Water Phase Results and $0\nu\beta\beta$ Prospects of the SNO+ Experiment

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SNO+ is a multipurpose neutrino detector located in 2 km underground in Sudbury, Canada. The experiment is taking data and the first results from water phase on invisible nucleon decay search and solar neutrino analysis will be presented. The ultra-pure water inside the detector is currently being replaced by liquid scintillator, which will then be loaded with ^{130}Te to provide high sensitivity for neutrinoless double beta decay search starting next year. Further substantial improvements to the sensitivity could be achieved in an economical and straightforward manner by increasing the loading. The nature of the tellurium loading technique, projected $0\nu\beta\beta$ sensitivities and future prospects will also be presented.
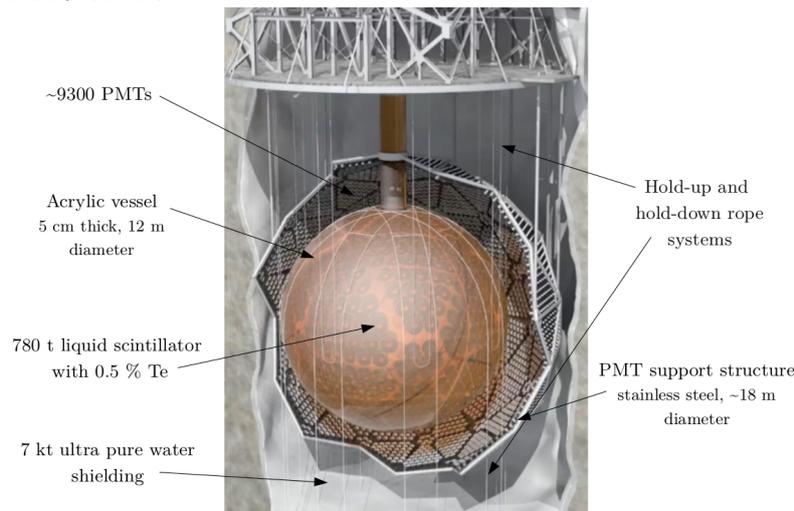
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1. Introduction

The main physics goal of the SNO+ experiment is the search for neutrinoless double beta decay in ^{130}Te. In this process, two neutrons in the same nucleus decay simultaneously, creating two electrons and a daughter nucleus with a proton number two units larger than the original nucleus. Contrary to a conventional double beta decay, no anti-neutrinos are emitted and the entire energy of the decay is carried away by the two electrons. The observation of this process would serve as a proof of lepton number violation and neutrinos being Majorana particles, indistinguishable from their antiparticle counterparts.

The following text gives an overview of the SNO+ experiment, summarises the recent results from the experiment and describes the prospects of the experiment in regards to neutrinoless double decay in the future. Special attention is paid to tellurium loaded scintillator that will be used for the $0\nu\beta\beta$ search.

2. The SNO+ Experiment

The kilotonne experiment [1] is hosted in the SNOLAB underground facility in Sudbury, Ontario, Canada. The rock overburden of 2092 m gives the experiment shielding from cosmic rays and their spallation products.

~9300 PMTs

Acrylic vessel
5 cm thick, 12 m
diameter

780 t liquid scintillator
with 0.5 % Te

7 kt ultra pure water
shielding

Hold-up and
hold-down rope
systems

PMT support structure
stainless steel, ~18 m
diameter

Figure 1: The SNO+ detector.

A schematic of the detector is shown on Figure 1. In the centre of the detector is a spherical acrylic vessel (AV) with a 6 m radius, which contains the detector target. The AV and its insides are watched by $\sim 10^4$ photomultiplier tubes (PMTs) mounted on a stainless steel support structure. The entire detector cavity, including the PMT array, is immersed in 7 kt of ultra-pure water (UPW) to provide shielding of the central regions from the natural radioactivity of the surrounding rock and the PMTs themselves.

There are 3 stages of the experiment, defined by the material contained within the AV. When high voltage was first turned on in SNO+ in December 2016, the AV contained ultra-pure water marking the start of the first stage. Water data taking has now finished and the UPW in the AV is being replaced with liquid scintillator. A few months of data taking with unloaded liquid scintillator

is anticipated in stage two. Finally, the scintillator will be loaded with tellurium for the $0\nu\beta\beta$ search, as discussed in Section 4.

