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A White Paper for Large Liquid Scintillation Detectors at DUSEL

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Abstract

We recommend the critical evaluation of a large-scale neutrino detector using liquid scintillating (LS) oil as the target and detection medium. A large LS detector at DUSEL (Lead South, Dakota) provides a complimentary tool for long-baseline neutrino studies with a GeV neutrino beam from Fermilab, and extends the research capabilities of this facility to detection of electron anti-neutrinos to energies less than 1 MeV, allowing investigations of geological, supernova, solar and reactor anti-neutrino studies. Such a detector would also provide for a sensitive search for proton decay. A large LS detector at Homestake expands the range of physics experiments and substantially enhances the multi-disciplinary nature of the laboratory.

We suggest including a large-scale liquid scintillation (LS) based neutrino detector in the mix of large-scale neutrino physics projects at the newly forming Deep Underground Science and Engineering Laboratory (DUSEL) in Lead, South Dakota. Substantial progress has been made on defining options for the centerpiece experiments employing water Cherenkov (WC) and liquid argon (LAr) instruments. Given new realizations about LS based instruments, that option should now be added to the options being actively considered for Long Baseline Neutrino Experiments (LBNE).

We advocate the development of directional resolution capabilities for low energy electron anti-neutrinos. This capability would significantly expand the science possibilities at DUSEL. The subject merits further study.

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I Introduction and Discussion of Three Detector Types

The use of liquid scintillators as the target and detection medium for neutrino experiments has a long history, starting with the first observations of neutrinos at reactors in the 1950's. A liquid detector with surrounding surface-mounted optical sensors has obvious advantages over segmented detectors for large volumes, since most of the cost is in the light detectors. Moreover the light output of scintillators is almost two orders of magnitude greater than Cherenkov radiation, thus permitting explorations to lower neutrino energies, or in reducing the number of photodetectors in a segmented detector. Further, charged particles which are below the Cherenkov threshold in water, can be detected in scintillating media. A misconception has been the presumed inability to reconstruct tracks and identify particles in scintillators for particles with GeV energies (as in typical accelerator-made beams of neutrinos). We have recently learned that indeed flavor identification (discerning muon from electron events) may be excellent and that in some regards, liquid scintillation detectors may challenge or even exceed the capabilities of water Cherenkov detectors. At the very least, we recognize the complementary characteristics of the three liquid technology detectors in scaling to large instruments in the greater than tens of kiloton class.

We start with a comparison of the three main detector technologies under consideration for large underground neutrino detection facilities, and then move on to discuss specifically the liquid scintillation detector possibilities.

Flagship projects for a new major underground laboratory (e.g., the Homestake mine - Sanford Laboratory and the developing DUSEL facility) are being evaluated at the US National Science Foundation and the Department of Energy. One flagship project under consideration is a very large neutrino detector that would also be a sensitive probe for proton decay. Two technologies for such a detector have dominated the discussions to date: Water Cherenkov (WC) and Liquid Argon (LAr) detectors. The most prominent method involves using large ultra-pure water containing vessel(s) in the 100,000 m^3 class, surrounded by 10^{4-5} photo-detectors to record signals generated by Cherenkov radiation, occurring after neutrino interactions in or around the huge cavity. The second, and in many ways more sophisticated though less demonstrated technology, involves a large bath of liquid argon. Tracks are drifted to recording electrodes by an electric field, and depending upon the density of electrodes, bubble-chamber-like detailed images can be produced from the recorded data.

We point out that large-scale liquid scintillation detectors have substantial merit for application at DUSEL, and that such a detector opens new physics channels for exploration. New realizations during this past year caused us to initiate this White Paper, and in the following sections we will sketch the attractions (and some drawbacks) that large LS detectors bring to the table, along with the relative merits of water Cherenkov and liquid argon based instruments.

DUSEL is not unique in considering a set of large detectors for a large underground laboratory; this is being done almost simultaneously in Europe in the LAGUNA consortium (more than 26 institutions in the LENA, GLACIER and MEMPHYS experiment groups).[1] Their baseline designs (though perhaps shifting with time) seem to be 600-800 kT for the WC detector MEMPHYS, 100 kT for the LAr detector GLACIER, and 50 kT for the LS LENA instruments, as illustrated in Figure 1. Since a great deal of effort has already been spent on this trio of

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[1] Key questions in particle and astroparticle physics can be answered only by construction of new giant underground observatories to search for rare events and to study sources of terrestrial and extra-terrestrial neutrinos. In this context, the European Astroparticle Roadmap of 03/07, via ApPEC and ASPERA, states: “We recommend a new large European infrastructure, an international multi-purpose facility of 10^5-10^6 ton scale for improved studies of proton decay and low-energy neutrinos. Water-Cherenkov, Liq. Scintillator & Liq. Argon should be evaluated as a common design study together with the underground infrastructure and eventual detection of accelerator neutrino beams. This study should take into account worldwide efforts and converge by 2010...” Furthermore, the latest particle physics roadmap from CERN of 11/06 states:
“A range of very important non-accelerator experiments takes place at the overlap of particle and astroparticle physics exploring otherwise inaccessible phenomena; Council will seek with ApPEC a coordinated strategy in these areas of mutual interest.” Reacting to this, uniting scientists across Europe, we propose here a design study, LAGUNA, to produce by 2010 a full conceptual design sufficient to provide policy makers and funding agencies with enough information for a construction decision. Has Europe the technical and human capability to lead future underground science by hosting the next generation underground neutrino and rare event observatory? We aim to answer this question. Certainly construction will exceed the capacity of any single European nation - to compete with the US and Asia unification of our scattered efforts is essential. Failure to plan now risks not only that our picture of Nature's laws remain fundamentally incomplete but also that leadership in the field enjoyed by Europe for 20 years falls away. EU FP7 input now is timely and will have major strategic impact, guaranteeing coherence and stimulating national funding. [from http://lartpc-docdb.fnal.gov/0002/000256/003/LAGUNA-FP7_PartB.pdf]

detectors for Europe, we can draw upon those studies, adding our specific new information, and considerations relative to the US location.

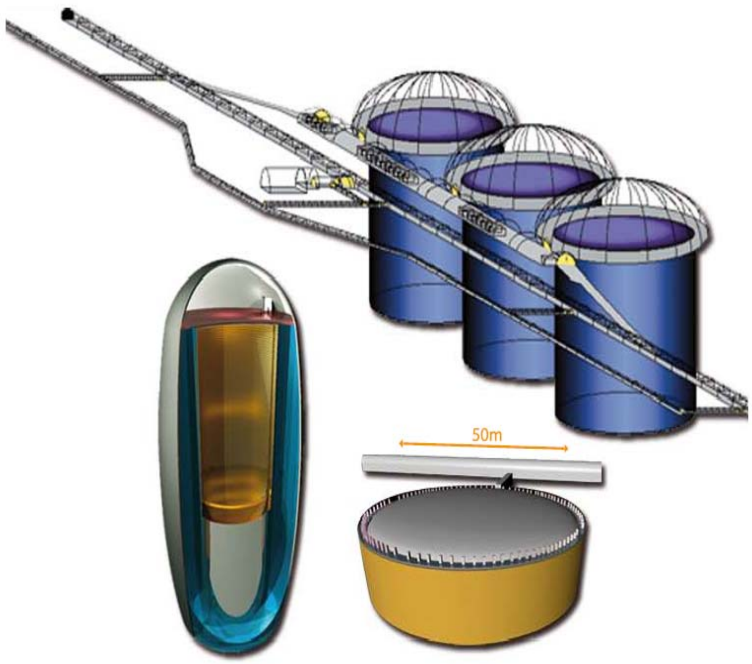

Figure 1 Cartoons of the three large underground neutrino detectors under consideration in the European LAGUNA project, MEMPHYS (700 kT Water Cherenkov), LENA (50 kT liquid scintillator) and GLACIER (100 kT liquid argon).

II Comparison of Technologies

The relative capabilities of these various technologies, as presented for LAGUNA, are shown in Table 1[i]. Not discussed here are the relative masses, photocathode coverage, density of electrodes and so on of the LAGUNA ensemble; these attributes are accepted in order to use the existing instrumental comparisons. Choices for DUSEL will surely be different, but the general contrast should be fair. Note however that the WC detector being considered for Europe is 700 kT, seven times the present baseline DUSEL device. Also the 100-kT GLACIER is 5 times larger than presently discussed LAr detector for DUSEL. Bear in mind that all specifications may well evolve before plans are fixed.

Table 1 Basic parameters of the baseline three detectors for the LAGUNA study[i].

