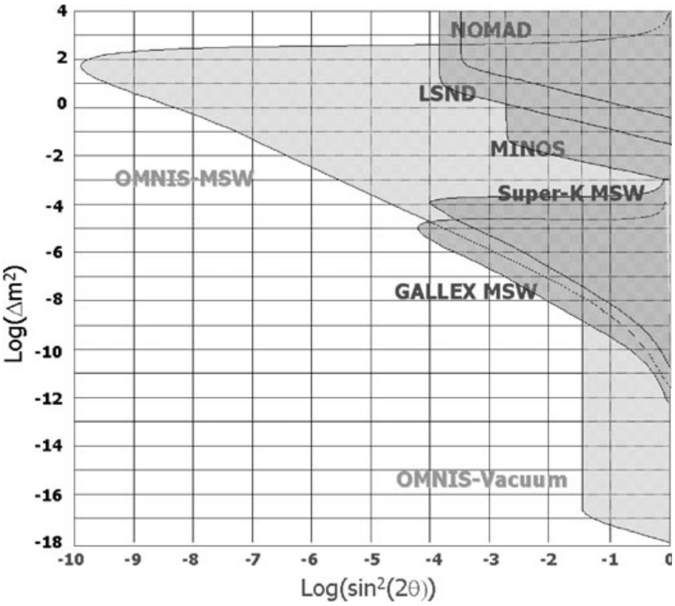

Figure 4. Plot of Δm^2 versus $\sin^2 2\theta_{12}$, showing the range of neutrino mixing parameters covered by OMNIS' signals for either ν_μ/ν_e or ν_τ/ν_e mixing, compared with the range covered by some existing terrestrial experiments. OMNIS' sensitivity to low values of $\sin^2 2\theta_{12}$ arises from MSW transitions in the very high matter density in the SN, and the sensitivity to low values of Δm^2 is due to the long vacuum mixing path. If the neutrino mixing is larger than 3×3, this sensitivity is very important.

physics. Note the importance of the LPC data in determining the actual mix of NC and CC events and hence, the fraction of the events that are from ν_e and from ν_x. This is crucial, e.g., in discriminating between enhancements in the two-neutron yield from oscillations, or from distortions in the neutrino spectrum from a pure Fermi–Dirac distribution.

Assuming a normal hierarchy and an adiabatic transformation in the envelope of the SN, the LMA solution suggests that up to 1/2 (corresponds to $\sin^2 2\theta_{solar} = 1$) of the original low-energy ν_e spectrum would be left intact when the neutrinos arrive at the Earth, with the remainder being the high-energy component. If $\sin^2\theta_{solar} = 0.75$, then 25% would remain intact. However, in addition, the angle θ_{13}, which is limited by reactor neutrino data, may be large enough to produce an adiabatic transformation at higher density. This would imply that the ν_e spectrum would be composed almost completely of the high-energy component as it arrives at the Earth, and would increase the OMNIS yield to $\sim$2500 events (for an 8 kpc distant SN), with the NC to CC event ratio also being critical. Thus OMNIS will provide excellent sensitivity to this least known parameter in the standard mixing parametrization, consistent with recent studies of the power of detecting SN neutrinos (Dighe and Smirnov 2000, Fuller *et al* 1999). Dighe and Smirnov (2000) indicated that SN neutrino data would determine the type of mass hierarchy that exists for the neutrinos, and would probe the mixing matrix element U_{e3}^2 to values as low as 10^{-3} to 10^{-4}.

SN neutrinos would be affected by an enormously large range of mixing parameters (figure 4), which shows neutrino mixing cast in the form of 2×2 mixing between the electron neutrinos and another active flavour. In the case of 3×3 mixing only, the δm^2 range has been narrowed down. However, the LSND experiment does not fit easily with this picture. Introduction of one or more sterile neutrinos would complicate the mixing picture. It is

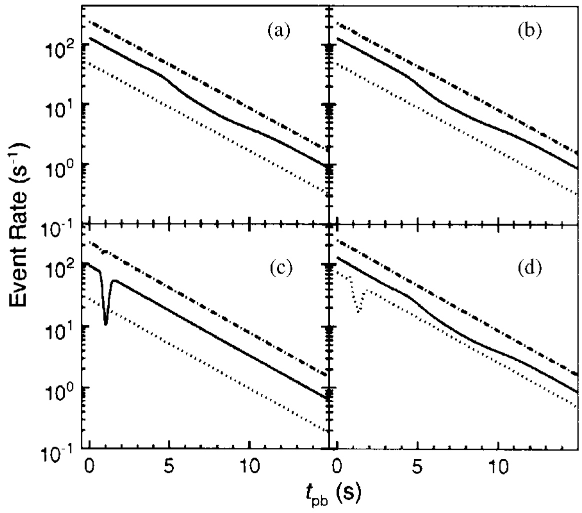

Figure 5. Event rates for ν_e CC (solid), $\bar{\nu}_e$ (dotted) and NC (dot-dash) in SNO as functions of time for (a) 3-active, (b) '3+1', (c) two doublet and (d) CPT violating schemes. From Schirato and Fuller (2002).

therefore crucial that OMNIS has sensitivity to such a large parameter space (The active–active parameter space is similar to the active–sterile space.)

3.3. Neutrino transformations and the core-collapse environment

Several recent papers (Fuller *et al* 1999, Dighe and Smirnov 2000, Barger *et al* 2001) have studied the consequences of neutrino transformation in the SN environment. A very recent study (Schirato and Fuller 2002) has extended those studies to include effects that might be seen when the shock wave following core bounce passes through the regions in which the transformations occur. Specifically, ν_μ and/or $\nu_\tau \leftrightarrow \nu_e$ transformations have been shown (Ahmad *et al* 2001, 2002) to be MSW transformations, with density and electron fraction parameters that are relatively well defined. However, the adiabaticity that is required for the MSW transitions would probably be destroyed during the short time that the shock wave (both its front and its rarefraction zone) passed through the MSW region. The actual effect on the neutrino signal emanating from the SN would depend critically not only on the density and electron fraction, but also on the neutrino mixing matrix.

For example, Schirato and Fuller (2002) showed that in a neutrino mass scheme in which the ν_μ and ν_τ were essentially degenerate and there was a sterile neutrino (a solution that would accommodate the LSND oscillation observation (Athanassopoulos *et al* 1998)) that was close to being degenerate with the ν_e (the 'two doublet' mass scheme), the ν_e CC event rate in SNO would exhibit a sharp dip, $\sim$0.3 s wide, and a reduction in amplitude of roughly a factor of 7, due to the passing shock wave. In CPT violating schemes (which would also accommodate the LSND result), a slightly less dramatic dip would occur in the ν_e CC spectrum. In other mass schemes, steps would be seen in the ν_e yield, although they might be difficult to observe. However, observation of the CC/NC event ratio would greatly enhance prospects for observing these effects, provided the statistics were adequate. Some of these results are illustrated in figures 5 and 6.

