

**A Letter Expressing Interest in Staging an Experiment at
SNOLAB
Involving Filling SNO with Liquid Scintillator Plus
Double Beta Decay Candidate Isotopes**

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M. Boulay, M. Chen^{*}, M. Di Marco, P. Doe, R. Ford, A. Hallin,
C. Kraus, J.R. Leslie, J. Maneira, R. MacLellan, A.B. McDonald,
R.G.H. Robertson, A. Wright

(a group within the SNO collaboration studying this option for the future use of SNO, on behalf of the whole collaboration. This proposal has not been officially approved by the SNO collaboration as the defined future configuration for SNO and, if pursued, would undoubtedly involve the establishment of a new collaboration with additional participants as well as a subset of the members of the present SNO collaboration.)

* contact person

SNO Filled with Liquid Scintillator Plus Double Beta Decay

1. Introduction

The experiment being proposed is to fill SNO with liquid scintillator. Transforming SNO into a liquid scintillator detector would boost the light yield by a factor of ~ 50 and would place protons in the detector as opposed to deuterons. This would enable:

- the detection of electron antineutrinos from natural radioactivity in the Earth (geo-neutrinos)
- the detection of electron antineutrinos from distant nuclear power reactors (e.g. Bruce, Darlington, Pickering) providing a way to confirm KamLAND-LMA neutrino oscillations via a sharp spectral distortion or oscillation “dip”
- the detection of low-energy solar neutrinos, such as *pep*, *CNO*, and ${}^7\text{Be}$

A liquid scintillator in SNO would preserve excellent supernova neutrino capabilities, including CC and NC reactions on both protons and carbon. Finally, and perhaps ultimately, a liquid scintillator serves as the medium in which a competitive, next-generation double beta decay experiment could be deployed. Several possible ways for deploying double beta decay candidate materials in SNO have been considered. The leading options currently being examined are dissolving Xe gas in liquid scintillator and the dispersion of Te or Nd nanocrystals in a liquid scintillator. A staged approach is envisioned, in which a first deployment of pure liquid scintillator would initiate the measurements described above, while the additional development work on the double beta decay options would continue. Concurrent measurements of double beta decay and antineutrinos (a coincidence signal) would be possible.

The purpose of this Letter of Interest is to notify the SNOLAB Executive and the SNO Long Range Plan committee of the serious interest in pursuing this idea as a future configuration of the SNO detector. A subset of the SNO collaboration would be interested in developing this experiment; in addition, potential new collaborators from outside SNO have indicated interest. Specific safety and infrastructure considerations for SNOLAB that are a consequence of this experiment include the deployment, storage and handling of about 1 kiloton of organic-solvent-based liquid scintillator underground.

2. Scientific Motivation

KamLAND is a neutrino detector with 1 kiloton of liquid scintillator. SNO filled with liquid scintillator (“SNO+”) would also be a 1 kiloton liquid scintillator detector and its physics targets would be somewhat similar to KamLAND’s; however, there are unique or different capabilities to this experiment, which are:

- SNOLAB’s deep site reduces the muon flux substantially, compared to Kamioka, removing ${}^{11}\text{C}$ as a background for a potential measurement of the flux of *pep* and *CNO* solar neutrinos
- muon-spallation also produces β -n decaying isotopes, such as ${}^9\text{Li}$ and ${}^8\text{He}$, which are backgrounds to the coincidence antineutrino signal; a reduction in these backgrounds would enable an improvement in effective antineutrino livetime-livevolume over

KamLAND (i.e. these events need to be vetoed around each passing muon, in space and time, and the resultant deadtime in SNO+ would be less)

- a longer reactor baseline is available that happens to put the sharp spectral distortion from the second oscillation maximum (for the best-fit LMA parameters) in an easily detectable region of the reactor antineutrino-induced positron spectrum, away from the spectral region where geo-neutrinos create some uncertainties
- Sudbury is located in the middle of thick continental crust rock, making the calculation of the expected geo-neutrino flux more reliable and thus making a geo-neutrino flux measurement more easily interpreted for geophysics, in comparison to KamLAND which is near continental and oceanic crusts – stated more simply, the geo-neutrino flux prediction for Kamioka has greater uncertainty than for Sudbury
- SNO+ offers an improved geo-neutrino to reactor neutrino “signal-to-background” ratio, allowing a cleaner extraction of the geo-neutrino signal
- two geo-neutrino data points around the globe (SNO+ and KamLAND) could allow, when combined with geophysical models, the global radioactivity mantle contribution to be separated from the contribution due to the local crustal geology