	GLACIER	LENA	MEMPHYS
Detector dimensions			
type of cylinder	1 vert.	1 horiz.	3-5 vert.
diam. (m)	70	30	65
length (m)	20	100	65

typical mass (kton)	100	50	600-800
Target and Readout			
type of target	liq. Argon (boiling)	liq. scintillator	water (opt 0.2% $GdCl_3$)
readout type	e- drift: 2 perp. views, 10^5 chnls, ampl. in gas phase; Cher. light: 27,000 8" PMTs, ~20% coverage; Scint. light: 1000 8" PMTs	12,000 20" PMTs, >30% coverage	81,000 12" PMTs, ~30% coverage

Comparisons of the different physical attributes of the three detection media are presented in Table 2. The chief difference is that liquid argon presents a moderately heavy nucleus and no hydrogen. Hydrogen is important for having free protons either as objects of possible proton decay or, as electron anti-neutrino targets (for inverse beta decay). Both carbon and oxygen in the media can form isotopes with unwanted decays impeding inverse beta detection. These products represent a problem only for the low energy (MeV) physics, and both are entirely manageable at the shielding depths considered for DUSEL (>4000 meters water equivalent depth, mwe). Density differences of WC and LS (LS ranging from 0.8 to 1.0) versus LAr favors the latter to have 40-50% more targets per unit volume. The radiation length of particular relevance for discriminating gammas from electrons (longer being better) favors LS in preference to WC and LAr. The cost per unit mass shows that WC is far less expensive than LS or LAr. This cost factor surely sets an economic upper limit on such detectors, probably in the 100 kT range, whereas we easily contemplate megaton WC detectors.

Table 2 Physical parameters of the three target liquids.

Property	Scint	Water	Argon
Z	1,12 (1-2:1)	1,16(2:1)	40
X_0 [cm]	42	36	20
ρ [gm/cm^3]	0.8 – 1.0	1	1.39
Λ_{int} [gm/cm^2]	75.7	84.6	117.2
Λ_{col} [gm/cm^2]	55.7	60.1	76.4
-dE/dx [gm/cm^2]	2.3	1.99	1.52
n (optical)	1.49	1.33	1.23
$\theta ms/\sqrt{X_0}$	2.1	2.3	3.1
~Cost [$/kg]	3	0.2	2

Comparisons of the physics possibilities with each of these three detectors are summarized in Table 3. Here we have assumed the following detector sizes: WC at 100 kT, LAr at 20 kT, and LS at 50 kT. Of high importance for the LBNE at DUSEL with the (planned) high power neutrino beam from Fermilab, is the ability to recognize electron appearance, and not to be fooled by single gamma production. All three detectors will do a good job at this, with errors in the one percent range, except the LAr should have superior rejection of gammas, and LS detectors may have some advantage over WC detectors if the gap between vertex and gamma shower is detectable (not shown yet).

An issue under study now, is just how good are WC and LS at rejecting the asymmetric π^o decays? WC detectors cannot distinguish between an electron and a gamma-induced shower. LS detectors may have an advantage in recognizing the gap between the nuclear recoil at the neutrino interaction point and the start of the electron-like shower 40 cm away (on average).

With an external magnetic field a LAr detector could determine the sign of the electron/positron charge. Such a magnetic field would probably only be applied when a new neutrino factory is built sometime in the future. Observation of positron annihilation is certainly possible in LAr, and may be possible (again study needed) in LS.

All three detector types could observe the following:

- Neutrinos from a galactic core collapse supernova
- Atmospheric neutrinos
- Solar neutrinos (WC sees only electron elastic scattering)
- Nucleon decay (although only WC and LS for free protons)

Importantly LS detectors offer the following significant advantages:

- Efficient recognition of nucleon decay into kaon modes (favored by SUSY models)
- Geoneutrino detection
- Detection of antineutrinos from distant nuclear reactors

Table 3 Summary of the physics potential of the three detector types considered herein for DUSEL. We take the WC detector as 100 kT, LAr as 20 kT, and LS detector as 50 kT.

Physics	50 kT Scint	100 kT Water	20 kT Argon
Long baseline			
LBL e appear	Yes	Yes	Yes
LBL e+/e-	No (?)	No	Yes
Free protons	Yes	Yes	No
Proton decay			
$e+\pi^0$, halflife sensitivity [yr]	$30*10^{33}$	$30*10^{33}$	$12*10^{33}$
ν-K, halflife sensitivity [yr]	$24*10^{33}$	$8*10^{33}$	$10*10^{33}$
Reactor electron anti-neutrinos			
Δm^2_{12}, θ_{12}	Yes	Iff Gd	No
Solar Neutrinos			
Solar ^{8}B neutrinos	Yes	Yes?	Yes

Solar *hep* neutrinos	Yes	Yes	Yes
Solar anti-neutrinos	Yes	No	No
Other physics signals			
Geoneutrinos	Yes	No	No
Atmospheric neutrinos	Yes	Yes	Yes
Number of events from SN burst	20000	40000	8000
Relic SN neutrino sensitivity[cm^2/s]	<1	~1	No
Indir WIMPs	Yes	Yes	Yes

For the LS option, detection of geoneutrinos and other low energy anti-neutrino signatures provides an opportunity to conduct transformative multi-disciplinary science that also has societal application in nuclear monitoring (which we do not further discuss here).

III Low Energy (MeV-scale) Electron Anti-neutrinos

A 50-kT LS detector at DUSEL uses the unique capability of the "Reines process" to access low energy physics. Electron anti-neutrino capture on a proton (neutron-inverse-beta-decay) produces a positron, which has energy proportional to the neutrino energy, and a neutron. The neutron then captures on a proton with a mean capture time of approximately 200 μs, producing a 2.2 MeV gamma. These two events, close in space and time, with known energy for the neutron capture gamma, makes a wonderful signature for observing electron anti-neutrinos.

By and large the physics involving low energy (few MeV) electron anti-neutrinos is restricted to the LS option, simply because the LAr has no free protons, and the WC threshold is too high (~4.5 MeV in SuperK). However, a WC detector loaded with Gd, may observe the neutron captures, although the energy resolution will be very limited in the range below approximately 4 MeV (hence about half of the reactor even spectrum will be unavailable to WC detectors, even in the best circumstances).

In this section we discuss scientific investigations resulting from the observation of low energy electron anti-neutrinos. We begin with reactor anti-neutrinos and potential precision measurements of neutrino oscillation parameters. Following is a description of transformational geological studies using geoneutrinos. Finally we present the possibility to search for non-standard interactions of solar neutrinos.

III.1 Reactor Anti-neutrinos

By observing electron anti-neutrinos from nuclear reactors it may be possible to measure the neutrino mixing parameter Δm^2_{12} to ~1% with a large LS detector at Homestake. Although the flux of anti-neutrinos from nearby nuclear reactors at Homestake is about 24 times smaller than that at KamLAND, the target mass (assuming 50 kT) is about 59 times larger, resulting in 1200-1300electron anti-neutrino interactions per year, comparable to that at KamLAND. The unoscillated spectrum, cross section and event energy distributions are shown in Figure 2. The advantage of Homestake is that the nuclear reactors are located further away (with a large number of reactors around 1400 km distant) which make ~10 wiggles in the energy spectrum, as shown in Figure 3.

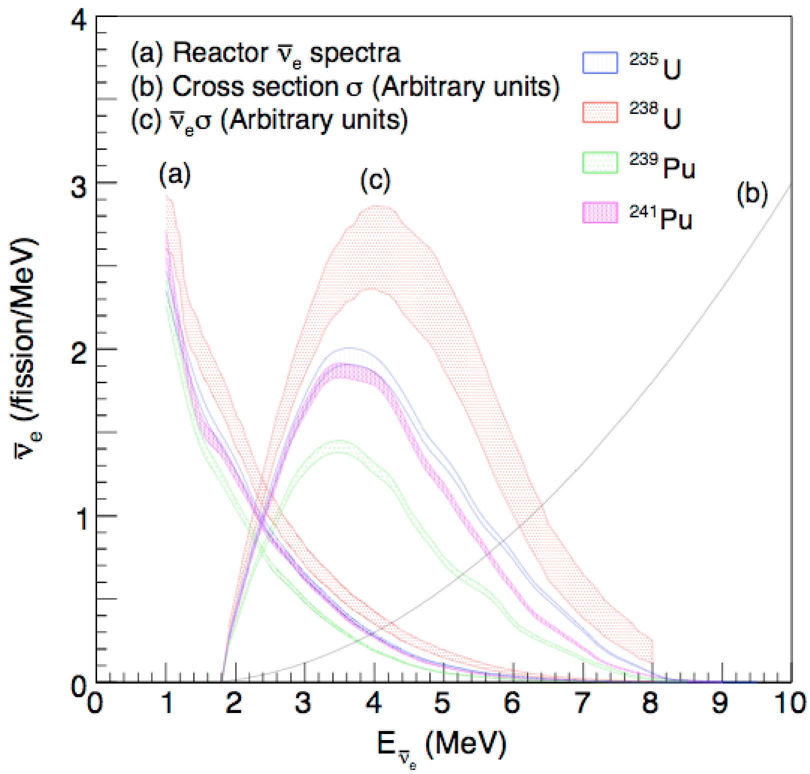

Figure 2 Unoscillated reactor spectrum, including the contributions of various reactor materials (a), the inverse beta cross-section (b), and the event rate (c)

This allows the Homestake experiment to improve upon the 3% KL measurement of Δm^2. It appears there will be some precision oscillation physics doable at Homestake with a large LS detector depending only upon distant nuclear power reactors. The only competition to such a measurement is the proposed Hanohano[ii] experiment.