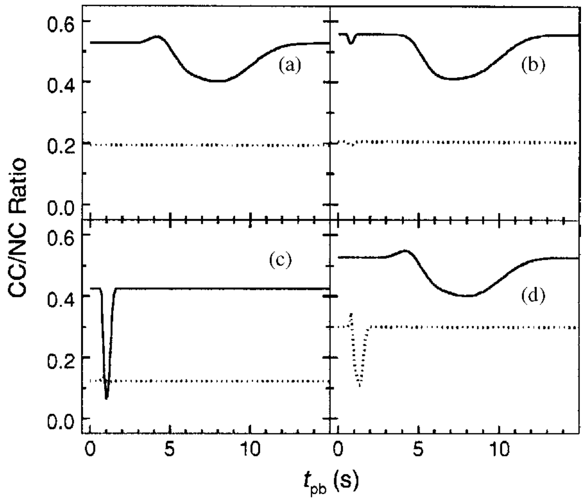

Figure 6. Ratios of ν_e (solid) and $\bar{\nu}_e$ (dotted) CC to NC event rates for SNO. Neutrino mixing schemes are (a) 3-active, (b) '3+1', (c) two doublet and (d) CPT violating. From Schirato and Fuller (2002).

Schirato and Fuller (2002) speculate that the energy distributions of the neutrinos, together with the higher threshold energies of lead, would make the signal in OMNIS considerably more dramatic than that predicted for SNO. Thus this is an important way to probe schemes involving sterile neutrinos. Furthermore, the statistics would be much greater.

4. Observation of nucleon decays

Nucleon decay (see, e.g., Pati and Salam (1973), (1974), Georgi and Glashow (1974), Babu *et al* (2000), Babu and Mohapatra (2001), Applequist *et al* (2001)) is arguably the most basic issue in modern physics. Most of the limits currently placed on the many possible decay modes (Particle Data Group 2000) have resulted from the large underground detectors. Most of these have come from Super-K, because of its large size and its ability to observe the relativistic leptons that are the ultimate products of many decay modes. However, OMNIS will be sensitive to some other decay modes for which Super-K has difficulty detecting the decay products.

A typical 'proton-decay' event (out of many possibilities; Particle Data Group (2000)) would be

$$p \rightarrow \pi^o + e^+ \tag{7}$$

where the event is observed in a water detector by observing the Cerenkov radiation from the e^+ and the γ-rays produced by the decay of the π^+. Because of the large size of Super-K, this decay mode has an excellent lower limit for its half-life: 5×10^{33} years (Smy 2001). The same applies to other decay modes in which a relativistic lepton is emitted; a three-body decay, e.g., is given by

$$p \rightarrow \mu^+ + \pi^+ + \pi^-. \tag{8}$$

The lower limit for its half-life is 1.3×10^{32} years (Particle Data Group 2000).

A much more difficult type of nucleon-decay event to detect is that in which no strongly interacting or charged particles are emitted, e.g.,

$$n \rightarrow \nu + \bar{\nu} + \nu. \tag{9}$$

Indeed, the half-life inferred for this decay mode is 5×10^{26} years, several orders of magnitude worse than the decays for the best-determined modes. This half-life was first measured (Berger *et al* 1991) by assuming that the neutrinos produced by some of the nucleon decays within the Earth would be observed in the Frejus detector. This decay could also be detected by considering nuclear signatures that are produced subsequent to the decay, as suggested by Totsuka (1986) and Ejiri (1993). Indeed, a search was conducted in Super-K for decays of neutrons in ^{16}O (Suzuki *et al* 1993) for the γ-rays that would have been produced subsequently, producing the current half-life limit. KamLAND, because of its low-energy threshold for detection in its ~900 ton liquid scintillator (CH_2), would be especially well suited for studying similar decays in ^{12}C (Kamyshkov and Kolbe 2002) via the subsequent γ-rays, possible neutrons and β's that would be emitted.

In OMNIS, interesting decay signatures could result from neutron decays in the lead and the chlorine in the lead perchlorate. If neutron decay occurred in ^{208}Pb, there would be expected to be a fairly high probability of emitting several neutrons (Boyd *et al* 2003), together with one or more high-energy γ-rays from the nucleus at the end of the decay chain, in this decay mode. The decay of a more deeply bound neutron would tend to produce a more highly excited nucleus, thereby tending to produce more neutrons. When the excitation energy of the decay product nucleus resulting from several possible neutron emissions fell below the one-neutron emission threshold, the de-excitation γ-ray would result. Detection of these signatures in coincidence would identify the event.

The most troublesome background for this type of event would be from events initiated in the lead by NC interactions from atmospheric neutrinos, which would proceed through the same nuclei, but would emit one more neutron than the nucleon decay events. The only way to remove this background would be to measure the frequency of such events initiated by CC interactions, infer the rate from NC interactions using those data, and see if a significant number of events remained.

Another way of identifying the $n \rightarrow \nu + \bar{\nu} + \nu$ decay mode would be from neutron decay of ^{35}Cl, which would have a high probability of populating ^{34}Cl after the decay in a sufficiently highly excited state to emit energetic γ-rays. The de-excitation to the ground state of ^{34}Cl would then produce an energetic β^+ decay, which could be identified from its Cerenkov radiation. Individual events of this type could not be identified, but several of them would allow measurement of a half-life of ^{34}Cl associated with the decay. Thus the identification of candidate nucleon decay events in this case would be a coincidence between the γ-ray(s) and the β^+, with the confirmation being the measurement of the correct half-life.

As with most such decay events, the dominant background for this mode would be from NC events initiated by neutrinos produced in the Earth's upper atmosphere. Such events would first produce a neutron from ^{35}Cl, which would then lead to the same neutron-decay-identifying sequence of signals as for neutron decay. However, the fact that the initial reaction would require a neutron to be emitted could provide the veto for this background, as the neutron would be detected in the LPC.

Because OMNIS will be in operation for several decades, it is anticipated (Boyd *et al* 2003) that these (both high-branching ratio) decay processes will produce limits for the three-neutrino mode of $\sim 10^{31}$ years for the lead, and of $\sim 10^{30}$ years for the chlorine, in ten years of running.

5. Principles and basic properties of supernova neutrino detection

As indicated in table 1, Super-K will observe $\sim 10^4$ events from an 8 kpc distant SN. These events will be predominantly due to the interaction

$$\bar{\nu}_e + p \rightarrow e^+ + n. \tag{10}$$

The CC events transfer nearly all the incident neutrino's energy to the positron (after mass corrections), so that the resulting Cerenkov radiation allows determination of the energy spectrum of the $\bar{\nu}_e$ from the SN. In addition, NC events will be detected from inelastic excitation of the ^{16}O to 1^- and 2^- giant resonances that are above proton and neutron emission thresholds (Langanke *et al* 1996). The branches for proton or neutron emission to excited states of the resulting ^{15}N and ^{15}O nuclei are appreciable, and will produce some detectable γ-rays from the de-excitation of the excited states. The threshold for this process is relatively high so it will sample only the higher energy neutrinos produced by the SN. Thus this yield will have excellent sensitivity to the high-energy tail of the ν_x, and to any processes that can affect it.