3. Water Results

The SNO+ collaboration recently published two papers using data taken between May and December 2017. In this period, the AV was filled with UPW and the particle interactions inside it were detected via Čerenkov radiation.
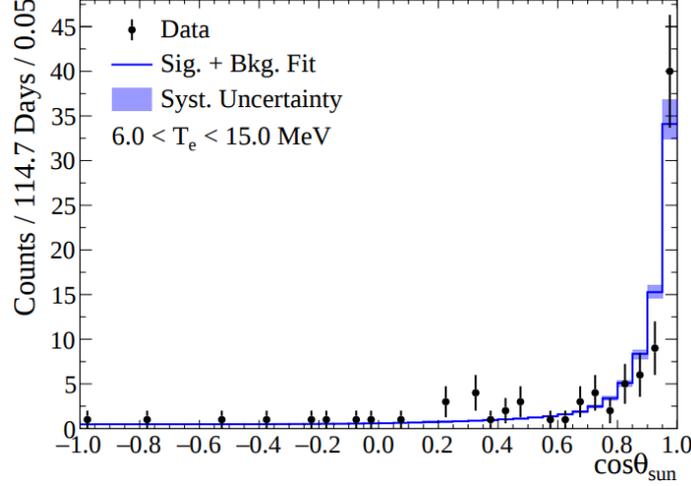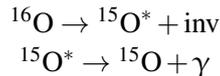

Figure 2: Histogram of event direction with respect to the direction of the Sun for events with reconstructed energy between 6.0 and 15.0 MeV. The peak at high $\cos\theta_{Sun}$ corresponds to neutrino scattering, whereas the low $\cos\theta_{Sun}$ region demonstrates close to zero radioactive backgrounds. Figure taken from [2].

In the first paper [2], an observation of elastic scattering of ^{8}B neutrinos from the Sun was made. In these events the recoil electron direction is highly correlated with the Sun's position. Therefore, the events were plotted in $\cos\theta_{Sun}$, which is the angle between the event's reconstructed direction and the direction from the Sun. The flux measured was:

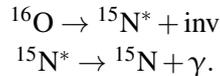$$2.53^{+0.31}_{-0.28}(\text{stat.})^{+0.13}_{-0.10}(\text{syst.}) \times 10^6 \text{cm}^{-2}\text{s}^{-1}$$

which is consistent with measurements by other experiments [3] [4]. Most importantly, this observation was made with very low backgrounds above 6 MeV as shown on Figure 2, which is especially relevant for the next stages of the experiment.

The second paper [5] involved a search for "invisible nucleon decay", in which no visible by-products are directly created. This analysis was based on searching for the de-excitation products (γs) from the excited nucleus left over after the invisible decay of nucleons in ^{16}O in water. For neutrons, the decay would be:

$$^{16}\text{O} \rightarrow {}^{15}\text{O}^* + \text{inv}$$
$$^{15}\text{O}^* \rightarrow {}^{15}\text{O} + \gamma$$

and for protons:

$$^{16}\text{O} \rightarrow {}^{15}\text{N}^* + \text{inv}$$
$$^{15}\text{N}^* \rightarrow {}^{15}\text{N} + \gamma.$$

In addition, 3 dinucleon decay modes were also considered: pp→inv, pn→inv and nn→inv. As a result, SNO+ was able to set the world's best livetime limits of invisible proton decay and 2 dinucleon decay modes [5].
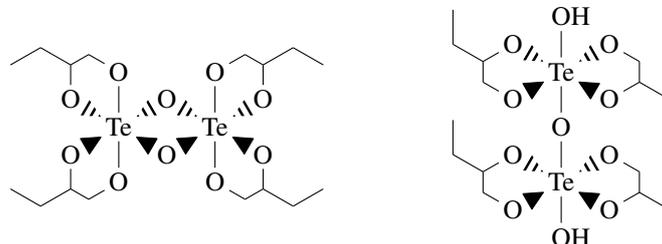
4. Tellurium Loaded Scintillator