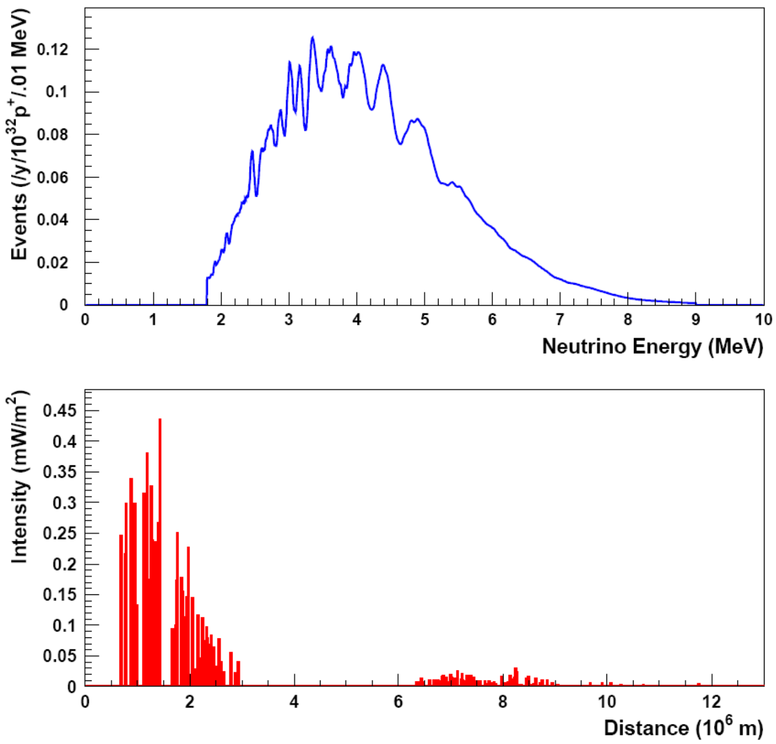

Figure 3 The top panel displays the perfectly measured energy spectrum of reactor anti-neutrino events at DUSEL. Spectral distortions reveal the solar mixing parameters. The bottom panel shows nuclear reactor intensity as a function of distance from DUSEL with a maximum at 1440 km.

III.2 Geoneutrinos

The decay of uranium and thorium in the Earth is the main energy source driving plate tectonics, the fundamental geological process that regulates the Earth's thermal evolution and shapes the Earth's surface. These decays also produce electron anti-neutrinos (geoneutrinos) with the maximum energy of uranium geoneutrinos reaching to 3.3 MeV, while that from thorium reaches to 2.25 MeV, as illustrated in Figure 4. Aside from measuring the total U and The flux, it is predicted that the ratio of the Earth's Th/U abundance ratio is about 4/1 and measuring deviations from this value could inform us on the processing of the crustal material.

Figure 5 shows the expected geoneutrino energy spectrum at Homestake along with signals from the sum of distant reactors (averaging over the neutrino oscillation wiggles in θ_{13}) and a hypothetical 6 TW natural reactor nuclear reactor at the Earth's core (discussed in Section III.3). The reduction in the reactor neutrino flux with respect to other possible sites improves the sensitivity to reactor antineutrinos at Homestake.

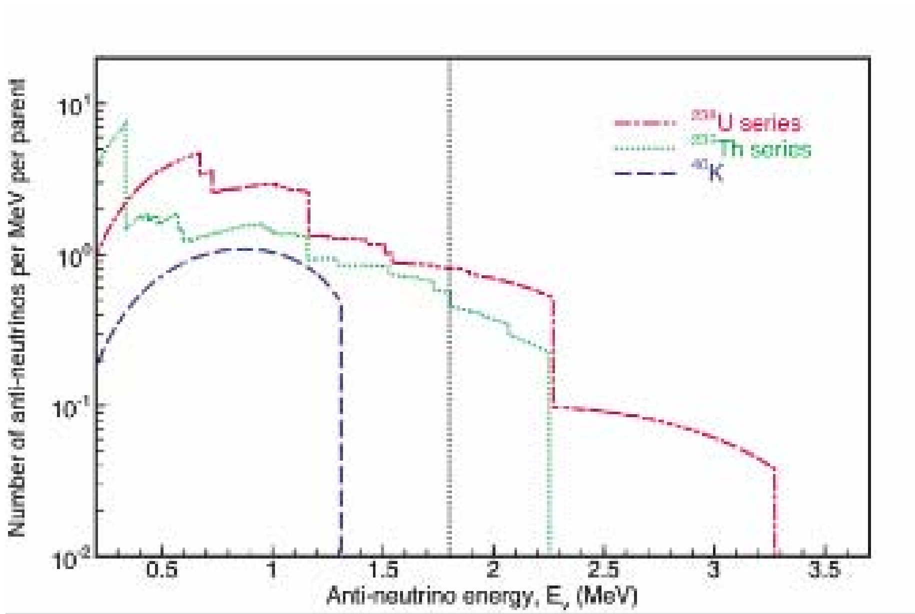

Figure 4 The expected ^{238}U, ^{232}Th and ^{40}K decay chain electron anti-neutrino energy distributions[iii]. The neutron-inverse-beta-decay detection reaction is only sensitive to electron anti-neutrinos to the right of the vertical dotted black line; hence it is insensitive to ^{40}K electron anti-neutrinos.

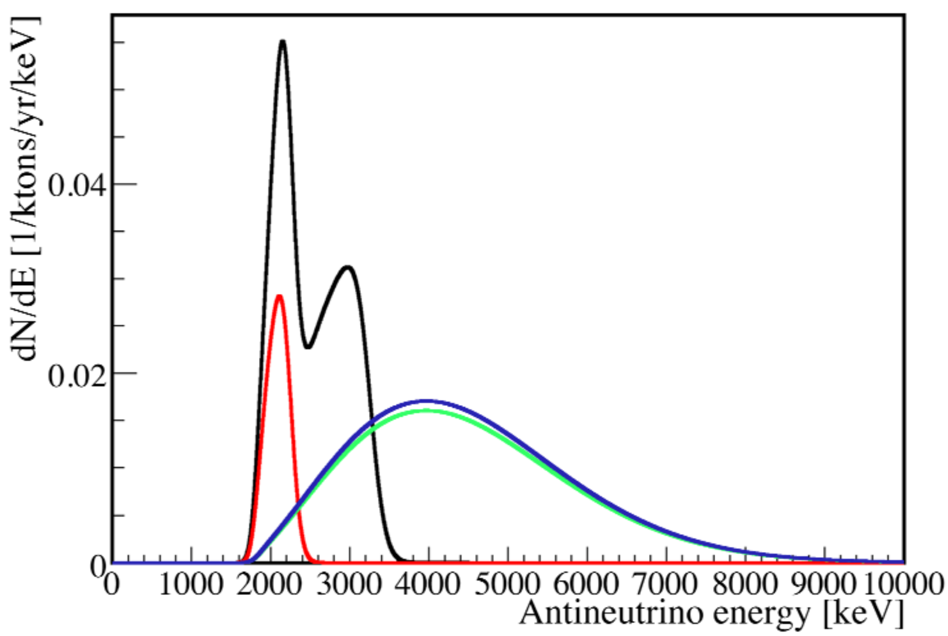

Figure 5 Neutrino event spectrum for Homestake[iv]. U geoneutrinos in black, Th geoneutrinos in red, sum of commercial reactors in blue and hypothetical 4.5 TW earth core geo-reactor in green.

Figure 6 shows the sensitivity of a 50-kT LS detector located at Homestake to various geoneutrino measurements compared to other current or planned detectors. Exploiting only existing and demonstrated technology such a detector could make the following measurements:

- Measure geoneutrino flux to ~5% (limited by systematic errors) in 1 year.
- Measure crustal geoneutrino flux to ~6% (limited by systematic errors) in 1 year after subtracting the background from the Earth's mantle.
- Measure the regional crustal ratio of thorium to uranium to <20% in several years.

These measurements are both worthwhile, and far better than can be achieved by the current or planned geoneutrino experiments (KamLAND, SNO+, and Borexino), simply due to the much greater detector mass. The proposed LENA detector would be competitive, while the proposed Hanohano detector would be complementary, measuring the mantle flux well and the crustal flux poorly.

