A New Technique to Load $^{130}$Te in Liquid Scintillator for Neutrinoless Double Beta Decay Experiments

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Abstract. The SNO+ collaboration has developed a new method to load liquid scintillator with tellurium in the form of organotellurates. This approach will be used in Phase I of the SNO+ experiment to achieve a 0.5% loading of natural Te by weight (corresponding to approximately 260kg of $^{130}$Te in the fiducial volume) with high light yield, enabling a projected half-life sensitivity of $\sim$1.96x10$^{26}$ years after 5 years of running.

1. Introduction
SNO+ builds on the infrastructure of the Sudbury Neutrino Observatory (SNO), with the heavy water replaced by 780 tonnes of an organic liquid scintillator. In Phase I of the experiment, a world-leading sensitivity to neutrinoless double beta decay will be pursued by mixing 3.9 tonnes (0.5% by weight) of $^{130}$Te into the scintillator. Thanks to its deep underground location, SNO+ will also achieve a unique potential during its isotope-free phase to probe the lowest energies of the solar neutrino spectrum. The experiment will additionally make important measurements of geo-neutrinos and anti-neutrinos and have excellent sensitivity to supernova neutrinos during both the double beta decay and solar neutrino stages of data taking.

The focus of this paper is describe a newly developed isotope loading technique that position the SNO+ experiment to make leading measurement in the search for neutrinoless double beta decay.

2. SNO+ Detector
The detector is located 2 km underground at the SNOLAB facility in Sudbury, Ontario. Its active scintillator is contained within a 12-meter in diameter acrylic sphere (AV) that is viewed by roughly 9500 photomultiplier tubes (PMTs) with an equivalent photocathode coverage of about 54. For additional background suppression from the surrounding Norite rock, the AV is submerged in ultrapure water within a Urylon-lined cavity of the experiment.

Figure 1: SNO+ detector.
3. Synthesis

A new method has been developed to load tellurium into scintillator based on linear alkylbenzene (LAB) so as to permit a search for neutrinoless double beta decay in the SNO+ detector with high sensitivity. The approach involves the simple synthesis of a tellurium complex with a single, safe distillable chemical and affords low radioactive backgrounds, minimal optical absorption and high light yields at the Phase I target loading of 0.5% Te by weight.

Synthesis is achieved by heated mixing of 1,2-butanediol (BD) with telluric acid (TeA) dissolved in water, followed by the careful evaporation of all water content. The complex is then formed via a condensation reaction, as illustrated in figure 2. We have verified that the BD is non-biogenic in origin, with a measured (AMS) ratio of ¹⁴C/¹²C ~ 3x10⁻⁶. The inherent U/Th levels have also been found to be ~1ppb or less, based on NAA and HPGe measurements. Furthermore, the BD is readily distillable and spike tests indicate purification factors of several thousand for a single pass, making it possible to easily achieve the U/Th target level of ~5x10⁻¹⁵.

A number of diagnostics are being developed to monitor both the synthesis process itself and the characteristics of the complex loaded in scintillator as a function of time. As one example, figure 3 shows plots based on IR spectra measured in situ that indicate the progression of the synthesis while the complex is being made. Other examples of diagnostics include NMR, ICP-MS and Karl Fisher titration in addition to monitors for temperature, humidity and viscosity.

A large-scale production of the complex for Phase I of the experiment will follow a three-stage approach: a laboratory small-scale synthesis, a prototype plant medium-scale and a final plant installed underground at the SNOLAB facility. At the time of writing, the first two stages have undergone construction and testing while the design of the underground plant is being finalized.
4. Stability
Sample stability of greater than 15 months has been explicitly demonstrated (i.e. since the development of the synthesized tellurium loading method), although a few samples have exhibited crystalisation behaviour indicative of exposure to water vapour. Based on various studies, we expect that this can be controlled by careful synthesis and handling, monitoring water content, extraction of water in a recirculation loop and the possible use of additives that have been shown to inhibit crystal formation.

![Graph](image1)

Figure 4: Normalised pulse height measurements of a 0.5% TeBD-LS sample as a function of time.

Figure 4 illustrates one of the stability monitoring examples using light yield measurement of a single batch of the complex dissolved in the LAB scintillator. Another technique not presented in this paper relies on a measurement of concentration of elemental tellurium with X-Ray fluorescence (XRF).

5. Optical Properties
At 0.5% Te loading, the light output is quenched by the complex to ~65% that of pure scintillator as shown in figure 5. In the current detector, this corresponds to ~390 detected photoelectrons per MeV of deposited energy. A similar detected light level could be achieved for a ~2% Te loading and no further R&D by upgrading the PMT array with high quantum efficiency tubes and improved concentrators. In addition, promising modifications of the loading technique to avoid much of the quenching are under investigation, which could allow even higher loading with better energy resolution.

![Graph](image2)

Figure 5: Pulse height spectra from $^{90}$Sr source.
As shown in figure 6, the measured optical extinction due to the complex has been found to be comparable to LAB over the wavelength range of interest, with extinction lengths notably larger than the detector scale. Further purification of the BD via distillation may improve this yet further.

6. Projected sensitivity
The projected sensitivity for Phase I of SNO+ with 0.5% Te loading using the technique described is shown in figure 7 in comparison with current experimental bounds. The experimentally measurable value of half-life is plotted versus the effective Majorana neutrino mass. Dependencies on matrix element values are indicated by the symbols, with different isotopes shown in different colours. The dashed lines indicate the scaling of sensitivities with lifetime (and $g_{\alpha}$).

![Figure 6: UV absorption+scattering of a 0.5% Te-BD compared with LAB.](image)

![Figure 7: Projected sensitivity compared with current experimental bounds.](image)