2.1. Low-Energy Solar Neutrinos

The monoenergetic *pep* solar neutrinos are calculated to 1.5% in the SSM. One could detect them by looking for the “Compton edge” from neutrino-electron scattering (as for ^7Be solar neutrinos). With a known source and negligible uncertainty in the reaction cross section, a measurement of the rate of *pep* solar neutrinos has the potential to be an O(%) precision measurement. This would allow a *pep* measurement to further and tightly constrain the mixing angle θ_{12} , similar to what’s being proposed by future *pp* experiments. In Bahcall and Peña-Garay, hep-ph/0305159 [1], they write that their analysis shows “that a measurement of the ν -e scattering rate by *pep* solar neutrinos would yield essentially equivalent information about neutrino oscillation parameters and solar neutrino fluxes as a measurement of the ν -e scattering rate by *pp* solar neutrinos.” The physics motivation and potential impact of this is the same as for future *pp* experiments. Precision determination of θ_{12} would be the goal, as well as illustration of the LMA solution’s increased survival probability at low energies. Furthermore, as precision solar neutrino observables are added to the overall picture, one starts to gain sensitivity to physics “beyond the simplest neutrino oscillation model.” The simplest model of three-neutrino active mixing, with LMA and atmospheric parameters, and small θ_{13} , has specific predictions for many observables; each observable should be tested with precision to provide sensitivity to deviations from this model due to additional new physics (e.g. CPT violation, sterile neutrino admixture, large θ_{13}). Measuring the flux suppression at the energy of the *pep* solar neutrinos could add such a precision test.

In addition to internal radioactivity, a background to the *pep* solar neutrino signal is production of ^{11}C in a liquid scintillator by muons, even underground. The KamLAND proposal [2] shows that this is a dominant background preventing them from observing these neutrinos. In the much deeper SNOLAB, with only 70 muons traversing SNO per day, it would be feasible to veto and/or tolerate the ^{11}C background.

For astrophysics reasons, detection of *CNO* and ${}^7\text{Be}$ solar neutrinos would also be interesting. A complete experimental understanding of neutrino production in the Sun would ideally include observation of the significant branch of neutrinos from ${}^7\text{Be}$ and the *CNO* contribution that arises from a completely different cycle of nuclear reactions. Neutrino oscillation physics would not necessarily be the goal of these measurements, although a low-energy ES measurement in SNO+ could be combined nicely with future low-energy CC measurements of *pp* and ${}^7\text{Be}$ solar neutrinos, by other experiments.

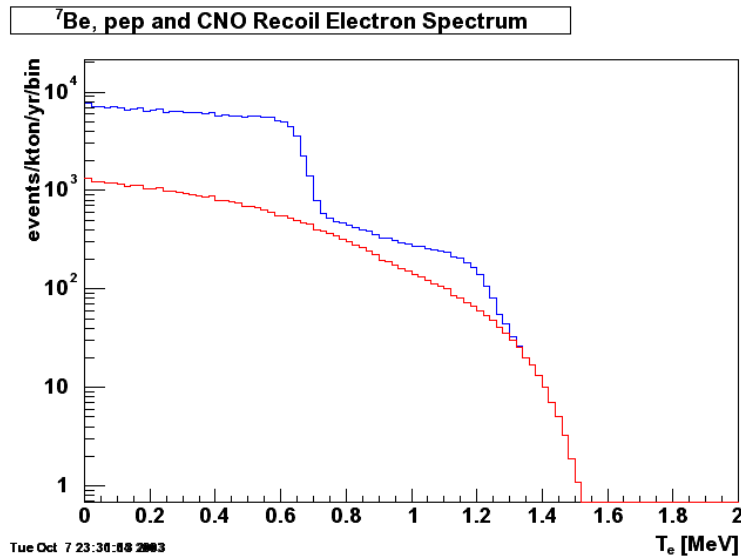


Fig. 1. Recoil electron spectrum for low-energy solar neutrinos in SNO filled with liquid scintillator. Backgrounds are not shown.

Fig. 1 is a plot of the expected LMA-oscillated rate and spectrum (with Gaussian scattering of data points) of low-energy solar neutrino-electron scattering events in SNO+, assuming the energy resolution of a liquid scintillator detector. Extracting the *pep* solar neutrinos from the *CNO* neutrinos, and both over backgrounds (not illustrated here) is going to be extremely challenging. But, if these measurements are going to be done anywhere, they are going to need the depth of SNOLAB.

2.2. Geo-Neutrinos

Geophysical neutrinos are interesting and KamLAND is on the verge of making the first detection. Though there are calculations and models, not enough is really known about the geo-neutrino spectrum to enable KamLAND to effectively use lower energy data in oscillation analysis fits. Regardless of their usability in a reactor oscillation analysis, detecting geo-neutrinos would be interesting on their own. Knowing something about the U and Th content in Earth's crust and mantle would provide breakthrough data for geophysics and geochemical models of Earth and Earth's thermal history. Uranium and thorium radioactivity is thought to account for 40% of Earth's total heat flux, but this is not really known with confidence and direct information coming from detecting the antineutrinos from natural radioactivity in the Earth would be extremely valuable.

Using the inverse beta decay reaction, antineutrinos on protons in the liquid scintillator produce positrons and neutrons. The neutrons are detected in delayed coincidence, when they capture about 200 μs later on hydrogen in the scintillator (2.2 MeV gamma). The coincidence signal is distinctive and there should be practically no background. KamLAND has essentially no unvetted antineutrino background.

Rothschild, Chen and Calaprice [3] calculated that Borexino would have 10 geo-neutrino events per year, KamLAND would have 29 events per year, and a 1 kton liquid scintillator in Sudbury would have 64 events per year. Sudbury is surrounded by the Canadian Shield, a thick section of the continental crust which has higher U and Th content than oceanic crust rock near Japan. It's pointed out in that paper (and also in the Raghavan et al. paper [4]) that measuring the flux of geo-neutrinos at different sites, such as Japan and Canada, would provide some ability to separate the contributions from the global mantle and from the local crustal geology near each detector, especially in the case of continental crust versus oceanic crust, as would be the case for Kamioka and Sudbury.