SNO operates with both light water and heavy water. Its light water will produce events from SN neutrinos as described above for Super-K. However, SNO's heavy water will also produce CC events from the reactions

$$\bar{\nu}_e + d \rightarrow e^+ + n + n \tag{11}$$

and

$$\nu_e + d \rightarrow e^- + p + p \tag{12}$$

and NC events from the reaction

$$\nu_x + d \rightarrow \nu_x + n + d. \tag{13}$$

The CC reactions produce energetic leptons that can be observed via their Cerenkov light, whereas the NC interactions can be observed by detecting their neutrons. The thresholds for all these processes are much lower than the NC threshold for Super-K, so even with the smaller size of SNO, it will produce a significant number of events.

KamLAND detects its $\bar{\nu}_e$ via the same interaction with the protons that produces events in Super-K and SNO. However, it will also observe interactions of the ν_x, and a few of the ν_e, with its C (KamLAND Proposal 1998). Of particular interest are the reactions initiated by ν_e and $\bar{\nu}_e$, which populate, respectively, the ground states of ^{12}N and ^{12}B. KamLAND will see the resulting β from the decay of those unstable nuclei in (very) slow coincidence with the β from the CC neutrino-induced interaction. NC interactions will proceed primarily through the 15.11 MeV state in ^{12}C, while will produce a sharp γ-ray peak. KamLAND's excellent energy resolution will make it possible to make accurate identifications of the reaction products.

OMNIS is expected to produce at least 2000 events from an 8 kpc-distant SN from its lead slab (LS) and lead perchlorate (LPC) modules. It will observe SN neutrinos by observing the secondary neutrons produced when the neutrinos interact with the nuclei in LS modules, or both Cerenkov light and neutrons from CC interactions of neutrinos in the LPC modules. Originally the proposed converter was rock (Cline *et al* 1990, 1994), but subsequently it was shown that order of magnitude improvements in neutron detection efficiency, cost and time resolution could be obtained by means of optimized geometry and high atomic number target materials, most notably lead (Smith 1997, Zach *et al* 2002, Smith 2001). It has a much higher neutron production efficiency (Fuller *et al* 1999 (FHM), Kolbe and Langanke 2000 (KL), Volpe *et al* 2002 (VACG), Engel *et al* 2003 (EMV)), as well as low neutron absorption, allowing most of the neutrons to scatter out of the target into an adjacent detector.

Lead produces events from NC interactions

$$\begin{aligned}\nu_j + {}^{208}\mathrm{Pb} \rightarrow \nu_j' + {}^{208}\mathrm{Pb}^* &\rightarrow {}^{208}\mathrm{Pb} + \gamma \quad \text{or} \\ &\rightarrow {}^{207}\mathrm{Pb} + \mathrm{n} \quad \text{or} \\ &\rightarrow {}^{206}\mathrm{Pb} + 2\mathrm{n}. \end{aligned} \tag{14}$$

Lead's thresholds for NC neutron emitting reactions are 7.37 MeV for one-neutron events and 14.11 MeV for two-neutron events. In addition, it can produce neutrons from CC interactions via

$$\begin{aligned}\nu_\mathrm{e} + {}^{208}\mathrm{Pb} \rightarrow \mathrm{e}^- + {}^{208}\mathrm{Bi}^* &\rightarrow {}^{208}\mathrm{Bi} + \gamma \quad \text{or} \\ &\rightarrow {}^{207}\mathrm{Bi} + \mathrm{n} \quad \text{or} \\ &\rightarrow {}^{206}\mathrm{Bi} + 2\mathrm{n}, \end{aligned} \tag{15}$$

with a threshold of 9.26 MeV for one-neutron events and 17.35 MeV for two-neutron events. The yield predictions for both the LS and LPC modules are summarized in table 1. They are given with some confidence, as the three recent estimates (KL, VACG, EMV) of the cross sections are in excellent agreement. We have based our rate estimates on the EMV cross sections, although the KL and VACG yields would be very similar. None the less, we plan to measure the cross sections with a neutrino beam. This is very important due to the present paucity of experimental results. Note that the 'lead' results are specifically for ^{208}Pb, but the yields for the other abundant isotopes, ^{206}Pb and ^{207}Pb, would be expected to be similar to those for ^{208}Pb (KL).

The CC events detected in the lead perchlorate can be used to determine approximate energies of the incident neutrinos. The energy of each electron produced will be equal to the energy of the incident neutrino minus the energy required to excite the state populated in ^{208}Bi. The states that will be populated initially in ^{208}Bi are clustered, either at around 15 MeV of excitation in ^{208}Bi (the Gamow–Teller (GT) resonance states and the isobaric analogue state) or around 21 MeV of excitation (the states populated by first forbidden transitions), as is indicated in figure 7. The GT resonance states and the IAS are spread over about 2 MeV (FHM), and will decay by emitting a single neutron. The states populated by first forbidden transitions decay by two-neutron emission. Thus measurement of the number of neutrons identifies the excitation energy of the states that are populated. That information, together with the energy of the electron produced in the $^{208}\mathrm{Pb}(\nu_\mathrm{e}, \mathrm{e}^-)^{208}\mathrm{Bi}$ reaction, will provide an estimate of the neutrino spectral shape. In particular, it should be able to do especially well in determining an average neutrino energy or temperature. The measurement of the cross sections described later taken together with calculations of the cross sections, will enhance the precision to which the entire neutrino spectrum can be determined.

The properties of the LS and LPC detectors are discussed below, and summarized in table 2.

6. Design features and mechanical details of OMNIS

6.1. Lead slab (LS) modules

We plan to build the LS modules of OMNIS from vertical planes of Gd-loaded scintillator detectors sandwiched in between planes of lead. Lead will also cover the top, bottom and ends of the modules to shield from ambient radiation. Plastic scintillators will be placed on top of the modules with sufficient overhang to veto events associated with cosmic-ray muons. All of these measures are designed to prevent any background events from being confused with SN neutrino events.