For phase I, SNO+ will deploy 4 t of natural tellurium (0.5 % by weight) inside the detector volume in the form of tellurium-loaded liquid scintillator. The liquid scintillator is comprised of linear alkylbenzene (LAB), a long chain aromatic molecule, and 2,5-diphenyloxazole (PPO) at the concentration of 2 g/L as a primary fluor. As most easily obtainable tellurium species are inorganic, a novel technique for tellurium loading into an organic solvent (LAB) had to be developed for SNO+. Furthermore, the tellurium loaded product has to satisfy all the following requirements:

- high radiopurity, high light yield and good optical properties to provide good sensitivity for the $0\nu\beta\beta$ search,

- long term stability and material compatibility to allow for multiple years of data taking,

- safety that complies with the stringent safety requirements of an underground mine.

The loading procedure involves mixing aqueous solution of telluric acid and 1,2-butanediol. Butanediol molecules attach to the OH sites of telluric acid via condensation, forming monomers of the tellurium-butanediol (TeBD) complex as depicted on Figure 3. Over time and with heat application, more complex molecules, such as the dimers shown in Figure 4, are formed and contribute to the TeBD complex. The water is evaporated off, leaving the complex, which is miscible with LAB.
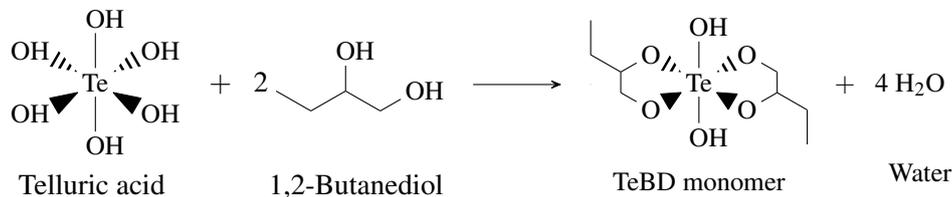
Figure 3: The synthesis of TeBD monomers from Te(OH)$_6$ and 1,2-butanediol via condensation reaction. Reaction shown for illustrative purposes; number of butanediol attachments can vary and other isometric forms are also possible.

Figure 4: Examples of possible TeBD complex dimers.

5. Amine Addition

The latest addition to the tellurium-loaded scintillator cocktail described in the previous section is N,N-dimethyldodecylamine (DDA). This is a tertiary amine with a long hydrocarbon tail. The

advantage of DDA is two-fold: it increases the light yield (LY) and it improves the resistance against water.

It has been observed that when low concentration (< 10 %) TeBD in LAB is put in contact with water vapour for prolonged time, the condensation reaction described above can proceed in backward direction (hydrolysis). As a result, the tellurium compounds can become no longer soluble in the organic liquid again and aggregate to form "flakes". DDA neutralises the TeBD mixture and associates ionically with the complex, which further helps the solubilisation in LAB and prevents hydrolysis. This protection against water exposure is demonstrated in Figure 5. Here the Te-loaded cocktail was mixed with variable amounts of DDA and exposed to extreme humidity (i.e. significantly higher than what is expected in SNO+). While flake formation was observed in samples without DDA within ~ 3 weeks, all samples with DDA:Te molar ratio > 0.1 remain uncompromised after > 2 years.

blank   DDA:Te = 0.10

DDA:Te = 0.25   DDA:Te = 0.50
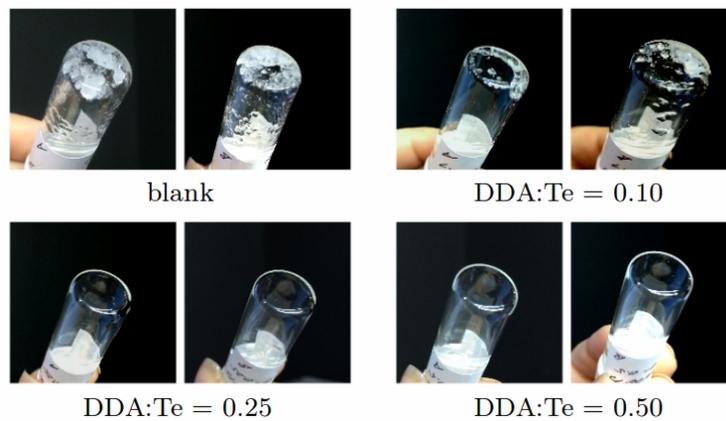
Figure 5: 1 % Te samples of TeBD in LAB+PPO 2 years after humidity exposure. Molar ratios of Te:DDA are stated. Duplicate samples for each concentration are shown.

