Search for Majorana neutrinos with the SNO+ detector at SNOLAB

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Abstract. The SNO+ experiment is adapting the Sudbury Neutrino Observatory (SNO) detector, in order to use isotope-loaded liquid scintillator as the active medium. SNO+ has multiple scientific goals, the main one being the search for neutrinoless double beta decay, the most promising signature for the possible Majorana character of neutrinos and for the absolute neutrino mass. Measurements of neutrinos from the Sun, the Earth, Supernovae and nuclear reactors are additional goals of the experiment. The detector consists of a 12m diameter spherical vessel, filled with 780 tonnes of Tellurium-loaded liquid scintillator, and surrounded by about 9500 PMTs. It is shielded by a large volume of ultra-pure water and the underground location at SNOLAB, Canada. This talk will review the Physics goals and current status of SNO+.

1. Introduction

The SNO+ experiment [1] at SNOLAB [2] in Canada aims to search for Majorana neutrinos through the observation of the neutrinoless Double Beta Decay (DBD). The neutrinoless-DBD (or 0νββ-decay) signal is proportional to an effective mass, $\langle m_\nu \rangle$, dependent on the neutrino mixing parameters U_{ek} and on the difference of squared masses measured by oscillations. The observation of 0νββ-decay would contribute to the determination of the neutrino absolute mass scale, the mass hierarchy and, in addition, reveal the Majorana character of the neutrino [3].

Since the late 1940s, early 1950s, that the search for Double Beta Decay with the emission of two neutrinos (2νββ) has been the subject of several experiments. The DBD nuclear process consists on $(A, Z) \rightarrow (A, Z + 2) + 2e^- + 2\nu$ and it is possible for a few isotopes with extremely long half-lives, so very small event rates. This process has been observed for the first time in 1950 in the decay of ^{130}Te in geochemical experiments and only in 1987 it has been observed by direct counting by Michael Moe's group in the decay of ^{82}Se. Later on many more of these events were observed [4].

The quest for Majorana neutrinos through the observation of neutrinoless Double Beta Decay (0νββ), i.e., $((A,Z) \rightarrow (A,Z + 2) + 2e– + 0\nu$, is a key topic research in fundamental physics in view of

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the neutrino properties as well as the completion or extension of the Standard Model of Particle physics. While the signature of $0\nu\beta\beta$ – a monoenergetic peak - at the $Q_{\beta\beta}$ is clear when compared to the continuous spectrum of $2\nu\beta\beta$, the process has so far not been observed. From this non-observation, limits on the $0\nu\beta\beta$ half-life and, correspondingly, on the effective neutrino mass, have been placed by several experiments. The best current limits are around 10^{25} years and 200 meV, respectively [4]. Sensitivities of about 100 meV are expected for currents experiments or under preparation, using ultrapure materials with very low radioactivity, employing active or passive shielding and located in underground laboratories [5].

Since the design of SNO+ is driven by the detection of low energy electrons from $0\nu\beta\beta$-decay, measurements of low energy pep/CNO solar neutrinos, Supernovae neutrinos as well antineutrinos from nuclear reactors and geoneutrinos are additional goals of the experiment.

2. The SNO+ experiment

2.1. Detector overview

The SNO+ detector [1] is based on the SNO detector but with a liquid scintillator that replaces the heavy water used by SNO. The project and design of SNO+ is driven by the detection of electrons from the DBD of radioisotopes such as ^{150}Nd, and more recently ^{130}Te, the choice made for the first phase of the SNO+ experiment. The natural Tellurium is dissolved in a liquid scintillator based on the idea of Raghavan for the Borexino detector [6], using ^{136}Xe. So, the basics of detection in SNO+ is the full energy loss of ionizing particles with production of scintillation of the active material. The scintillation light is detected by a system of photomultipliers (PMTs) and the number of photo-electrons measured is proportional to the energy of the particle (electrons, alphas, muons, etc.). So, in the language of Experimental High Energy Physics the SNO+ detector can be considered a homogeneous calorimeter, and since the final result is the counting of electrons, SNO+ can be considered also a counting detector.