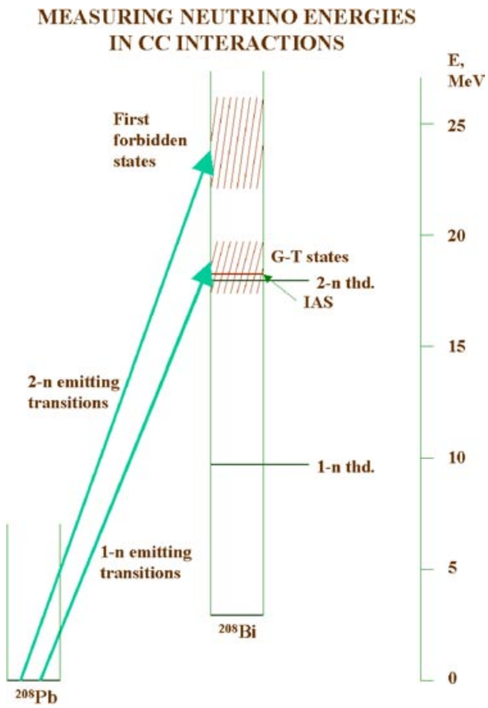

Figure 7. States that dominate the ^{208}Pb (ν_e, e$^-$)^{208}Bi reaction. The Gamow–Teller (GT) resonance states and the isobaric analogue state decay by single-neutron emission, while the states populated by first forbidden transitions decay by two-neutron emission.

A schematic diagram of an LS module is shown in figure 8. The optimum module parameters are determined by several considerations. For example, the light transmission through the scintillator determines the maximum length of the scintillator, which in turn determines the width of the modules. Although the neutrons lose little energy in each elastic collision, their total energy loss prior to when they get to the scintillator limits the thickness of the lead slabs. Cost minimization was obtained from the trade-off between neutron detection efficiency (which decreases with increasing lead slab thickness) and the relative cost of the lead and the neutron detectors.

Detailed Monte Carlo simulations have been performed (Zach *et al* 2002, Smith 2001) to determine OMNIS' neutron detection efficiency and to optimize the design details with respect to both detection efficiency and cost. The neutrons, estimated (KL) to be emitted with $\sim$1 MeV of energy, were found to lose almost all of their energy by scattering from the protons in the scintillator in $\sim$100 ns following the neutrino–nucleus interaction. They then thermalize and capture on the Gd in the scintillator in a mean time of $\sim$30 μs (confirmed by tests of a Gd-loaded liquid scintillator detector), producing several γ-rays totalling nearly 8 MeV Knoll (1989). This doublet of signals will identify the neutrons. Our simulations, assuming alternating vertical slabs of lead and scintillator, have shown that with an LS thickness of 50 cm and a plastic scintillator section thickness of 25 cm, a single-neutron detection efficiency of $\sim$35% and a two-neutron efficiency of $\sim$12% would be achieved (Zach *et al* 2002). This detection strategy would also maintain a background neutron detection level of less than 1 per second for all of the OMNIS lead modules. Since the singles data would also be recorded, the double-event identification strategy could be relaxed (off-line) during the peak SN neutrino

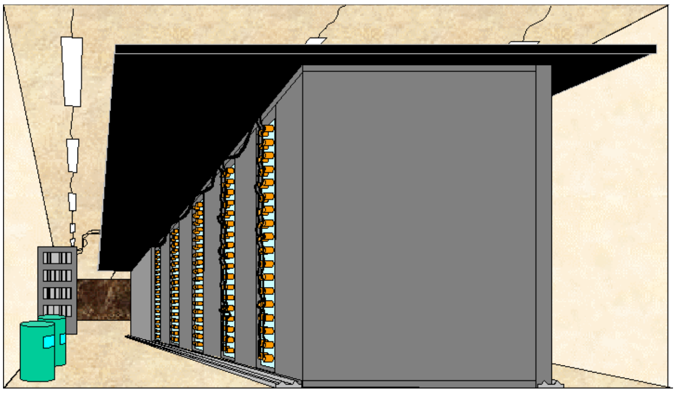

Figure 8. Schematic drawing of a half kton LS module in the WIPP. The lead doors enclosing the ends are not shown so that the location of the PMTs may be seen. The muon veto detectors are seen at the top.

Table 2. Details of the lead slab (LS) and lead perchlorate (LPC) modules, as currently envisioned. Electrically isolated units are planned in the event of a close SN. A small number of events will also occur in the scintillator.

Parameter	Lead slab system	Lead perchlorate system
Mass (total) kt	2.2	0.54
Mass (lead) kt	2.1	0.34
Number of modules	4 modules	8 pairs
Module/pod dimensions	4 m × 3.5 m × 6 m	4.0 m dia × 1 m
Number of sub-units	28	16
Reactions	(i) ${}^{A}\mathrm{Pb}(\nu_e, \nu_e')^{A}\mathrm{Pb}$	(i) ${}^{A}\mathrm{Pb}(\nu_e, \nu_e')^{A}\mathrm{Pb}$
	(ii) ${}^{A}\mathrm{Pb}(\nu_e, \nu_e'\ \mathrm{n})^{A-1}\mathrm{Pb}$	(ii) ${}^{A}\mathrm{Pb}(\nu_e, \nu_e'\ \mathrm{n})^{A-1}\mathrm{Pb}$
	(iii) ${}^{A}\mathrm{Pb}(\nu_e, \nu_e'\ 2\mathrm{n})^{A-2}\mathrm{Pb}$	(iii) ${}^{A}\mathrm{Pb}(\nu_e, \nu_e'\ 2\mathrm{n})^{A-2}\mathrm{Pb}$
	(iv) ${}^{A}\mathrm{Pb}(\nu_x, \nu_x')^{A}\mathrm{Pb}$	(iv) ${}^{A}\mathrm{Pb}(\nu_x, \nu_x')^{A}\mathrm{Pb}$
	(v) ${}^{A}\mathrm{Pb}(\nu_x, \nu_x'\ \mathrm{n})^{A-1}\mathrm{Pb}$	(v) ${}^{A}\mathrm{Pb}(\nu_x, \nu_x'\ \mathrm{n})^{A-1}\mathrm{Pb}$
	(vi) ${}^{A}\mathrm{Pb}(\nu_x, \nu_x'\ 2\mathrm{n})^{A-2}\mathrm{Pb}$	(vi) ${}^{A}\mathrm{Pb}(\nu_x, \nu_x'\ 2\mathrm{n})^{A-2}\mathrm{Pb}$
	(vii) ${}^{A}\mathrm{Pb}(\bar{\nu}_e, \bar{\nu}_e'\ \mathrm{n})^{A-1}\mathrm{Pb}$	(vii) ${}^{A}\mathrm{Pb}(\bar{\nu}_e, \bar{\nu}_e'\ \mathrm{n})^{A-1}\mathrm{Pb}$
	(viii) ${}^{A}\mathrm{Pb}(\bar{\nu}_e, \bar{\nu}_e'\ 2\mathrm{n})^{A-2}\mathrm{Pb}$	(viii) ${}^{A}\mathrm{Pb}(\bar{\nu}_e, \bar{\nu}_e'\ 2\mathrm{n})^{A-2}\mathrm{Pb}$
	(ix) ${}^{A}\mathrm{Pb}(\nu_e, \mathrm{e}^-)^{A}\mathrm{Bi}$	(ix) ${}^{A}\mathrm{Pb}(\nu_e, \mathrm{e}^-)^{A}\mathrm{Bi}$
	(x) ${}^{A}\mathrm{Pb}(\nu_e, \mathrm{e}^-\ \mathrm{n})^{A-1}\mathrm{Bi}$	(x) ${}^{A}\mathrm{Pb}(\nu_e, \mathrm{e}^-\ \mathrm{n})^{A-1}\mathrm{Bi}$
	(xi) ${}^{A}\mathrm{Pb}(\nu_e, \mathrm{e}^-\ 2\mathrm{n})^{A-2}\mathrm{Bi}$	(xi) ${}^{A}\mathrm{Pb}(\nu_e, \mathrm{e}^-\ 2\mathrm{n})^{A-2}\mathrm{Bi}$
Observables	(i) nothing	(i) γ-rays
	(ii) and (iii) neutrons	(ii) and (iii) neutrons
	(iv) nothing	(iv) γ-rays
	(v) to (viii) neutrons	(v) to (viii) neutrons
	(ix) nothing	(ix) Cerenkov light
	(x) and (xi) neutrons	(x) and (xi) neutrons+Cerenkov light