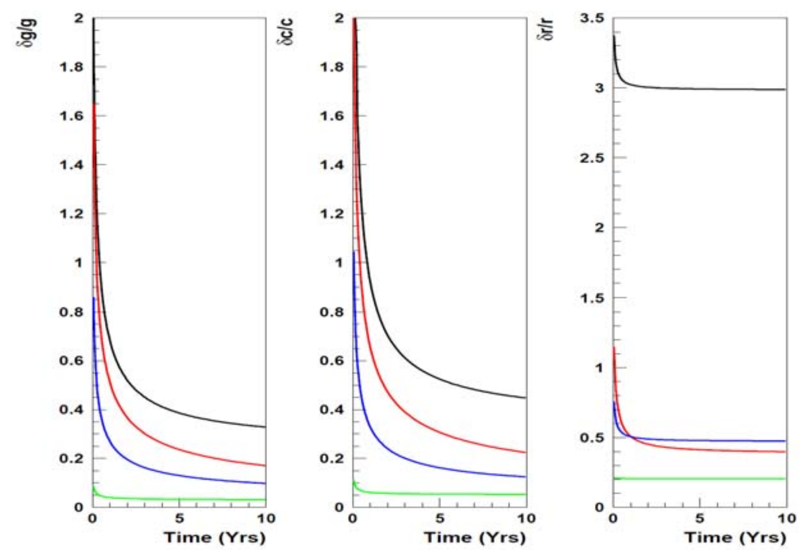

Figure 6 Fractional uncertainty as a function of observation period for various detectors (KamLAND=black, Borexino=red, SNO+=blue, and 50-kT DUSEL=green). ***Left panel:*** **δg/g = geo-neutrino rate fractional uncertainty. The reactor-related systematic uncertainty comes from not knowing the reactor rate perfectly. It scales as ($R_{reactor}/R_{geonu}$)*0.04. This is unfortunate for KamLAND. The factor of 0.04 comes from 3% errors in both the energy scale and the oscillation parameters added in quadrature. Borexino and SNO+ suffer from low mass. For detectors with reasonably low reactor background (all detectors except KL) the systematic limitation comes from uncertainty in the exposure, ~3%.** ***Middle Panel:*** **δc/c = crustal rate fractional uncertainty. This systematic error includes not knowing how much mantle signal to subtract. This term, contributing in quadrature, is (R_{mantle}/R_{crust})*0.20, where the 20% is a guess at the uncertainty in the mantle flux (BSE error).** ***Right panel:*** **δr/r = Th/U ratio fractional uncertainty. The ultimate limitation here is uncertainty in the fraction of the uranium rate at about 3 MeV. According to calculations, each percent uncertainty in this fraction contributes about 5% systematic uncertainty to δr/r.[v] The curves in the plot have 4%- 3% from energy scale and 3% from oscillation parameters taken in quadrature. Two other systematic terms contribute, which are quite sensitive to the reactor rate. The big DUSEL detector wins with size and low reactor background. It is interesting to see that Borexino eventually bests SNO+ due to lower reactor background.**

Ultimately, geoneutrino based exploration of the planet, like seismic studies which yield a density profile of the earth, tells us about the composition of the earth's interior, particularly the abundances of important trace elements (those that presumably account for all of geodynamics). Mapping the world's distribution of sources of electron anti-neutrinos can resolve many issues associated with the formation and evolution of the earth, processes driving sea floor spreading, the origins of hot spot volcanoes (like Hawaii and Yellowstone), and the energy driving the production of the earth's geomagnetic field.

III.3 Solar Anti-neutrinos

If the electron neutrino has a non-zero transition magnetic moment it could transform into an anti-neutrino as it traverses the solar magnetic field. The distinctive signature of the inverse beta decay allows for effective background suppression, so a large-volume LS detector probably stands the best chance to discover such non-standard effects in the energy region of solar neutrinos. However, terrestrial anti-neutrinos (especially from nuclear reactors) as well as the DSNB pose sizeable backgrounds to these searches. Vice versa, solar anti-neutrinos might pose a background for DSNB detection, depending on the relative fluxes.

IV Supernova Neutrinos

While the dominant neutrino detection channel in LS in case of a galactic core-collapse SN is the inverse beta decay, a 50 kT detector would be large enough to exploit a variety of reaction channels accessible to all neutrino flavors. In the standard SN scenario that describes the explosion of an 8 solar mass progenitor star at the center of the Milky Way, between 10,000 and 15,000 events would be detected. The numbers vary with the assumed SN neutrino spectra and with the occurrence of matter effects in the stellar envelope. An overview of the detection channels and their rates is given in Table 4.

Table 4 Expected reaction rate in a 50-kt LS detector for a "standard" supernova at the center of the Milky Way.

Channel	Rate
1 $\bar{\nu}_e + p \rightarrow n + e^+$	7500-13800
2 $\bar{\nu}_e + {}^{12}C \rightarrow {}^{12}B + e^+$	150-610
3 $\nu_e + {}^{12}C \rightarrow {}^{12}N + e^-$	200-690
4 $\nu_e + {}^{13}C \rightarrow {}^{13}N + e^-$	~10
5 $\nu + {}^{12}C \rightarrow {}^{12}C^* + \nu$	680-2070
6 $\nu + e^- \rightarrow \nu + e^-$	680
7 $\nu + p \rightarrow \nu + p$	1500-5700
8 $\nu + {}^{13}C \rightarrow {}^{13}C^* + \nu$	~10

More than half of the events are caused by the inverse beta decay (1) which allows a precision measurement of the electron-anti-neutrino energy spectrum and the temporal evolution of the flux. The excellent energy resolution of a large-volume LS detector offers the possibility to study the imprints of matter effects in the anti-neutrino spectrum that are a result of the transit through the matter-potential of the progenitor star envelope or of the Earth. As the occurrence of these effects is closely linked to the size of the mixing angle θ_{13} and the neutrino mass hierarchy, SN neutrino detection in LS is also sensitive to these up to now undetermined neutrino parameters. Moreover, the statistical displacement of final state neutrons relative to the positron signal might be used to point back at the origin of the neutrino burst, which can be used to determine the position of the SN even if it is optically obscured.

The charged current (CC) reaction of electron neutrinos on carbon (3) will be mainly used to determine the electron neutrino flux. The event signature is very similar to the CC reaction of electron anti-neutrinos (2). However, statistical subtraction of the electron anti-neutrino flux, which is determined very accurately by channel 1, can be used to isolate the electron neutrino signal at a 10 % level. The remaining uncertainty is mainly due to the uncertainties of the reaction cross sections. Including information of the electron anti-neutrino spectrum and the slightly different decay times of the product isotopes ^{12}B and ^{12}N might further improve the separation.

While channels 1-4 allow the discrimination of electron neutrinos and anti-neutrinos, channels 5-8 are accessible for all neutrinos independent of their flavors or anti-flavors. The NC reactions on carbon (5 and 8) are flux measurements only and bear no spectral information. Both elastic electron scattering (6) and proton scattering (7) on the other hand provide spectral data for the combined flux of all flavors. While electron scattering is mainly sensitive to electron neutrinos, the signal on protons is dominantly caused by muon and tau neutrinos (and their anti-flavors) as their expected mean energies are larger. Due to the strong dependence of the measured event rate on the mean neutrino energy, proton scattering is very sensitive to the temperature of the SN neutrinosphere.

V Diffuse Supernova Neutrinos

Core-collapse SN explosions throughout the universe have generated a cosmic neutrino background, the diffuse SN neutrino background (DSNB). It contains both information about the SN neutrino spectrum and the redshift-dependent SN and star formation rate. Based on current knowledge of these input parameters, the predicted flux is 100 $cm^{-2}s^{-1}$, which is about eight orders of magnitude smaller than the solar neutrino flux (in the few MeV range). The currently best upper limit of on the electron anti-neutrino component of the flux is set by the Super-Kamiokande experiment with a value of 1.2 $cm^{-2}s^{-1}$ above 19.3 MeV .

A large-volume LS detector will outperform a WC detector in this measurement due to its better background rejection. As the detection reaction for the electron anti-neutrinos is the inverse beta decay, the LS is able to take advantage of the coincidence signal of positron and neutron, while the neutron is invisible in a WC unless e.g. Gadolinium is added. Spallation products as well as invisible muons that set the relatively high threshold in the SK measurement do not pose a background in LS. LAr detectors on the other hand are sensitive to the electron neutrino component of the DSNB. However, solar ^{8}B neutrinos set the LAr detection threshold to 16 MeV.

In LS, reactor and atmospheric electron anti-neutrinos are an indistinguishable background to the DSNB signal. Reactor anti-neutrinos restrict the DSNB search to energy above 10 MeV, the exact limits depending on the detector site. Atmospheric neutrinos begin to dominate the DSNB signal above 25 MeV, the exact value again depending on the detector site as the geographic latitude influences the atmospheric neutrino flux. These background sources define an energy window for DSNB detection as shown in Figure 7 or a 50-kt LS detector in Pyhäsalmi (Finland). Depending on the SN spectrum and rate, about 10 events per year are expected for a 50-kt fiducial mass. In this context, Homestake is a favorable location as both reactor and atmospheric fluxes will be lower than depicted in Figure 7, enlarging the detection window to 9-26 MeV and the detectable event rate by about 10%.