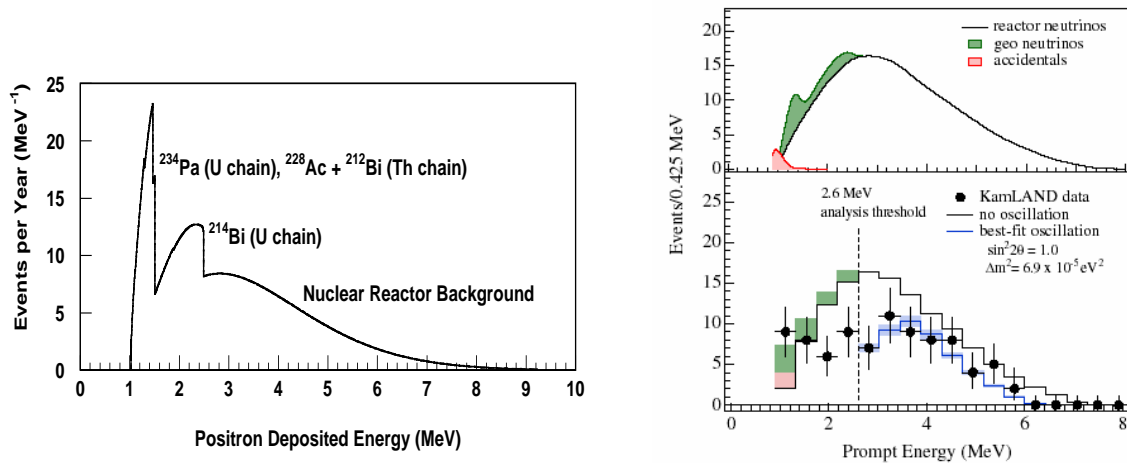


Fig. 2. Left, from [3], calculated geo and reactor neutrino signals in Borexino, as an illustration of what one might expect in SNO+. Energy resolution was not included in this plot. Right, from [5], calculated geo and reactor neutrino signals for KamLAND, for which the geo/reactor ratio is less favourable (for geo-neutrino studies).

Fig. 2 illustrates the shape of the positron spectrum produced by geo-neutrinos, calculated for Borexino and KamLAND. A clear observation of geo-neutrinos would constitute a fundamental discovery. The geo/reactor event rate ratio of 64/87 for SNO+ is the most favourable and would be better than that for Borexino (10/29), illustrated, left in Fig. 2, and much better than the ratio for KamLAND, nominally a reactor neutrino experiment.

2.3. Reactor Neutrinos

The Bruce Nuclear Generating Station is 240 km from SNO. Pickering and Darlington are approximately 300 km from SNO. KamLAND numbers can be scaled to estimate event rates in SNO+. KamLAND had an exposure of 162 ton-yr, with an expectation of 87 events. KamLAND reactors are ~180 km away (in reality more complicated since many reactors at different distances surrounding Kamioka contribute); for ease, one can scale by $(180/240)^2$. The total effective power for KamLAND is 82.5 GWth at 180 km

(calculation done using KamLAND's reported, integrated total thermal power flux of 254 Joule/cm² during 145.1 days livetime). Bruce NGS has 14 GWth capacity, at full power for 6 reactors. Pickering and Darlington add 16 GWth capacity (4 reactors at each complex) at (240/300)², for a total of 24 GWth effective power at 240 km. Scaling power and distance to estimate the event rate gives an expectation of 87 events for 1 kton-yr exposure in SNO+. The reactor neutrino event rate in SNO with scintillator is not negligible, and it is possible to explore the physics potential.

For the best-fit LMA parameters (global solar plus KamLAND fit), the survival probability curve for a baseline of 180 km places the second oscillation maximum in KamLAND right around the threshold imposed in their analysis due to geo-neutrinos. Uncertainties in the predicted geo-neutrino spectrum might interfere with the observation of a spectral distortion in KamLAND data due to neutrino oscillations, and vice versa. Ideally, one would like to move the spectral distortion feature away from 2.5 MeV.

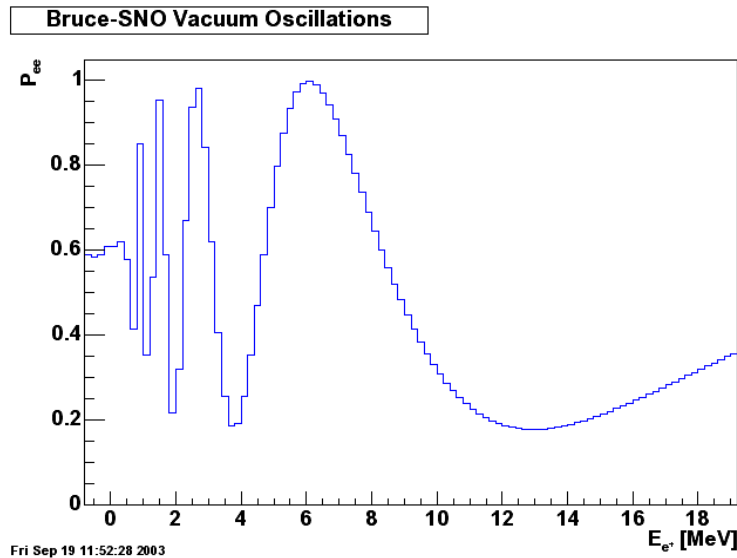


Fig. 3. Oscillation survival probability for a baseline of 240 km (Bruce to SNO).