event rate; the real events would overwhelm the backgrounds during those few seconds. This would increase the single-neutron detection efficiency, judging from our Monte Carlo simulations, up to 50%, and the two-neutron detection efficiency to 25%.

6.2. Lead perchlorate (LPC) modules

LPC dissolves in water to produce a clear colourless liquid, so the $\mathrm{Pb}(\nu_e, \mathrm{e}^-)$ interactions that occur within its volume will produce Cerenkov radiation, detection of which, along with

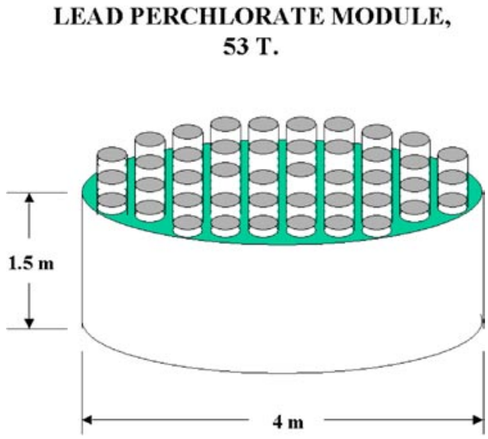

Figure 9. Schematic drawing of a possible 53 ton lead perchlorate (LPC) module. The diameter is 4 m, and the thickness is 1.5 m. The PMTs required for such a module could be packed on both ends, as indicated.

detection of the neutrons also emitted in the event, will allow the determination of the energy of the incident ν_e, as discussed above. The CC interactions will produce detectable signals that have Cerenkov light in coincidence with one or two neutrons (Elliott 2000). Since the neutrons will be captured and detected with high efficiency ($\sim$100% in the central regions of the LPC modules) on the chlorine, producing an 8.6 MeV γ-ray, this pair of signals will measure the one-neutron to two-neutron event ratio, which is needed to fully understand the signals produced in the LS detector modules. The LPC will identify NC interactions from the γ-ray from the neutron capture with no accompanying Cerenkov radiation, or for the no-neutron case, a de-excitation γ-ray. LPC can detect events in which no neutrons are emitted, so can also determine the low-energy part of the ν_e energy distributions. The no-neutron events are expected to add a few per cent to the total number of events shown in table 1.

A tentative design of OMNIS' LPC component has it housed in 20 cylindrical calorimeters, each of 19 m^3 volume. However, the PMT arrays could also distinguish Cerenkov-light-producing events from the neutron capture pulses, an important feature. Each module will have highly reflective walls and PMTs arrayed along its ends, as shown schematically in figure 9. These modules would have sizes smaller than the $\sim$4 m attenuation length for LPC (Elliott 2000). They would be arranged in pairs, and might have neutron detectors at both ends, to increase the probability of capturing the neutrons produced in the neutrino–lead interactions. The 1.06 kton of LPC, with a 20% water admixture, is actually 0.43 kton of lead. The general features of an LPC detector have been studied (Elliott 2000), but extensive R&D is planned to determine materials that can withstand the chemical effects of LPC over decades-long periods of time. In addition, Monte Carlo simulations will be performed to determine the optimal geometries for the modules. Chemical safety issues will also have to be considered, although the small sizes of the individual modules will help greatly in this regard. We plan to build several LPC modules, the last of which would be an $\sim$50 ton LPC prototype, which would ultimately be operated as one of the 20 LPC modules.

The LPC would be expected to be more efficient in detecting neutrons than would be the LS modules, and this has been confirmed by Monte Carlo simulations. Detection results from the neutrons being captured on the ^{35}Cl in the LPC. The cross section for this is so much larger than that for any other capture process (e.g., on the protons in the water component) that the

8.6 MeV of γ-rays emitted in the capture should produce a readily identifiable signal, even with moderate energy resolution for which we are designing the LPC modules (Elliott 2000).

6.3. Other features of OMNIS

The electronics for both the LS and LPC modules will be rather standard in principle, as they simply have to provide the interface between the photomultipliers and the data acquisition system. However, SNe are sufficiently rare that one must take precautions to be sure that the event is not missed. Thus data will have multi-disk storage and backup needed to ensure continuous running and to protect against a failure mode which could lose the data from a SN. Furthermore, all events must be recorded so that, if a SN is observed, the singles events can be analysed off-line without imposing the neutron-event-identifying signal doublet.

The cosmic-ray veto counters will consist of plastic scintillators that will be placed above the LS and LPC modules. Their optimum, and most cost effective, design appears to be that developed by the MINOS collaboration. The arrays for the LS modules will be two dimensional, and will essentially occupy the width of the ceiling of the drift in which they are located, thus providing excellent cosmic-ray muon rejection for most possible incident angles. We plan to install veto counters both above and below the LPC modules, since identification of grazing (muon) events necessitates the two sets of veto counters to achieve good resolution.

An important feature of SN neutrino detection involves a SN that occurs close to Earth. OMNIS' data will be stored in buffers which will be subsequently downloaded so as to minimize the deadtime that would accompany the high event rate from a close SN. OMNIS will also have a modular design; since maintenance of OMNIS would require shutting down only one module at a time, only a small fraction of OMNIS would ever be shut down when a SN occurred.

7. The sites for supernova neutrino detectors

Since cosmic-ray backgrounds must be reduced by orders of magnitude from the levels observed at the surface of Earth for the event rates in the large detectors to be handled by the electronics and data acquisition, they all have been built in underground sites. Super-K is located in the Japanese Alps near Kamioka, at a depth of 2200 mwe. SNO is located in the Creighton Mine near Sudbury, Ontario, Canada. It is at a depth of 6000 mwe, providing excellent discrimination against cosmic-ray muons. KamLAND is also located in Japan, near Kamioka, at essentially the same depth as Super-K.