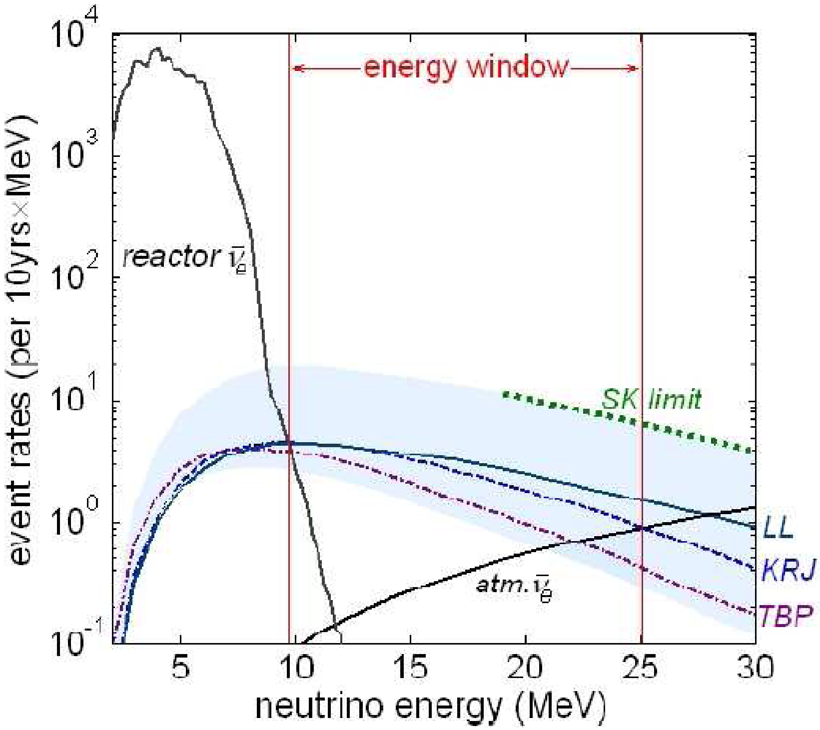

Figure 7[vi] Low energy spectra for electron anti-neutrinos in the range where the neutrinos resulting from supernovae throughout the universe may be observed. The blue swath gives the range of models, and several are illustrated as LL, KRJ and TBP. Because the atmospheric neutrinos are quite a bit lower in the range of 12-20 MeV, LS detectors have a good chance to make this observation.

Fast neutrons created by muons passing the rock surrounding the detector are able to mimic the coincidence signature inside the designated detection window. It has also been pointed out that NC reactions of atmospheric neutrinos on ^{12}C followed by neutron emission will constitute a sizeable background. However, recent studies indicate that these backgrounds could be efficiently rejected by pulse shape analysis of the prompt event. At DUSEL, about 4 m of active water/LS shielding the target volume would be required for a sufficient suppression of the fast neutron background.

VI Solar Neutrinos

Figure 8 shows the expected neutrino flux from various nuclear reactions in the Sun. The experience with Borexino has shown that it is possible to reduce the radioactive contamination of a LS detector enough to allow the measurement of the solar neutrino spectrum down to energies of a few hundred keV. The spectroscopic performance of a 50-kt detector will probably be inferior to the 0.3-kt Borexino detector as the photoelectron yield will most probably be lower. Nevertheless, the neutrino event rates of a large LS volume will surpass the signal in Borexino by at least two orders of magnitude. In contrast, it is very unlikely that the threshold of a comparable WC or LAr detector will pass significantly below 5 MeV. Both will merely be able to measure solar ^{8}B and *hep* neutrino fluxes.

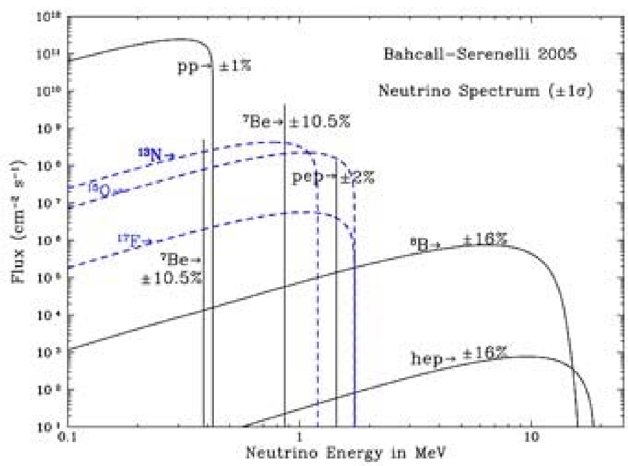

Figure 8 Neutrino energy spectra for the various reactions occurring in the Sun.[vii]

Most likely, it will be necessary to reduce the fiducial volume compared to other measurements to gain additional shielding from external gamma rays. In the following, a very conservative fiducial volume of merely 18 kT is chosen to provide an additional shielding layer of 3 m against external gamma-ray background. Table 5 lists the expected rates for the neutrinos emitted in the pp chain and the CNO cycle, using the most recent solar model predictions. The detection threshold will be around 250 keV due to the intrinsic contamination of the scintillator with ^{14}C.

Table 5 Summary of event rate for various reactions in a LS detector where we have assumed a restricted fiducial volume of only 18 kT to reduce external radiation. The event rates are separated into the different reactions producing neutrinos in the Sun and are based on two different solar metallicities.

Channel	Source	Rate [d^{-1}]	
		BPS08(GS)	BPS08(AGS)
$\nu + e^{-} \rightarrow \nu + e^{-}$	*pp*	24.92±0.15	25.21±0.13
	pep	365±4	365±4
	hep	0.16±0.02	0.17±0.03
	^{7}Be	4984±297	4460±268

	^{8}B	82±9	65±7
	CNO	545±87	350±52
$\nu + {}^{13}C \rightarrow {}^{13}C^{*} + \nu$	^{8}B	1.74±0.16	1.56±0.14

About 25 *pp* neutrino-induced electron backscattering events per day are expected. It is doubtful whether this rate is sufficient to be distinguished from the overwhelming ^{14}C background. About 5000 ^{7}Be neutrino events per day are expected: Presuming background levels comparable to Borexino, the high statistics will allow a measurement of the ^{7}Be neutrino flux with accuracy unprecedented in neutrino physics. It might be particularly interesting to search for temporal variations in the detected rate: Preliminary analyses indicate that one year of exposure will be sufficient to identify count rate modulations on a level of 1.5%. The result is to a large extent independent of frequency and phase. In this way, temporal variations of neutrino production rates caused by temperature and density changes in the solar core could be probed.

After two years of Borexino data taking it is evident that the detection of CNO and *pep* neutrinos delicately depends on the background level induced by cosmogenic ^{11}C beta decays, caused by the muon-induced knock-out of neutrons from ^{12}C. The ^{11}C production rate is mainly a function of the rock overburden shielding the detector. Operated at a depth of 4000 mwe (meters water equivalent), the ratio of the CNO/*pep* neutrino signal to ^{11}C background rate would be 1:5, a factor 5 better than at the depth of Borexino. A high-statistics measurement of about 500 CNO neutrinos per day will provide valuable information on solar metallicity, especially if the contributions from the individual subfluxes can be distinguished. At the same time, the measurement of the *pep* neutrino flux could be used for a precision test of the electron neutrino survival probability in the MSW-LMA transition region. The onset of the transition region could be tested utilizing low-energy ^{8}B neutrinos. The charged current reaction on ^{13}C is due to a threshold of more than 2 MeV only accessible to ^{8}B neutrinos: About 500 counts per year are expected, offering a background-free channel due to the coincidence structure of the signal.

VII Dark Matter Annihilation Neutrinos

A large-volume LS detector would be very sensitive to electron anti-neutrinos originating from the annihilation of light dark matter particles. The observational window is very similar to the one for the observation of the DSNB: It is mainly governed by reactor, diffuse SN and atmospheric neutrinos. Figure 9 shows the expected signal in LS, assuming a typical annihilation cross section. The discovery potential will be very large as the annihilation neutrinos create a discernible line in the energy spectrum that corresponds to the mass of the dark matter particle. On the other hand, the low background level in this energy regime will also allow one to put a very stringent limit on the existence of dark matter of MeV mass scale if no signal is detected.

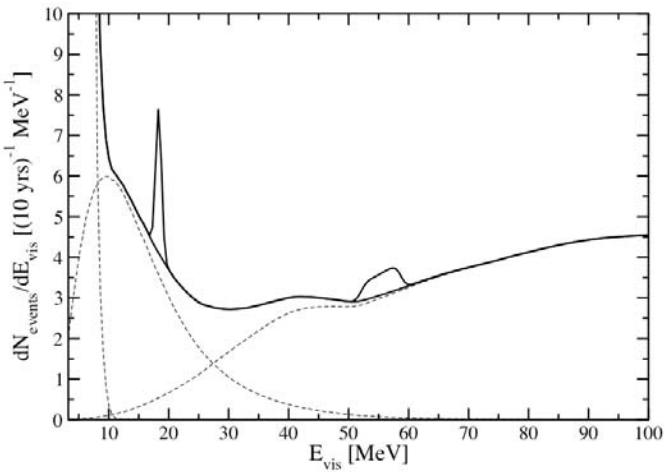

Figure 9 Expected energy spectrum for electron anti-neutrinos from dark matter annihilation (peaks). The dashed lines from left to right show the expected reactor, DSNB, and atmospheric electron anti-neutrino energy spectra.