The second oscillation maximum would be moved to higher energies at longer baselines (constant L/E). For a baseline of 240 km, the distance between Bruce and SNO, the second oscillation maximum shows up between 3.5-4.0 MeV, an almost ideal place in the reactor antineutrino-induced positron spectrum. It should be clearly visible, as shown in Fig. 3; it does not appear too high in energy, where the reactor neutrino rate diminishes, and it is sufficiently removed from the region where geo-neutrinos are present. The rapid survival probability oscillations at low energy, also seen in Fig. 3, would be washed out by energy resolution in an experiment. Thus, uncertainties in the shape of the reactor neutrino spectrum “under” the geo-neutrinos, with oscillations averaged out, would have much reduced impact on the extraction of the geo-neutrino spectrum, and vice versa.

The bottom line for geo and reactor neutrinos is this. It is conceivable that KamLAND, with increased statistics, will be able to make the first observation of geo-neutrinos and will be able to observe some shape distortions in their positron spectrum. But, if the most

distinctive spectral feature (the second oscillation maximum) lies at or below the geo-neutrino analysis threshold, it could be difficult for KamLAND to extract quality information on either. A floating geo-neutrino spectrum and oscillation combined analysis could be (and already has been [6]) performed; however, realistically, with such large uncertainties in the geo-neutrino spectral shape (because it is not known – it has never been measured!), it would be difficult to have confidence in either the geo-neutrino spectral shape or the oscillation spectral distortion coming from this type of analysis of KamLAND data. Thus, it may turn out to be indeed rather important to continue reactor neutrino oscillation studies at longer baselines, providing confirmation of neutrino oscillations via clear observation of a “dip,” and thereby also allowing a cleaner extraction of the spectral characteristics of the geo-neutrinos.

2.4. Double Beta Decay in SNO+

Double beta decay could be considered as a possibility for a future experiment in the SNO detector after heavy water is removed. The SNO detector provides a very low background volume capable of holding 1000 tonnes of liquid and viewed with about 60% effective photocathode area coverage. This may provide an opportunity to observe double beta decay transitions by dispersing appropriate materials in SNO, either as nanoparticles, dissolved chemicals or absorbed gas in a liquid scintillator, or as large crystals suspended in water or liquid scintillator as proposed for CAMEO or CANDLES.

Whereas it is known that double beta decay measurements with scintillators are difficult because of the limitation of the energy resolution to greater than 5% FWHM or so, this exercise has been undertaken because the possibility exists that backgrounds, other than that from the 2ν process, might be effectively restricted in SNO filled with liquid scintillator, for some of the candidate isotopes. In addition, there is the possibility to measure external backgrounds (and some of the internal backgrounds) by direct counting of the scintillator with the double beta material removed. Combining this potential for low backgrounds with the ability to work at large masses (perhaps 10 tonnes or so) of a variety of materials with different nuclear matrix elements influencing the double beta decay could provide an advantage for these proposed measurements.

In the technique suggested by CAMEO or CANDLES, the liquid scintillator serves merely as shielding and/or as a veto against external events. The successfulness of the macroscopic crystal technique hinges on control of the intrinsic radiopurity of the inorganic scintillating crystals, a question which has not been explored by our study group. Thus, this technique is not discussed in detail in the present LOI (but could be revisited at a later date, because the use of inorganic crystals such as CaF_2 or CdWO_4 has the advantage of greater light output than liquid scintillator alone).

Table 1 shows the parameters for various nuclei that have relatively high energies for double beta decay. All the 0ν lifetimes are calculated, of course, and must be considered to be uncertain by factors of 2 or more because of nuclear matrix element uncertainties. The ratio of 2ν to 0ν rates are tabulated, since the tail of the 2ν double beta decay process is a background to the 0ν , and the larger this number, the more unfavorable the background. Several nuclei stand out for various reasons: Ca for the high energy, Nd for

Isotope	Energy [MeV]	2v $T_{1/2}$ [yr]	0v $T_{1/2} * m_\nu^2$ [yr eV ²]	2v/0v Rates Ratio	Abundance [%]
⁴⁸ Ca	4.27	4×10^{19}	3×10^{24}	7.5×10^4	0.19
¹⁵⁰ Nd	3.37	7×10^{18}	3×10^{22}	4×10^3	5.9
⁹⁶ Zr	3.35	2×10^{19}	5×10^{23}	2.5×10^4	2.8
¹⁰⁰ Mo	3.03	8×10^{18}	1×10^{24}	1.3×10^5	9.6
⁸² Se	3.00	9×10^{19}	6×10^{23}	7×10^3	9.2
¹¹⁶ Cd	2.80	3×10^{19}	5×10^{23}	1.7×10^4	7.5
¹³⁰ Te	2.53	3×10^{21} G	5×10^{23}	1.7×10^2	34.5
¹³⁶ Xe	2.48	5×10^{21} C	2×10^{24}	4×10^2	8.9
⁷⁶ Ge	2.04	1×10^{21}	2×10^{24}	2×10^3	7.8

Table 1. Data for high energy double beta decay candidates. G means determined by geochemical measurement and C means calculated rather than measured.

the high decay rate for 0v, Te for natural abundance. Te and Xe look very good for the 2v rates, but these are the two cases for which recent, clear 2v measurements are missing. Also it should be noted that the matrix element calculations for the heavier nuclei like Nd may be the most uncertain.