OMNIS is planned for two sites: The Waste Isolation Pilot Plant near Carlsbad, NM and the National Underground Science Laboratory near Lead, SD. The site in which we plan to begin constructing the LS components of OMNIS is the WIPP. With a depth of $\sim$650 m (2000 mwe), and with tunnels and infrastructure supported by the DOE, the WIPP provides an excellent and accessible site for OMNIS. It also is planned to have a long life, currently at least 40 years, and is ready for immediate occupancy.

However, we also hope to site approximately half of OMNIS in the NUSL if that site, or some other NUSL site, does become a national facility. Constructing OMNIS in two sites would provide significant benefits, e.g., in eliminating the possibility that power glitches at a single site might mimic the signal from a SN. The NUSL has the advantage that it is extremely deep; as much as 7200 mwe. This might be important in operating a nucleon decay search facility.

A further possibility for a separate but networked site exists in the UK Boulby Mine, currently set up for dark matter experiments. However, the UK group is also interested in constructing a 500 to 2000 ton OMNIS there.

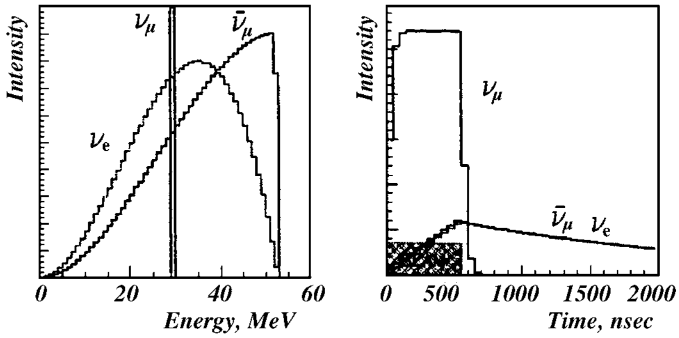

Figure 10. The time and energy spectra of the different flavour neutrinos from a stopped pion beam. From the ORLaND Proposal.

8. Calibrating the neutrino–lead interaction cross section

We plan to do an experiment at a neutrino factory, e.g., a successor to ORLaND or LANSCE, using the neutrinos produced by the decays of a stopped pion beam, to measure the cross sections for neutrinos on lead. Such a facility would produce a monoenergetic 30 MeV ν_μ beam, and ν_e and $\bar{\nu}_\mu$ beams that have well-defined distributions from 0 to 53 MeV, as shown in figure 10. Furthermore, the ν_μ arrive at essentially the same time as does the primary beam, while the $\bar{\nu}_\mu$ and ν_e arrive over a much longer time scale; this will facilitate identification of the neutrino that causes each event. The information obtained from this experiment would provide an important input to the Monte Carlo simulations. More importantly, it would provide a test of the theoretical neutrino–lead cross sections, hence of the relative merits of the different approaches to calculating neutrino–nucleus cross sections. Thus this experiment is important in its own right.

The neutrino spectra from a stopped pion beam are ideal for 'calibrating' the response of lead to SN neutrinos. The neutrino energies are in the energy range of the SN neutrinos. Notably, the ν_x energies are below the thresholds for muon and τ production, so that, as with SN neutrinos, they will produce only NC interactions. Furthermore, the ν_e energy continuum spectrum will provide an excellent means of measuring the energy dependence of the response of lead to both CC events and NC events.

One of the LPC modules will be used in this experiment, as those modules would have the capability to discriminate between NC and CC events, and would provide energy information for the CC events in the same way as would OMNIS. Thus these modules would provide all the information regarding the neutrino–lead cross sections that is needed to determine the response of lead to SN neutrinos. The parameters assumed for such an experiment are given in table 3, in which the assumed fluxes of neutrinos, the total size of the LPC detector, the anticipated cross sections (from FHM) and the anticipated yields are given. As can be seen, an excellent calibration could be obtained with $\sim$1 month of running at the assumed neutrino flux. The fluxes have been given generic values; yields with other values would simply scale with the neutrino flux. Although this experiment would be conducted at the Earth's surface, effects of cosmic-ray backgrounds could be reduced to acceptable levels using the pulsed structure of the beam.

A recent experiment (Krasznahorkay *et al* 2001) has been performed to elucidate the SN neutrino response function. A second experiment (Fujiwara 2001) is planned to study

Table 3. Assumed parameters and estimated yields for the various modes of neutrino–lead interactions resulting from a stopped pion beam. The detection efficiency was assumed to be 100% and the $Pb[ClO_4]_2$ to H_2O mixture to be 80:20. Note that the differences in NC cross sections result from the energy averaging of the different flavours. The cross sections are from Engel *et al* (2003).

Neutrino beam and detector parameters			
Assumed ν_μ flux	1×10^{10} m^{-2} s^{-1}		
Assumed ν_e flux	1×10^{10} m^{-2} s^{-1}		
Assumed $\bar{\nu}_\mu$ flux	1×10^{10} m^{-2} s^{-1}		
Detector area normal to the neutrino flux	12.5 m^2		
Thickness of detector	1.0 m		
Cross sections in cm^2	0-neutron	1-neutron	2-neutron
Neutral current, ν_e		1.4×10^{-40}	5.0×10^{-41}
Neutral current, $\bar{\nu}_\mu$		1.7×10^{-40}	7.5×10^{-41}
Neutral current, ν_μ		9.2×10^{-41}	1.2×10^{-41}
Charged current, ν_e	4.6×10^{-40}	2.3×10^{-39}	1.3×10^{-39}
Resulting yields per day	0-neutron	1-neutron	2-neutron
Neutral current ν_e		0.56	0.2
Neutral current $\bar{\nu}_\mu$		0.68	0.3
Neutral current ν_μ		0.37	0.05
Charged current ν_e	1.8	9.2	5.2

coincidences between the states populated and the neutrons they produce. These two experiments will identify the states in the several resonances that influence the yields of the neutrino-induced reactions, and measure the energies of the neutrons emitted, of importance to their detection efficiency. Clearly, however, the measurement of the neutrino–lead cross section must also be done to extract the full scientific potential from OMNIS' detection of SN events.

9. Concluding summary and prospects

There is every indication that current world interest in long term running of SN neutrino detectors will continue into the future for many astrophysical and neutrino physics phenomena. The list of topics discussed, or hinted at, in this proposal is summarized below:

- Stellar collapse diagnostics through measurement of neutrino spectra.
- Observation of neutrino spectra to infer effects such as deviations from a non-zero chemical potential Fermi–Dirac distribution.
- Observation and diagnosis of possible collapse to a black hole.
- Direct measurement of neutrino mass eigenstates at unprecedented levels.
- Measurement of several types of neutrino transitions or oscillations.
- Determination of neutrino spectrum for ν-process.
- Observation of late-time phenomena.