VIII GeV Neutrino Event Reconstruction with Scintillation Detectors

In the spring of 2009 it was realized that one may be able to accomplish detailed neutrino physics with events in the range around 1 GeV, which is favored for long-baseline neutrino experiments involving a neutrino beam made at an accelerator.[viii] The key notion is that while a detector of sensitivity such as KamLAND, designed for MeV energy neutrinos from reactors, and having 250 photoelectrons/MeV in response, will have so many hits per PMT that some will be close to the earliest possible arrival time, as dictated by Fermat's principle.

This is sketched in Figure 10, which shows the outgoing Huygens' wavelets (in green) from the (red) muon track. The Fermat Surface is composed of sections of a sphere, connected by a conical region. The conical surface is coincident with the Cherenkov surface, but differs from it in neither being coherent nor polarized. Note that the Huygens wavelets are real in this case and do not cancel out, and the ice-cream-cone shaped volume is filled with photons traveling in various directions.

Each PMT in a detector with coverage similar to that of KamLAND, will have many hits, and thus this Fermat surface will be very well defined by those first times of arrival. First simulations showed that fitting to the early times provided excellent resolution in space, at least as good as WC, and that separation between a single muon (quasi-elastic muon neutrino interaction) and an equal energy electron shower was essentially complete.

It turns out that finding the "center of time" immediately yields a point near the start of the track, and a calculation of the "center of charge" yields a point in the middle of the track. Using the total light as a proxy for energy and hence track length one can immediately construct a test track, and take fitting from there. Of course this was done with a simplistic Monte Carlo program and more realistic simulations are needed to say anything meaningfully quantitative, but initial results were very encouraging.

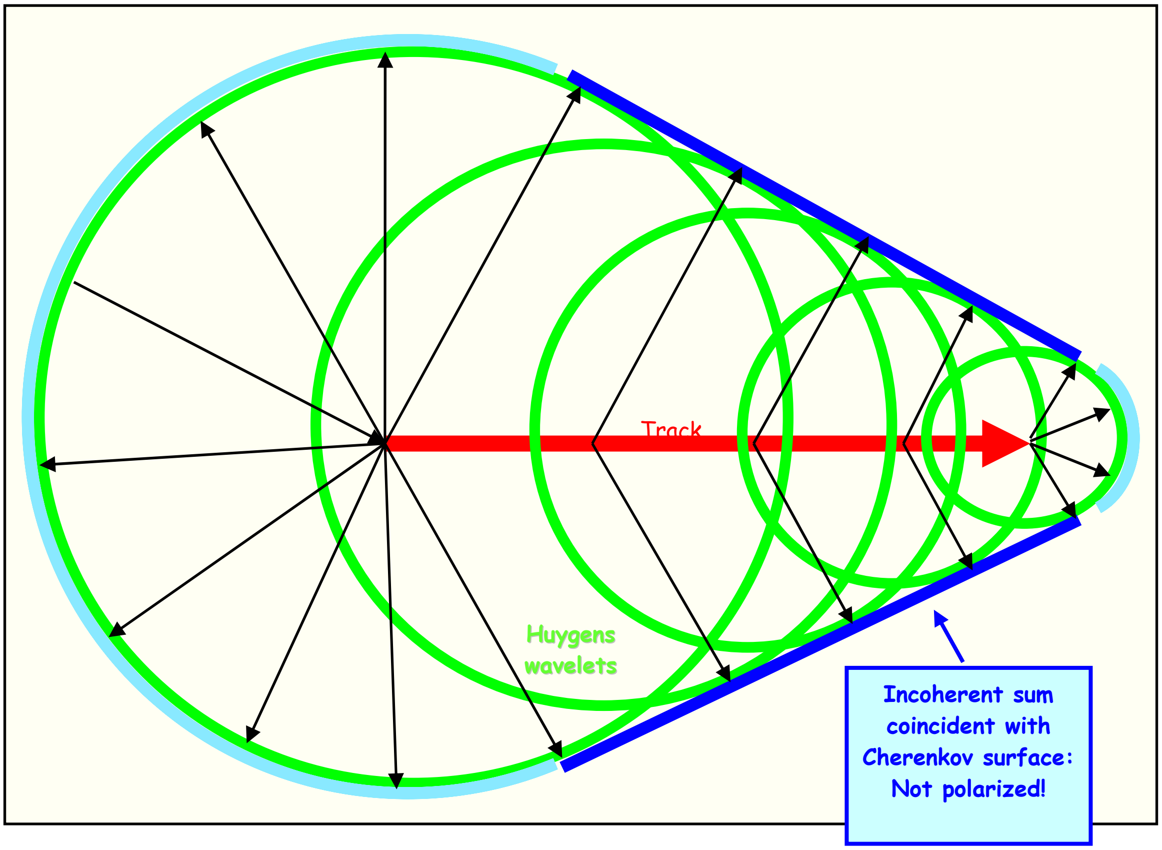

Figure 10 Snapshot cartoon of the Fermat Surface from a single muon like track in liquid scintillator.

Fortunately two other groups have taken this suggestion seriously and have made some progress. Nikolai Tolich and colleague Jaromir Kaspar at University of Washington, Seattle, reported at the ANT09 meeting that they had done some GEANT4 simulations and found that they could easily distinguish shower types based on timing histograms alone.[ix]

Secondly, Juha Peltoniemi of Finland has written a paper about his initial attempts at using liquid scintillator as a tracking detector.[x] His technique involves using the whole waveform from each PMT to fit a menu of pre-calculated possible event types (which is fortunately small for neutrino energies under consideration here). Figure 11 below is from Juha's recent paper and show amazingly good 3.15% neutrino energy resolution (given one knows the incoming direction, as in a long baseline experiment) on an incoming 2 GeV neutrino.

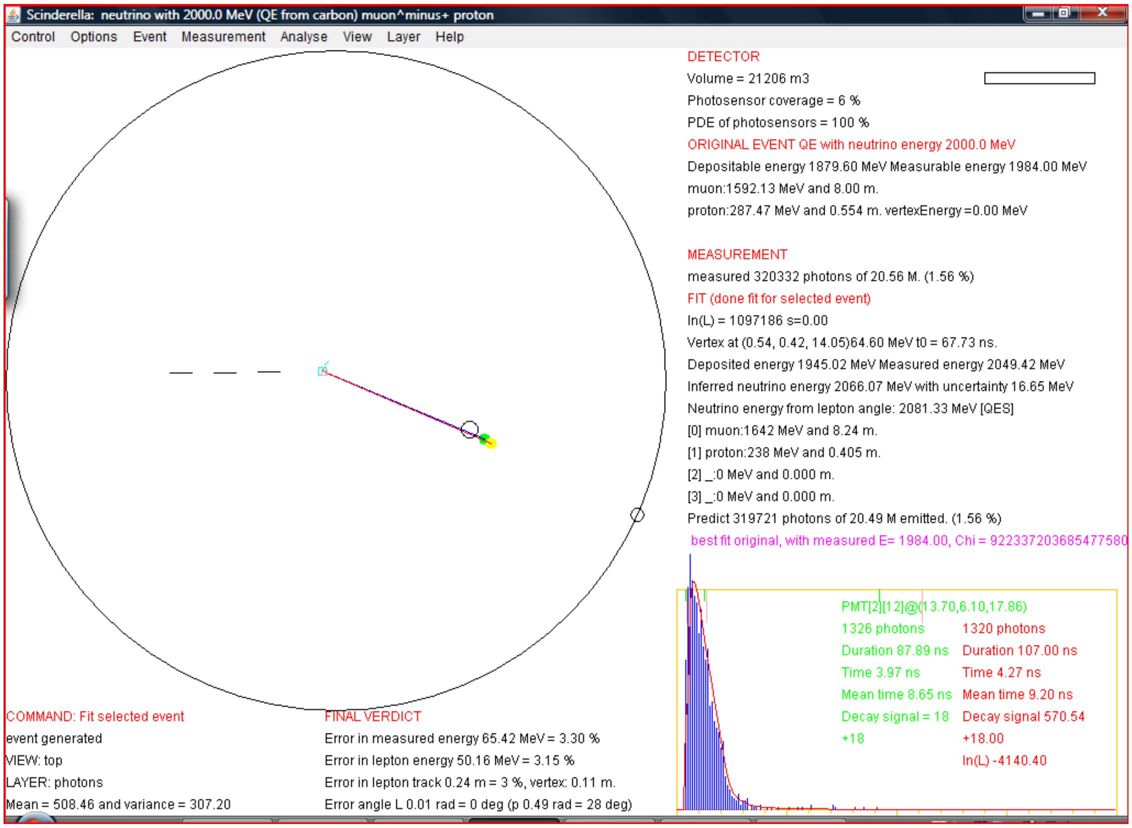

Figure 11 Scinderella reconstruction of a 2 GeV quasi-elastic neutrino event in liquid scintillator. Note 3.15% resolution of neutrino energy, as well as short stub reconstructing recoil nucleon.