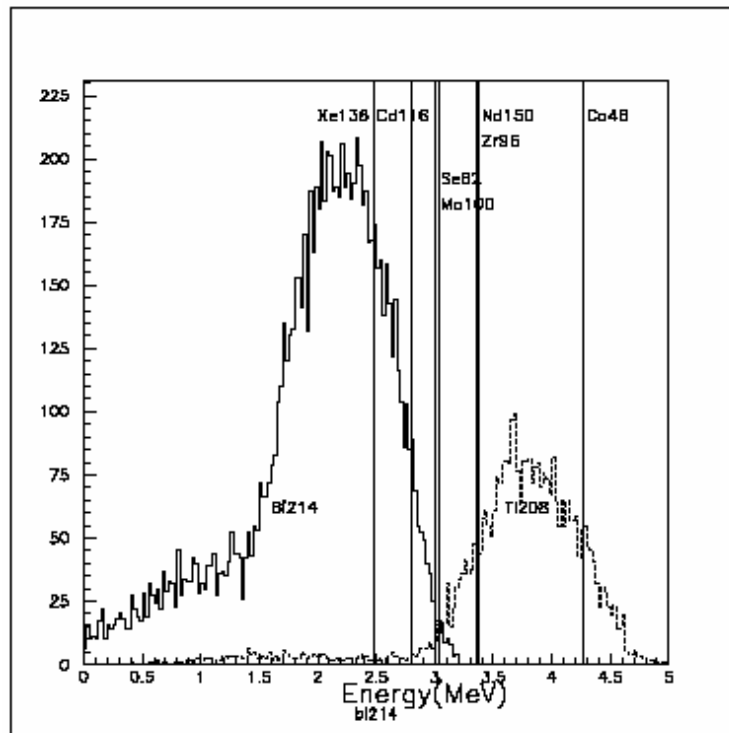


Fig. 4. The location in energy of neutrinoless double beta decays, overlaid on the spectra expected for one year of U or Th decays in SNO+ at an assumed purity of 1×10^{-16} g/g for each of these elements. Note that Te has a 0v double beta energy of about 2.53 MeV, very near that for Xe.

2.4.1. Radioactive Backgrounds

Internal and external radioactivities in a large, liquid scintillator detector impact a double beta decay experiment differently, and are considered separately here. Fig. 4 shows the energies for zero-neutrino double beta decay for a number of elements with the highest energies, compared to the internal background that would appear in the SNO+ detector from uranium and thorium decay chains at an impurity level of 1×10^{-16} g/g. When U or Th chain decays occur internal to the liquid scintillator volume, the detector functions as a calorimeter, recording the total energy of β - γ decays. Uranium chain activity shows up as ^{214}Bi up to 3.2 MeV, as shown in Fig. 4. Thorium chain activity shows up as ^{208}Tl up to 5 MeV, also seen in Fig. 4.

Apart from external backgrounds, Xe and Te face internal backgrounds that would be determined by the internal ^{222}Rn levels in the liquid scintillator volume. The Bi-Po β - α delayed coincidence (^{214}Po $t_{1/2} = 164 \mu\text{s}$) can be used to effectively tag decays of ^{214}Bi ; a suppression factor of 50 or greater could be achievable. Nd, on the other hand, would have internal backgrounds set by intrinsic Th contamination in the scintillator. These internal ^{208}Tl decays might also be tagged. The α decay of ^{212}Bi precedes ^{208}Tl decay, which has a half-life of 3.03 minutes. This α -Tl coincidence could thus be used to veto this background, if the counting rate is low enough in the vicinity of 600 keV (the effective energy where the alpha would appear in a spectrum from a liquid scintillator).

KamLAND quotes background for the U chain at 4×10^{-18} g/g equivalent of U in equilibrium and ^{232}Th at an equivalent level of 5×10^{-17} g/g. These are lower than the nominal value used to plot Fig. 4. It should be noted that the internal radon background in SNO to date has been about 1.7×10^{-14} g/g U equivalent, so radon would have to be controlled in SNO+ by improved sealing of the AV region.

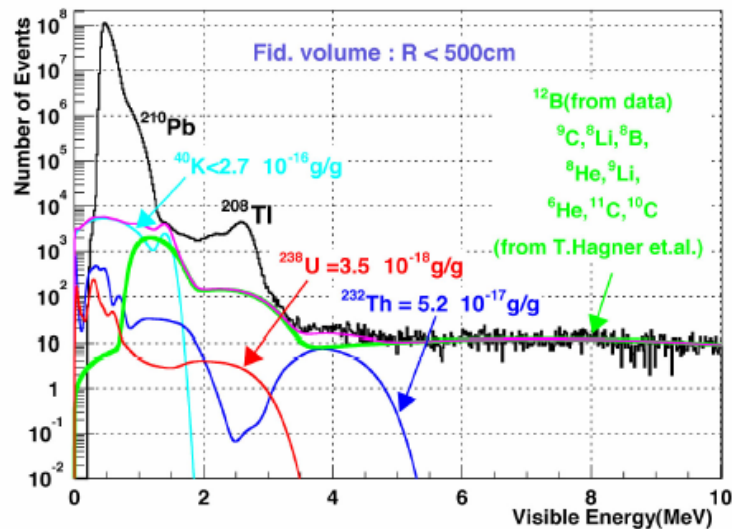


Fig. 5. Radioactive backgrounds as observed by KamLAND for a fiducial volume cut of 500 cm. The calculated contribution from cosmogenic activity (most of it easily vetoed) is shown in green. U and Th contributions are shown at their achieved levels of radiopurity, as determined by measurements of Bi-Po coincidences in their decay chains.