While this is not an exhaustive list, it is certainly a list that impacts a large number of the highest priority scientific issues identified by the National Academy of Science 'Committee on the Physics of the Universe', and we believe that it fully justifies building and supporting OMNIS, the Observatory for Multiflavour Neutrinos from Supernovae.

Acknowledgments

RNB acknowledges the support of the US National Science Foundation grants PHY-0140255 and PHY-0242877. PFS acknowledges the partial support from an Individual Emeritus Research Grant by the Leverhulme Trust. GCM acknowledges US Department of Energy grant DE-FG02-02ER41216.

Appendix. The OMNIS collaboration

David B Cline[6], (Co-PI) Professor of Physics and Astronomy, University of California at Los Angeles, Los Angeles, CA 90095, USA
Todd Haines[6,7], (Co-PI) Staff Member, Los Alamos National Lab, Los Alamos, NM 87545, USA
Evan R Sugarbaker[6], (Co-PI) Department of Physics, Ohio State University, Columbus, OH 43210, USA
Richard Talaga[6], (Co-PI) Staff Member, Argonne National Lab, Argonne, IL 60439, USA
Richard N Boyd, Professor of Physics, Professor of Astronomy, Ohio State University, Columbus, OH 43210, USA
William Burgett, Visiting Assistant Professor, University of Texas at Dallas, Dallas, TX 75083, USA
J W Dawson, Electronics Engineer, Argonne National Lab, Argonne, IL 60439, USA
G R Drake, Electronics Engineer, Argonne National Lab, Argonne, IL 60439, USA
Ervin J Fenyves, Professor of Physics, University of Texas at Dallas, Dallas, TX 75083, USA
George M Fuller[6], Professor of Physics, University of California at San Diego, La Jolla, CA 92093, USA
M C Goodman, Staff Member, Argonne National Lab, Argonne, IL, 60439, USA
J J Grudzinski, Mechanical Engineer, Argonne National Lab, Argonne, IL 60439, USA
V J Guarino, Mechanical Engineer, Argonne National Lab, Argonne, IL 60439, USA
Robert Haight, Staff Member, Los Alamos National Lab, Los Alamos, NM 87545, USA
Michael Hencheck, Associate Professor of Physics, University of Wisconsin at Green Bay, Green Bay, WI 54311, USA
Dennis Hofer, Acting Manager Experimental Program Support, WIPP, Carlsbad, NM 88221, USA
Toshitaka Kajino, National Astronomical Observatory, Mitaka, Tokyo, Japan
Thomas LeCompte[6,8], Staff Member, Argonne National Lab, Argonne, IL 60439, USA
Kent Ludwig, Mechanical Engineer, Ohio State University, Columbus, OH 43210, USA
Gail McLaughlin, Assistant Professor of Physics, North Carolina State University, Raleigh, NC 27695, USA
Bradley S Meyer, Professor of Physics, Clemson University, Clemson, SC 29634, USA
Anthony Mezzacappa, Oak Ridge National Lab, Oak Ridge, TN 37831, USA
Alexander St J Murphy, Lecturer, University of Edinburgh, Edinburgh, EH9 3JZ, UK
Roger Nelson[6], Chief Scientist, Waste Isolation Pilot Plant, Carlsbad, NM 88221, USA
Michael M Nieto, Staff Member, Los Alamos National Lab, Los Alamos, NM 87545, USA
Robert Scherrer, Professor of Physics, Ohio State University, Columbus, OH 43210, USA
Peter F Smith[6], Rutherford Appleton Lab., Chilton, Oxfordshire OX11 OQX, UK
R W Stanek, Staff Member, Argonne National Lab, Argonne, IL 60439, USA

[6] Members of the Steering Committee.
[7] Project Director.
[8] Project Manager.

Steven Stochaj, Assistant Professor, New Mexico State University, Las Cruces, NM 88003, USA
Jonathan Thron, Staff Member, Argonne National Lab, Argonne, IL 60439, USA
John Ullman, Staff Member, Los Alamos National Lab, Los Alamos, NM 87545, USA
Mark Vagins, Research Scientist, University of California at Irvine, Irvine, CA 92697, USA
Paul Voytas, Assistant Professor of Physics, Wittenburg University, Springfield, OH 45501, USA
Joel Webb, Manager of Program Development, Carlsbad Environmental Monitoring and Research Center, New Mexico State University, Carlsbad, NM 88220, USA
Fred Wietfeldt, Assistant Professor of Physics, Tulane University, New Orleans, LA 70118, USA
James R Wilson, Staff Member, Lawrence Livermore National Lab, Livermore, CA 94550, USA

References

Abdurashitov J N *et al* (SAGE Collaboration) 1999 *Phys. Rev. Lett.* **83** 4686
Ahmad Q R *et al* (SNO Collaboration) 2001 *Phys. Rev. Lett.* **87** 071301
Ahmad Q R *et al* (SNO Collaboration) 2002 *Phys. Rev. Lett.* **89** 011301
Altmann M *et al* (GNO Collaboration) 2000 *Phys. Lett.* B **490** 16
Apollonio M *et al* (CHOOZ Collaboration) 1999 *Phys. Lett.* B **466** 415
Applequist T, Dobrescu B A, Ponton E and Yee H-U 2001 *Phys. Rev. Lett.* **87** 181802
Arnett D 1996 *Supernovae and Nucleosynthesis: An Investigation of the History of Matter from the Big Bang to the Present* (Princeton, NJ: Princeton University Press)
Aschenbach B 1998 *Nature* **396** 141
Athanassopoulos C *et al* (LSND Collaboration) 1998 *Phys. Rev. Lett.* **81** 1774
Athanassopoulos C *et al* (LSND Collaboration) 1998 *Phys. Rev.* C **58** 2489
Babu K S, Pati J C and Wilczek F 2000 *Nucl. Phys.* B **566** 33
Babu K S and Mohapatra R N 2001 *Phys. Lett.* B **518** 269
Bahcall J N 1989 *Neutrino Astrophysics* (Cambridge: Cambridge University Press)
Bahcall J N and Piran T 1983 *Astrophys. J.* **267** L77
Barger V, Marfatia D and Wood B P 2001 *Phys. Lett.* B **498** 53
Barish B C 2000 *Nucl. Phys.* B **91** 141
Baumgarte T W, Janka H-Th, Keil W, Shapiro S and Teukolsky S 1996 *Astrophys. J.* **468** 823
Beacom J 2000 Private communication
Beacom J, Boyd R N and Mezzacappa A 2000 *Phys. Rev. Lett.* **85** 3568
Beacom J, Boyd R N and Mezzacappa A 2001 *Phys. Rev.* D **63** 073011
Beacom J and Vogel P 1996 *Phys. Rev.* D **58** 053010 and 093012
Berger C *et al* (Frejus Collaboration) 1991 *Phys. Lett.* B **269** 227
Bethe H A and Brown G E 1995 *Astrophys. J.* **445** L129
Bionta R M *et al* (IMB Collaboration) 1987 *Phys. Rev. Lett.* **58** 1494
Boehm F *et al* 2000 *Nucl. Phys.* B **91** 91
Boyd R N 1999 *Heavy Elements and Related New Phenomena* ed R Gupta and W Greiner (Singapore: World Scientific) p 893
Boyd R N, Rauscher T, Reitzner S D and Vogel P 2003 *Phys. Rev.* D at press
Brown G E and Bethe H A 1998 *Astrophys. J.* **423** 659
Burrows A 1990 *Ann. Rev. Nucl. Part. Sci.* **40** 181
Cleveland B *et al* 1998 *Astrophys. J.* **496** 505
Cline D B, Fuller G M, Hong W P, Meyer B and Wilson J 1990 *Astrophys. Lett. Commun.* **27** 403
Cline D B, Fuller G M, Hong W P, Meyer B and Wilson J 1994 *Phys. Rev.* D **50** 720
Dighe A S and Smirnov A Yu 2000 *Phys. Rev.* D **62** 033007
Run Mine Doe 2000 Specification sheets, private communication
Dragicevich P M, Blair D G and Burman R R 1999 *Mon. Not. R. Astron. Soc.* **302** 693
Ejiri H 1993 *Phys. Rev.* C **48** 1442