We have thought about finding a method for reconstructing events without prejudice about event topology, namely to find some visualization which makes few assumptions, working towards bubble chamber like pictures. One idea tried was to make plane wave fits in clusters or patches of PMTs, thus generating a direction of the outgoing Fermat surface at each PMT location. These rays can then be pointed backwards and should cross at the true track(s). While this does work, it is not as nice as one would like due to local surface curvature and the finite time resolution of the first photon arrival. A (hopefully) better method, being explored at present, employs "back propagation". This idea is simply that one may start a pretended Huygens wavelet at each PMT, with known relative time, and run these spheres backwards, searching for overlapping clusters in time and space (and possibly amplitude as well). The goal is to generate event pictures without initial assumptions on the event topology. While such visualization is not absolutely required, experience teaches us that having such ability to "scan" events is very powerful.

It will also be very useful to attempt to extract a few real events from KamLAND. KamLAND is far from ideal for this purpose, being too small to contain events of GeV energies well, and being far from optimized for high amplitudes in the PMTs. The other problem is that KamLAND is not deep enough not to have an overwhelming background of penetrating cosmic ray muons in a similar range of energies as we seek (signal to noise around 10^{-7}). (This will not be a problem at Homestake at the far more sheltered 4800 foot level). During the upcoming

(2010) run with a neutrino beam towards SuperK from J-PARC, there will be a few events in KamLAND, and we hope to extract those.

Obviously there is much to be done here, but the initial results from three different groups are most encouraging and we think definitely worthy of in-depth study.

IX Outstanding Issues and Recommendations

We outline some issues needful of study for large LS detectors at DUSEL.

Size: We are not confident about the proper size for such a detector. A fiducial volume of 100 kT surely would yield great science, but may not be necessary. We know that the size of existing instruments (100 ton Borexino, 600 ton KamLAND and soon the 1000 ton SNO+) is far too small for the science program at DUSEL. Indeed, different scientific studies dictate different detector sizes. The LENA group in Europe has settled on a 50 kT instrument, twice the fiducial volume of SuperK. This size is motivated by the SUSY-favored proton decay mode to neutrino plus kaon and the relic supernova neutrino flux. There is also a limiting scale size in LS instruments, which is the attenuation length for light in the LS, which may be as short as 20 m, in contrast to WC detectors (without any doping in the water) for which it is on the 100 m scale. For this reason, the LENA group has moved towards a relatively tall and thin detector.

Geometry: While the LENA group favors a 100-m tall vertical cylinder with 30-m diameter in an ellipsoidal cavity, this needs to be re-evaluated for Homestake. One might think about two smaller instruments, for example, 30-m diameter with 50-m height. This would probably ease cavity excavation, and would permit the two to make full time coverage in the case of a SN neutrino wave arrival. Lessons from earlier US oil-based detectors (LSND and MiniBooNE) may be useful here.

LS Container: Radiation from surrounding rock and the PMTs is a large background for low energy neutrino studies. To mitigate this, Borexino and KamLAND relied on either a single nylon bag (KamLAND) or two concentric nylon bags (Borexino) to separate the LS from sources of external radiation. The outer volumes are filled with non-scintillating material. SNO+ will use an acrylic container for the LS, which will be surrounded by water. These containers also need to prevent the migration of radon into the LS. For such a large detector it is not clear that these technologies will work and other solutions, such as spraying a thin film over the inner walls of the detector to prevent radon migration should be investigated. Also surrounding the highest sources of external radiation with individual barriers, as opposed to a large inner container should be investigated.

LS Studies: Liquid scintillator recipes are largely black magic, commercially secret and the result of heritage prescriptions. Certainly some good work has been done by recent groups, but without adequate understanding of the chemistry and physics of the processes. Moreover, good models of light propagation in said liquids are lacking (due to complex emission and overlapping absorption spectra, and scattering phenomena). With a new generation of large LS detectors comes the need for optimization of LS optical properties, including a premium not only on light output, but rapidity of emission. A few percent gain in LS properties can result in millions of dollar savings in phototubes, so this endeavor is well worthwhile.

Neutrino Directionality Studies: As discussed in the appendices, doping the LS with materials to enable some initial neutrino direction resolution potentially has a huge payoff. This area of study includes simulations and laboratory work, including chemistry. While achieving directionality for few-MeV neutrinos is not necessary for the major physics problems addressed above, the payoff to achieving such is large and some effort deserves to go into this work. We need geoneutrino studies to determine model sensitivity achievable.

Photon Detector Studies: While the light detection challenges for an LS detector are similar to those for a WC detector, there are differences in the need for pixelization, total photocathode coverage and desired time resolution. Moreover, if typical large photomultipliers are employed, the LS detectors will have special needs for large dynamic range and good light pulse reproduction (for GeV neutrinos, as explained above). The dynamic range problem could be resolved by the employment of large numbers of smaller PMTs

System Design Studies and Electronics: Principally these issues are similar to those for the WC detector with the added need for more dynamic range, lots of pixels and more fine timing. The most demanding time and energy resolution requirements will come from the geoneutrino science.

GeV Neutrino Reconstruction: Much study is necessary to determine how well LS detectors can perform compared to a huge WC detector. We do not yet know if the trick of using the first photons in (the Fermat Surface) will be adequate or whether employing the whole waveform will be useful and maybe necessary.

Sample GeV Event Reconstruction: Nothing will convince people of the efficacy of doing GeV physics with LS as will production of a few demonstration events from the KamLAND (or BOREXINO) experiment. The statistics are not good, and the detector not optimal for this application, but it should be possible to make a proof-of-principle.

LBNE Simulations: Simulations of interactions from a Fermilab beam need to be done, paralleling all the work done for a WC detector, demonstrating its capabilities for observing θ_{13} and potential CP violation.

Reactor Anti-neutrino Studies: The possibility for precision measurements of neutrino oscillation parameters involving mixing between the first and second mass eigenstates needs additional study. This entails an analysis of simulated reactor anti-neutrino data for the DUSEL site establishing the precisions possible in the mixing angle and mass-squared difference.

Project Planning: A key issue is fitting a possible large LS detector into the rapidly coalescing plans for DUSEL. Decisions about priorities and sequencing, including cavity construction are fast approaching, and the LS option is certainly lagging compared to WC and LAr. Along with the considerations for both those detectors, there remains the apparition of the instance in which θ_{13} is either zero or too small to be useful. In such an unhappy instance, LS may provide an "offramp", opening up the world of geoneutrino physics (and all the other concomitant low energy physics).

The purpose of this White Paper has been to encourage our community to take a closer look at the potential for a large liquid scintillation detector at DUSEL. There are many issues that need simulation and laboratory work before a large LS detector can be designed for DUSEL, and we hope to begin serious work on these as quickly as funding can be made available.

Acknowledgements:

Much of the information in this report was aided by work done groups in Japan and Europe. We want to acknowledge the use of material from the KamLAND Collaboration, particularly the RCNS group at Tohoku University. Other work has been taken from our friends in the LENA Collaboration, at the Technical University of Munich (and other institutions). For the GeV neutrino reconstruction we want to thank particularly Juha Peltoniemi.

Appendix 1.0 Geoneutrinos with Directionality

Directional measurement with ~30 degree resolution would allow discrimination of mantle models (nadir angle plots). The technology for achieving this resolution requires research and development. The achievement of directionality also has impact upon the application of detectors to remote reactor monitoring, a matter of national security.

We have only recently realized that with potentially achievable angular resolution, one might pick out the mantle neutrino signature from the dominant (and nearly horizontal) local crustal signal (see Figure 12). The neutron initial direction carries the neutrino direction, but the neutron scatters wildly before capture in normal scintillating liquid, with only a small residual correlation with direction as illustrated in Figure 13 (red). Loading of the scintillation liquid with materials with high neutron capture cross sections, and materials also having more easily located capture position, makes possible much better directionality (Figure 13 blue).

An excellent choice would be loading with ^{6}Li, which produces an alpha particle, nicely locating the capture location. However, there are two problems: light attenuation may suffer, and the alpha light emission is very feeble, due to Birks' quenching phenomenon. If directionality can be realized, then measurement of the mantle neutrino flux may become possible. Indeed, an angular precision of about 0.5 radians would enable resolution of competing mantle models (Figure 14).