In contrast to internal backgrounds, when radioactivity is external to the liquid scintillator the backgrounds are gamma peaks, such as at 2.6 MeV from the thorium decay chain and 2.4 MeV from the uranium decay chain. Fig. 5 shows the counting rate in the KamLAND detector. This plot clearly reveals the presence of external radioactivity backgrounds (in KamLAND), and in particular the 2.6 MeV gamma from ^{208}Tl (thorium chain). [As an aside, the background in KamLAND, shown in green in Fig. 5, arises from muon-induced radioactivity and would be reduced substantially at SNOLAB's depth and eliminated completely by muon-follower cuts.]

It is immediately apparent from Fig. 5 that external background could dominate in the region around 2.6 MeV, if not controlled significantly. This would impact Xe and Te double beta searches. Simulations are in progress to examine external backgrounds for SNO+ in the region below 3 MeV. However, data from the KamLAND detector indicate that the number of 2.6 MeV gammas detected in a given central fiducial volume is reduced by a factor of about 10 for each reduction of fiducial radius by 0.5 meters. This is used below to make an estimate of the 2.6 MeV background in a restricted central fiducial volume.

2.4.2. ^8B Solar Neutrinos as a Background

The relatively flat background rate for ^8B solar neutrinos (elastic scattering reaction) is about 37 counts per year for 5% FWHM at 3.3 MeV, for 1000 tonnes of liquid scintillator and a ν_e flux of 0.35 SSM. This is a small background that has the benefit of being well studied and quantifiable outside the double beta counting region.

2.4.3. 2ν Rate in the 0ν Region

Elliott and Vogel [7] have discussed the 2ν background for a given resolution. They indicate that the ratio of the zero-neutrino signal to the background from the two-neutrino process varies inversely as the sixth power of the zero-neutrino peak width. It is clear from this that the detector resolution, or equivalently the number of detected photons per MeV of deposited energy is a very important factor in the measurements.

Table 2 summarizes some of the expected signal and background rates for an experiment that has 10 tonnes (1% loading in SNO+) of enriched material in liquid scintillator. The KamLAND numbers for U, Th were used for the radioactive background estimates. The signal rates assume the full fiducial volume, but it is clear that there will have to be a restriction of the fiducial volume to a substantial degree and reduction of external radioactivity to deal with the external background below about 2.8 MeV.

The S/B calculation uses the Elliott-Vogel formula, calculating the ratio for the upper half of the zero-neutrino peak. The resolution was assumed to be determined by $(\text{NHIT})^{-1/2}$ with 450 NHIT per MeV, (where NHIT, the number of phototubes hit in an event, is used as a measure of the energy of an event). This figure is a very preliminary estimate for liquid scintillator based upon a simple extrapolation from the Borexino Counting Test Facility.

Isotope Compound	Count Rate [yr ⁻¹] for 10 tonnes enriched isotope and $m_{\nu \text{ eff}} = 50 \text{ meV}$	S/B for 0ν/2ν (upper-half peak)	Internal U [yr ⁻¹] at $4 \times 10^{-18} \text{ g/g}$	Internal Th [yr ⁻¹] at $5 \times 10^{-17} \text{ g/g}$	External 2.6 MeV γ Concern?
⁴⁸ CaF ₂	45	0.24	-	289	No
¹⁵⁰ Nd ₂ O ₃	1990	2.3	-	256	No
⁹⁶ ZrO ₂	163	0.36	-	256	No
¹⁰⁰ Mo	104	0.05	1	120	Yes
⁸² SeO ₂	152	1.1	1	120	Yes
¹¹⁶ CdWO ₄	56	0.37	1	-	Yes
¹³⁰ TeO ₂	128	30	2	-	Yes
¹³⁶ Xe	38	13	2	-	Yes
⁷⁶ Ge	68	1.7	2	-	Yes

Table 2. Summary of signal and background rates. Rejection of internal U background via tagging of Bi-Po delayed coincidences included a rejection factor of 50 in this table.

Because of the limitation imposed by the energy resolution in a liquid scintillator and the need to identify the neutrinoless double beta decay signal above the tail from the 2ν background, potential candidates from this list are Te, Xe and Nd, the best three with respect to the 0ν/2ν. Ge, Se and Nd are significantly worse than Te and Xe; however, the Nd double beta decay energy is above 2.6 MeV (external ²⁰⁸Tl γ 's not a concern) and it is interesting to consider the best candidate from that category.

External radioactivity and internal radioactivity will have to be controlled very carefully, in particular for both the scintillation medium and the double beta decay material itself. For loading at 1%, the required radiopurity of the double beta materials are lowered by that factor (i.e. one can tolerate a factor 100 higher contamination in the double beta materials compared to the liquid scintillator).