Figure 6 shows the comparison between the light yield of unloaded scintillator mixture, 1 % Te-loaded scintillator without DDA and 1 % Te-loaded scintillator with DDA. While introducing tellurium into the scintillator quenches some of the light, a portion of it can be gained back by the addition of DDA. The molar ratio of Te:DDA= 0.5 is chosen for SNO+ to optimise the LY. As a result, the expected light output is improved by ~ 15 % with DDA.

6. $0\nu\beta\beta$ in Phase I

Tellurium-130 was chosen by the SNO+ collaboration as the double beta isotope due to its following properties: high abundance in natural tellurium (34 %), long $2\nu\beta\beta$ half-life (7.9×10^{20} yrs) and relatively high Q value (2.5 MeV). Furthermore, using the techniques described above, it is possible to introduce the isotope into the scintillator while maintaining good optical and light yield corresponding to 460 PMT hits/MeV in the SNO+ detector. Finally, an underground processing plant has been built to purify the telluric acid [6], aiming to result in the overall levels of uranium and thorium contaminations in the AV to be below 1.3×10^{-15} and 5×10^{-16} g/g [1], respectively.

The chosen energy region of interest (ROI) for the $0\nu\beta\beta$ is centered around the Q value and is asymmetric (-0.5σ - 1.5σ) due to the presence of the irreducible $2\nu\beta\beta$ background at its lower edge. In the ROI, the main backgrounds for the search are expected to be (in order of decreasing
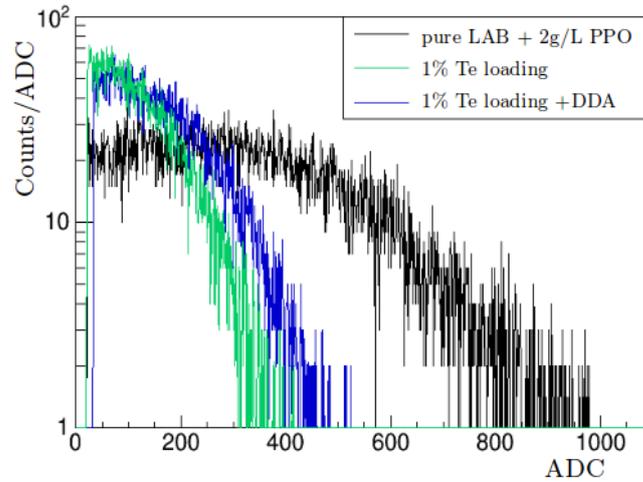
Figure 6: Relative light yield spectra for unloaded (black) and loaded LAB+PPO with (blue) and without DDA (green). Measured with a ^{90}Sr source.

contribution): the solar ^{8}B neutrino elastic scattering, internal U and Th chain radioactivity, external gamma rays (from the PMTs, support ropes, AV material etc.), $2\nu\beta\beta$ and products of cosmic ray spallation. 9.47 background events are expected in the ROI per year altogether. As a result, SNO+ is expected to reach the sensitivity of

$$T_{1/2}^{0\nu} > 2.1 \times 10^{26} \text{ yrs}$$

after 5 years of data taking with 0.5 % Te.

Figure 7 shows the SNO+ projected sensitivity compared to other $0\nu\beta\beta$ experiments in 2024. In this plot, the half-life was weighted by the isotopic phase-space factor, which makes it possible to compare the sensitivity across isotopes. As evident from the plot, SNO+ phase I has the potential to have world leading sensitivity to $0\nu\beta\beta$.

7. Future Prospects

The SNO+ collaboration is continuing the efforts in Te-loaded scintillator R&D for future phases of the experiment. An improved loading technique involves including DDA not only as an additive to the scintillator cocktail, but as a catalyst during the synthesis. This way, the light yield is improved even further compared to what is discussed in section 5. As shown on Figure 8, loading of $\geq 4\%$ of Te is realisable while maintaining good LY.