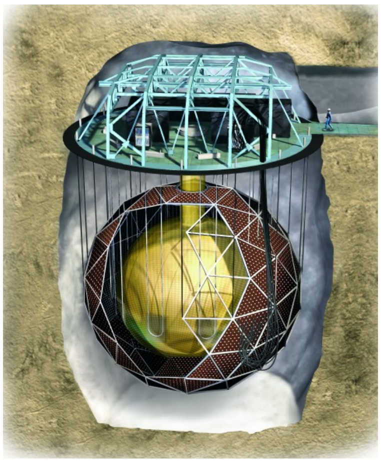

Figure 1. Artistic view of SNO+ in its cavity 2km deep.

Figure 2. SNO+ physicist cleaning the top part of the AV.

SNO+ is located 2 km underground at SNOLAB and consists of a 12 m diameter acrylic vessel (AV) containing 780 tonnes of liquid scintillator. The scintillator will be loaded with 0.3% of natural tellurium, equivalent to 2340 kg, or 800 kg of ^{130}Te, in the initial phase. The AV is located inside a cavity in the rock, and a geodesic structure around the AV supports the system of 9500 photomultipliers tubes with QE ~20% coupled to a set of reflectors to increase the geometric coverage to 55%. The acrylic vessel and the PMT structure are immersed in 7000 tonnes of ultrapure water (10^{-13} to 10^{-14} g of U/Th per g of water) to shield the liquid scintillator from radioactivity from the rock surrounding the underground cavity and the PMTs. The diffusion of radon from the rock is stopped by a thick liner of Urylon. The AV is sustained by a system of ropes to compensate the buoyancy of the scintillator with a density of 0.86g/cm^3. The ropes have been carefully chosen minimising the radioactivity impurities of the order of ppb for the U/Th isotopes and ppm for ^{40}K. An artistic view of the detector is shown in figure 1, and in figure 2 a SNO+ physicist finalising the cleaning of the top part of the detector is seen and the hold-down rope system is also visible.

A new readout system, 20 times faster, and new calibration systems were designed and are being implemented. A new optical system of 96 LEDs/plastic fibers for calibration and monitoring the PMT response, including time and charge information, and a system of 20 quartz fibers for transparency measurements, have been built and partially installed in the detector (see talk of L. Seabra in these proceedings [7]).

A mechanism for the deployment of radioactive sources is designed and under construction. Natural radioactive sources from the background, as well as new radioactive sources (AmBe for neutrons and γ-rays, ^{16}N, ^{24}Na, ^{48}Sc, ^{57,60}Co, ^{65}Zn for γ-rays and ^{90}Y for betas) are being developed for setting the absolute energy calibration. Natural sources part of the background, such as ^{14}C, ^{208}Tl, ^{214}Bi, ^{210}Po, etc... will also be extensively used.

2.2. Neutrinoless DBD search with liquid scintillators

Measuring events of extremely small rates and with energies in the range of 1 to 5 MeV needs large volume detectors such as SNO, and large mass of the DBD isotope, even at small loading and a very low background. To reach the low levels of Borexino [8] background SNO+ requires: (i) a very good intrinsic radiopurity of the scintillator, (ii) a fiducial volume to reject external backgrounds, (iii) the choice of materials with ultra-low levels of radioactivity, (iv) the purification of cosmogenically activated contaminants; (vi) the knowledge of irreducible background from solar neutrinos, (vii) and for $Q_{\beta\beta}$> 2 MeV, the identification of many backgrounds with delayed coincidence (alpha or beta) tagging .