With these three candidates, two techniques for loading these elements in SNO+ are being explored. For Xe, the idea of dissolving Xe gas in liquid scintillator is being considered. For Te and Nd, the possibility to disperse material in liquid scintillator in the form of nanoparticles is being investigated.

2.4.4. Dissolved Xe Gas

In 1994, Raghavan published a paper [8] in which he noted that liquid scintillator would absorb about 2% by weight of xenon gas. This would be a way to pursue double beta decay in SNO+ with about 20 tonnes of Xe. The advantages of ¹³⁶Xe are:

- it should introduce no problems with absorption and scattering of scintillation light beyond the properties of the liquid scintillator
- the 2ν background is favourably small
- Xe gas can be readily removed from the liquid and reintroduced, enabling a source-in, source-out series of measurements and confirmation of low Xe-unrelated backgrounds

The disadvantages of Xe are:

- the transition energy (2.48 MeV) is close to that from external 2.6 MeV gammas
- containment of the Xe gas needs to be investigated

When Borexino investigated the possibility of Xe in liquid scintillator, loss of Xe gas via diffusion through the thin nylon vessel in Borexino was identified as a potential problem. This problem would be solved in SNO+ due to the thick acrylic vessel in use. However, the SNO acrylic vessel is not sealed on top and there are cover gas considerations to examine if Xe gas were to be deployed in SNO+.

The zero-neutrino double beta decay rate per year at $m_{\nu \text{ eff}} = 50 \text{ meV}$, for 20 tonnes of enriched Xe, is 76 events. The decay energy of 2.5 MeV makes it essential that the external background of 2.6 MeV gammas from the Th decay chain be restricted to a very low level. Detailed work is required for a proper estimate of this background, but as an indication of the possibility for a measurement, a simple extrapolation was made from some spectral data presented by the KamLAND collaboration for their rate of 2.6 MeV gammas as a function of fiducial volume radius. From these rates, it was concluded that for a fiducial radius of about 3 meters, the detected rate of 2.6 MeV gammas could be as low as about 0.6 per year. For 20 tonnes of *natural* Xe dissolved in a full 1000 tonnes of liquid scintillator, the expected zero-neutrino rate in that fiducial volume would be: $76 \times 0.125 \times 0.089 = 0.85$ per year, for 50 meV effective neutrino mass.

2.4.5. Nanoparticles Suspended in Liquid Scintillator

The properties of some of the elements listed in Table 2 may be suitable for loading of liquid scintillator with metallic oxide nanoparticles. Rayleigh scattering of light by small particles in liquid varies as the sixth power of the particle radius and so can be made relatively small for nanoparticles of radius of 4 nanometers or less. Such particle size has been developed commercially for many materials and commercial suppliers of ZrO_2 , Nd_2O_3 , etc., are available. Light absorption in some of the metal oxides, such as ZrO_2 and TeO_2 , is small in the optical region because optical photons have energies smaller than the substantial band gaps in these insulators. Nd_2O_3 and SeO_2 do have absorption in the optical, for bulk material. These materials are being studied in nanoparticle form as it is known that in nanocrystalline form many materials exhibit very different optical properties compared to their bulk form. There is even the possibility that nanoparticles dispersed in liquid scintillator may be designed to be active in the scintillation process, and this is also being investigated.

To study scattering lengths and absorption in candidate double beta oxide materials, some preliminary measurements have been initiated at Queen's University of attenuation lengths and scattering for samples of nanoparticles suspended in water and organic liquids. These preliminary studies show that at a weight fraction of 1% of ZrO_2 in an organic liquid scintillator, the absorption length is expected to be greater than 30 meters and the Rayleigh scattering length calculated for 4 nm nanoparticles of ZrO_2 in liquid scintillator is about 11 meters at 380 nm. TeO_2 is another possibility for a metal oxide material with a long absorption length.

The ability to make nanopowders in controlled sizes exists in industry and ZrO₂ nanopowders, for example, can be made for less than \$1 per gram. The use of enriched isotopes would be expensive, of course, and has not been investigated as yet for any of the cases. The control of radioactivity in the nanoparticle material is also very important and needs to be considered in detail. One technique that is used for production of some nanoparticle materials is the cracking of organometallic compounds. This process has been used in the production of pure nickel for the Neutral Current Detectors in SNO and is known to be relatively free of U and Th chain impurities.

Examining the potential for Te, one finds that for 10 tonnes of *natural* Te, in the form of tellurium oxide dispersed throughout 1000 tonnes of liquid scintillator, the zero-neutrino decay rate in a 3 meter fiducial volume would be $128 \times 0.125 \times .345 = 5.5$ per year. Te, as for Xe, would require a deep fiducial volume cut to establish an external background-free region. S/B estimates look encouraging; however, a commercial supplier of tellurium oxide nanoparticles has not yet been identified, due to materials safety considerations.

Examining the potential for Nd, one observes that the external background would be much less of a concern (enabling a larger fiducial volume) and that the challenge would be internal radioactivity and optical properties to enable adequate resolution to restrict the two-neutrino background. However, the high calculated zero-neutrino decay rate makes this an attractive candidate if these can be controlled. Some very preliminary measurements are being performed on 0.5% Nd₂O₃ nanoparticles dispersed in pseudocumene. Attenuation lengths of several meters have been observed and further studies are in progress as there is some indication that impurities in the pseudocumene from the supplier may be affecting the observed attenuation.