Furthermore, it is possible to start to increase the loading using the DDA-catalysed synthesis without any other upgrades or removal of any Te already present in the detector. Hence, SNO+ could undergo a smooth transition from phase I to phase II with minimal downtime. The projected sensitivity for phase II (assuming 4 % loading) is also shown on Figure 7 reaching deep into the inverted hierarchy depending on the model.

8. Summary

The SNO+ experiment is running, published first physics results and is currently filling its main volume with unloaded scintillator. The collaboration developed a reliable method for loading
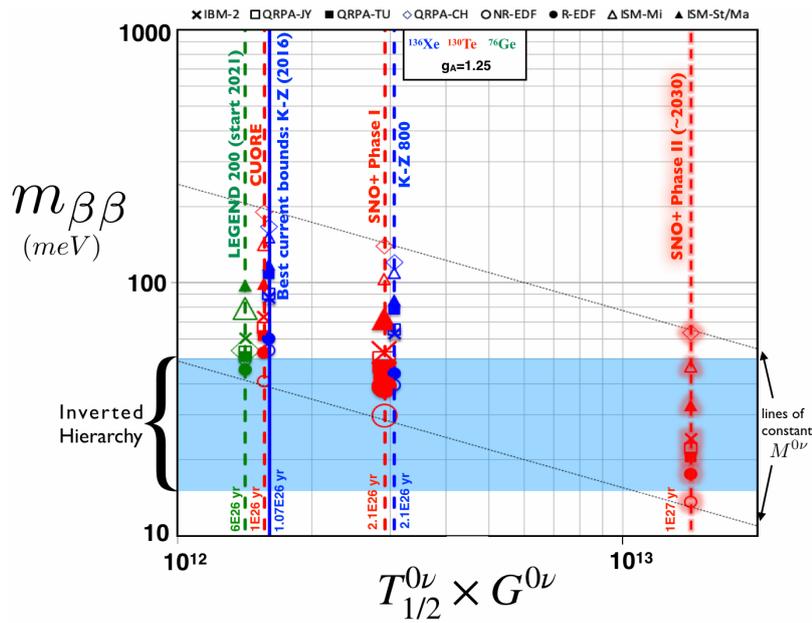
Figure 7: Projected 2024 $0\nu\beta\beta$ sensitivities. Phase-space weighted half-life is used for the vertical axis to provide isotope and model independent measure for sensitivity. Horizontal axis provides a conversion to the effective Majorana mass for various models (represented by the various symbols). SNO+ phase II is assuming 4 % Te loading via the DDA-catalysed synthesis and no other detector upgrades.
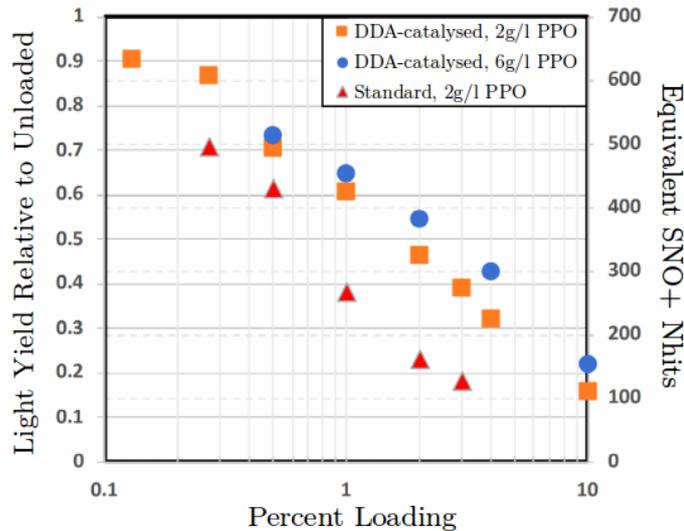
Figure 8: Light quenching curve for the DDA-catalysed synthesis with 2 g/L PPO (orange squares) and 6 g/L PPO (blue circles) compared to the standard synthesis employed for SNO+ phase I.

tellurium into organic liquid scintillator. Together with outstanding advantages of tellurium-130 as $0\nu\beta\beta$ isotope, large exposure and low experimental backgrounds, this results in world leading expected sensitivity to neutrinoless double beta decay.

Acknowledgements

References

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