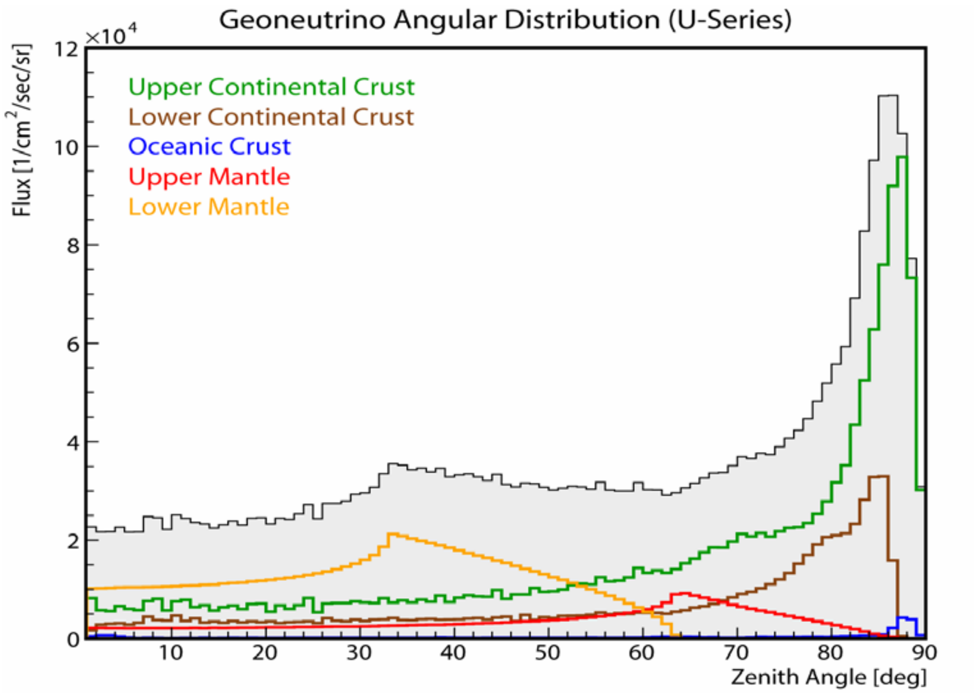

Figure 12 Angular distributions of geoneutrinos from various layers of the earth.

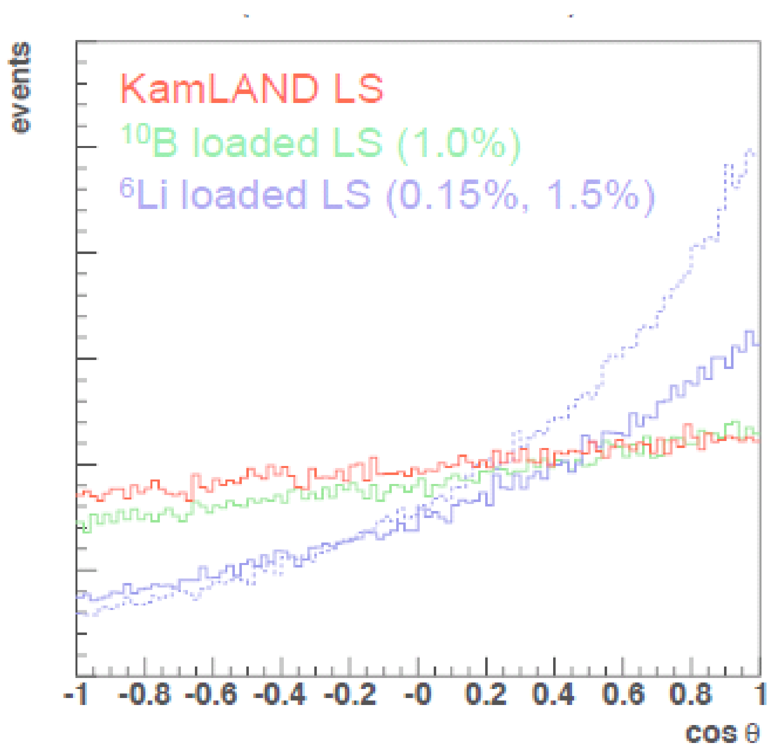

Figure 13 Examples of possible neutrino directionality achievable with several LS loadings to improve neutrino capture. Lithium loading results in an alpha particle emission which is challenging to detect.

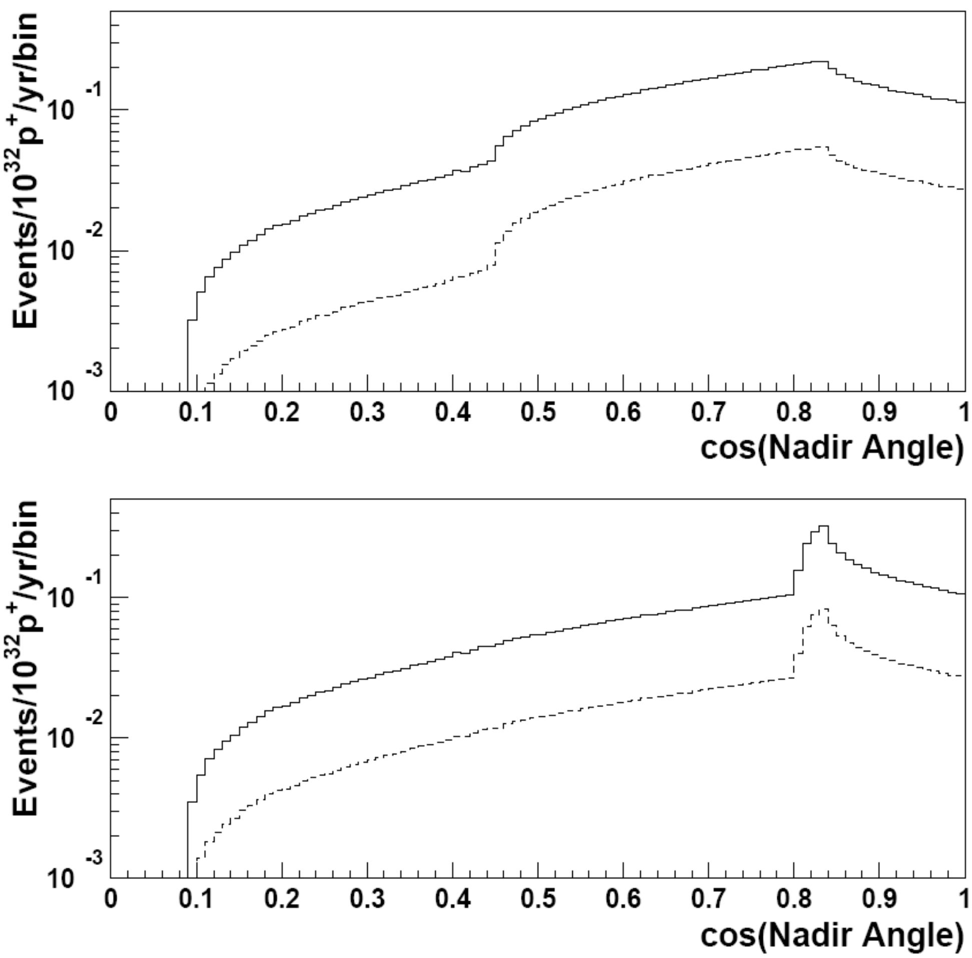

Figure 14 Mantle flux geoneutrino directions from two geological models: layered mantle (top) and uniform mantle with enriched D" layer (bottom).

Appendix 2.0 Geo-reactor

Geo-reactor models[xi] suggest the existence of one or more natural nuclear reactors within the deep earth. However the location(s) and output power are loosely defined. Reactor fission products undergo beta decay with the emission of electron anti-neutrinos, which routinely escape the earth and have spectra similar to those of nuclear power reactors, going up to several times the energy of the natural decay chain neutrinos. Neutrino mixing distorts the energy spectrum of the electron anti-neutrinos. Characteristics of the distorted spectrum observed at the earth's surface could specify the location of a geo-reactor, discriminating the models and facilitating more precise power measurement. Measurements of anti-neutrino direction would further constrain geo-reactor models. As one can see from Figure 5, a geo-reactor of typical expected magnitude could have a flux contribution at Homestake similar in size to that of the sum of distant power reactors. Given that the daily power output of the reactors can be well known to around 1%, we can certainly then seek a natural geo-reactor added to this known flux at the level of a few percent, or say 50 MW. Known time variation of the power reactors and other signatures could strengthen such a discovery, and help locate the source.

It must be said that geochemists strongly disfavor the possibility of a geo-reactor within the Earth's iron core, on the grounds of the nature of U & Th are highly lithophilic elements (which partition strongly into silicate phases rather than iron metal). There is arguably a greater chance that U and Th could collect at the core mantle boundary. While geologists remain skeptical about such a possibility, there are a number of observations to be explained, such as the anomalous amount of ^{3}He (and some other noble gas isotope curiosities) in volcanic emissions in places such as in Hawaii and Iceland. Moreover, the area near Homestake is interesting due to the hotspot underneath Yellowstone, allowing for a potentially revolutionary discovery, should the hot spots be powered by a natural reactor (a notion disfavored by geologists). Discovery of one or more natural geo-reactors, while appearing to be a long shot, has the potential for revolutionary change in geology. With a large LS detector at Homestake, we could easily detect a geo-reactor of any significant size and, if found, begin to study the source (by the spectrum and any time variation).

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