Elliott S 2000 *Phys. Rev.* C **62** 065802
Engel J, McLaughlin G C and Volpe C 2003 *Phys. Rev.* D **67** 013005
Fujiwara M 2001 Private communication
Fukuda Y *et al* (Super-Kamiokande Collaboration) 1999 *Phys. Rev. Lett.* **82** 2430
Fukuda S et al (Super-Kamiokande Collaboration) 2001 *Phys. Rev. Lett.* **86** 5651
Fuller G M, Haxton W and McLaughlin G 1999 *Phys. Rev.* D **59** 085005
Georgi H and Glashow S L 1974 *Phys. Rev. Lett.* **32** 438
Groom D E *et al* 2000 *Eur. Phys. J.* C **15** 1
Hampel W *et al* (GALLEX Collaboration) 1999 *Phys. Lett.* B **447** 127
Hannestad S and Raffelt G 1998 *Astrophys. J.* **507** 339
Hatano K, Fisher A and Branch D 1997 *Mon. Not. R. Astron. Soc.* **290** 360
Haxton W, Langanke K, Qian Y-Z and Vogel P 1997 *Phys. Rev. Lett.* **78** 2694
Hirata K W *et al* (Kamiokande Collaboration) 1987 *Phys. Rev. Lett.* **58** 1490
Janka H-T, Keil W, Raffelt G and Seckel D 1996 *Phys. Rev. Lett.* **76** 2621
KamLAND Proposal, http://kamland/lbl/gov/KamLAND.US.Proposal.pdf
Kamyshkov Y and Kolbe E 2003 *Phys. Rev.* D **67** 076007
Knoll G 1989 *Radiation Detection and Measurement* 2nd edn (New York: Wiley)
Yang S 1997 *PhD Thesis* California Institute of Technology
Kolbe E and Langanke K-H 2001 *Phys. Rev.* C **63** 025802
Krasznahorkay A, Akimune H, Fujiwara M, Harakeh M N, Janecke J, Rodin V A, Urin M H and Yosoi M 2001 *Phys. Rev.* C **64** 067302
Langanke K and Martinez-Pinedo G 2003 *Rev. Mod. Phys.* **75** 819
Langanke K, Vogel P and Kolbe E 1996 *Phys. Rev. Lett.* **76** 2629
Mann W A 2000 *Nucl. Phys.* B **91** 134
McLaughlin G C, Fetter J M, Balantekin A B and Fuller G M 1999 *Phys. Rev.* C **59** 2873
Meyer B, McLaughlin G and Fuller G 1998 *Phys. Rev.* C **58** 3696
Mezzacappa A, Calder A C, Bruenn S W, Bondin J M, Guidry M W, Strayer M R and Umar A S 1998 *Astrophys. J.* **493** 848
Murphy A S 1999 *Proc. MINOS Collaboration Meeting, (June)*
Myra E S and Burrows A 1990 *Astrophys. J.* **364** 222
Pati J C and Salam A 1973 *Phys. Rev.* D **8** 1240
Pati J C and Salam A 1973 *Phys. Rev. Lett.* **31** 661
Pati J C and Salam A 1974 *Phys. Rev.* D **10** 275
Pons J A, Reddy S, Prakash M, Lattimer J M and Miralles J A 1999 *Astrophys. J.* **513** 780
Qian Y-Z, Fuller G M, Mathews G J, Mayle R W, Wilson J R and Woosley S E 1993 *Phys. Rev. Lett.* **71** 1965
Qian Y, Haxton W, Langanke K and Vogel P 1997 *Phys. Rev.* C **55** 1532
Qian Y-Z, Vogel P and Wasserburg G J 1998 *Astrophys. J.* **494** 285
Raffelt G 1996 *Stars as Laboratories for Fundamental Physics* (Chicago, IL: University of Chicago Press)
Raffelt G 2001 *Preprint* astro-ph/0105250
Reddy S, Bertsch G and Prakash M 2000 *Phys. Lett.* B **475** 1
Schirato R and Fuller G M 2002 *Preprint* astro-ph/0205390
Smith P F 1997 *Astropart. Phys.* **8** 27
Smith P F 2001 *Astropart. Phys.* **16** 75
Smy M 2001 Invited talk at *NNN'01 Workshop (Louisiana State University, Baton Rouge)*
Sobel H 2000 *Nucl. Phys.* B **91** 127
Strom R G 1994 *Astron. Astrophys.* **288** L1
Suzuki Y *et al* (Kamiokande Collaboration) 1993 *Phys. Lett.* B **311** 357
Tammann G A, Löffler W and Schröder A 1994 *Astrophys. J. Suppl.* **92** 487
Totani T, Sato K, Dalhed H E and Wilson J R 1998 *Astrophys. J.* **496** 216
Totsuka Y 1986 *Proc. 7th Workshop on Grand Unification/ICOBAN '86* ed J Arafune (Singapore: World Scientific) p 118
Totsuka S 1990 *Int. Symp. Underground Physics Experiments (Science Council of Japan, April)*
Totsuka S 1991 Report ICRR-227-90-20, Keck 9101351
Van den Bergh S 1993 *Comments Astrophys.* **17** 125
Volpe C, Auerbach N, Colo G and Van Giai N 2002 *Phys. Rev.* C **65** 044603
Wallerstein G *et al* 1997 *Rev. Mod. Phys.* **69** 995
Woosley S E, Hartmann D H, Hoffman R D and Haxton W C 1990 *Astrophys. J.* **356** 272
Zach J J, Murphy A S, Marriott D and Boyd R N 2002 *Nucl. Instrum. Methods Phys. Res.* A **484** 194