2.4.6. Summary of Double Beta Decay Possibilities

Studies of double beta decay possibilities in liquid scintillator in SNO are clearly at a very preliminary stage. However, the potential for measurements with large amounts of several different materials, the possibility of studying external backgrounds by removal of the double beta material and the use of a significant installed experimental capability in the SNO detector lead us to pursue further consideration of these possibilities.

3. Infrastructure Needs

The following lists some of the infrastructure needs of SNO+:

- Basic Requirement: requires use of the SNO cavity and SNO detector (AV, PMT's, electronics, SNO light water system)
- Other Basic Requirements (power, space, etc.) are those of the present SNO experiment, with the addition of:
 - space is needed for a liquid scintillator handling and purification system, whose size would be comparable to the SNO heavy water system
 - liquid scintillator purification is envisioned to include some or all of:
 - water extraction (low impact on the laboratory)
 - solid column adsorption (very little impact on the laboratory)
 - vacuum degassing (moderate impact on the laboratory)
 - ultra-pure nitrogen stripping (moderate-high impact on SNOLAB)
 - distillation, only if deemed absolutely necessary for extracting low-energy solar neutrino physics (high impact on SNOLAB)
 - Xe gas handling system, that includes storage, gas-liquid mixing, and Xe gas extraction (possibly using elements from above)
 - possibly nanoparticle dispersion apparatus, in an underground clean room
- Background Tolerances: have already been discussed and considered in the scientific motivation section of the LOI and much is already known from SNO
- Special Facilities: SNOLAB should consider the benefits of supplying ultra-pure nitrogen for use by multiple experiments (e.g. as cover gas); liquid scintillator purification and handling is a special facility requirement of this experiment, as would be the Xe gas handling system
- Safety: organic liquids, even those with low flash points and low toxicity, have special handling and disposal requirements; these issues should undergo study by the experimental collaboration, in conjunction with SNOLAB
- Fabrication Processes: possibly nanoparticle dispersion processing underground
- Low Background Counting: no separate facility is thought to be needed for the liquid scintillator and Xe components; development of the nanoparticle option could benefit from low background counting in SNOLAB

The most important issue here – raising this issue is the main reason for submission of the LOI at this time – is the liquid scintillator handling issue. 1000 tonnes of liquid scintillator would need to be transported underground, handled, stored and purified underground. Safety and technical details need to be examined together with SNOLAB.

Some questions that need to be addressed include:

- do materials handling limitations exist for SNOLAB that would impact the composition of the liquid scintillator being considered for the experiment?
- what are the hazards associated with transport and handling of liquid scintillator underground?
- what additional hazards are associated with purification systems being considered?
- what impact on the laboratory does operation of purification systems have (i.e. power consumption, cooling requirements, discharge or disposal)?
- what failure scenarios exist? how would they be mitigated and/or avoided?

4. Progress on R&D and Technical Feasibility

Low background liquid scintillator development for this project benefits from experience developed in the Borexino and KamLAND experiments. Technical feasibility is currently being evaluated and basically just involves the optimization of the liquid scintillator cocktail for optical, chemical and purification properties, and for nanoparticle compatibility, should that option be pursued. It is extremely likely that the antineutrino physics goals (geo and reactor neutrinos) would be easily attainable, given our present knowledge of the technical feasibility.

As for the double beta decay options, simulations and studies are underway to evaluate whether competitive limits would be achievable. The Xe option has technical questions to be addressed, including handling and containment of Xe and has the cost question to consider (20 tonnes of Xe is a lot of xenon, enriched or not!). The Te or Nd nanoparticle option is novel. It requires demonstration of high loading in a liquid scintillator with minimal degradation of optical properties and it requires investigation of radiopurity of the nanoparticle materials, and methods of initial and continual dispersion in the liquid scintillator. Costs have not yet been addressed in detail.

Overall, by 2007, the date for removal of heavy water from SNO, the liquid scintillator component of this project could be ready to undergo installation. Technical feasibility, handling details and safety considerations could be demonstrated and worked out in that time. While measurements would be underway with pure liquid scintillator, additional development time for the double beta decay options would be available, if needed. A long range program, which could include both double beta decay options if both are successfully developed, could be considered.

5. Overall Summary

This study group has concluded that there is significant scientific motivation and significant interest from within the SNO collaboration (plus expressions of interest from potential participants external to SNO) to warrant this Letter of Interest to SNOLAB. SNO filled with liquid scintillator plus double beta decay candidate isotopes offers: potential fundamental discoveries (geo-neutrinos, reactor neutrino oscillation “dip” confirmation, and observation of neutrinoless double beta decay or competitive, next-generation limits), unique capabilities (the ability to pursue low-energy solar neutrinos at the deepest underground site, a necessity), and novel aspects (investigation of nanotechnology as a general technique for dispersion of a variety of double beta decay candidate isotopes in liquid scintillator). As the SNO collaboration moves forward with its Long Range Plan, and as R&D continues, this project group plans to work closely with SNOLAB to assure that technical, safety and infrastructure needs would be in place in the underground laboratory.

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