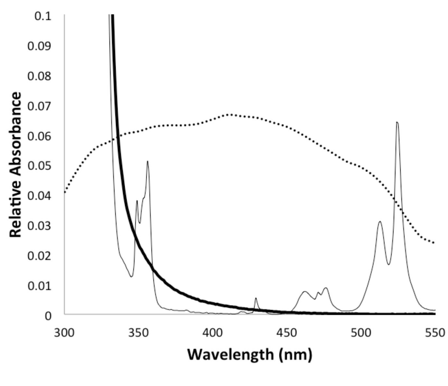

Figure 3. Absorbance vs λ (nm) for 0.3% Te (—) and 0.3% Nd (---) loaded scintillator without 2nd WLSs or fluors, and SNO+ PMTs QE(λ) (····).

Figure 4. The transparent liquid scintillator.

The liquid scintillator chosen by the SNO+ collaboration after a program of R&D was Linear AlkylBenzene (LAB) with 2g/l of the PPO fluor (2,5-diphenyloxazole) that optimises the match of the scintillating light with the PMT quantum efficiency spectra as shown in figure 3. The main requirements of the scintillator were: (i) chemical compatibility with the acrylic vessel (ii) high radiopurity (Borexino levels) (iii) high light yield, (iv) good optical transparency (figure 4) and low scattering, (attenuation lengths larger than 10 m were achieved, but probably will decrease after loading with ^{130}Te) [9] and absence of absorption peaks in the region of the PMT maximum QE (λ), fast response, of about 5 ns, (vi) safety, i.e. low toxicity and high flash point (150ºC). To minimise cosmogenic activation, a purification system for distillation and water extraction is presently being installed at the underground laboratory. A scintillation light yield of ~10000 photons/MeV corrected for the PMT QE of ~20%, geometric coverage of 55% and absorption in the scintillator, resulted on typical values of 200-300 detected photoelectrons/MeV [9]. As is typical of liquid scintillator experiments, SNO+ has intrinsically worse energy resolutions than solid state detectors, making it harder to distinguish the $0\nu\beta\beta$ decay peak from background γ-ray lines and from the two-neutrino DBD continuous spectrum. However, this is compensated by having a large isotope mass and very low backgrounds, and other ways of reducing them, as will be described in the next section.

2.3. Data analysis

The ionizing particles, from isotopes decay or cosmic rays reaching the scintillator, excite the scintillator producing photons that travel through the volume and are detected by the PMTs. The number of photoelectrons viewed by the PMTs is corrected by the PMT QE and by the geometric efficiency coverage and attenuation coefficient depending on distance. The electronics allows the measurement of the time of arrival and the charge of each PMT hit, within a 400ns window. The event position is reconstructed with the PMT timing information. A fiducial volume of about 20% of the liquid scintillator is defined, in order to reject the external backgrounds. The event energy is obtained from the number of hits corrected by its position. Delayed coincidences are used to identify some of the radioactive backgrounds [10].

The DBD analysis is done with the energy spectrum after removing or constraining the background and the candidate events to the $0\nu\beta\beta$ peak are counted. So, we can consider SNO+ a counting experiment using calorimeter techniques.

3. Neutrinoless DBD with SNO+

3.1. The source of DBD-decay for SNO+

With the aim of searching for Majorana neutrinos through DBD processes, several isotopes candidates have been considered. Some even-even nuclei are usually β-decay energetically forbidden but double decay is allowed. From the 35 naturally occurring isotopes energetically DBD allowed, among them ^{78}Ge, ^{130}Te, ^{136} Xe, ^{150}Nd, etc, only 10 of them were observed [4]. The main characteristics of those DBD isotopes are their extremely long half-life (>10^{18} years), a $Q_{\beta\beta}$ of the order 1 MeV to 5 MeV, and a natural abundance about 10% or less. Only one known DBD-isotope, ^{130}Te, presents a high natural abundance of about 34.1% although with a low $Q_{\beta\beta}$ of 2.53 MeV and a half-life 7.14x10^{20} years. ^{150}Nd has a higher $Q_{\beta\beta}$ of 3.4 MeV but its natural abundance is only 3.6 %. SNO+ has chosen ^{130}Te as first option.

3.2. DBD Background and signal

The sources of background for neutrinoless DBD searches with SNO+ detector are internal and external. Beta particles from $2\nu\beta\beta$ are an irreducible background although lower for ^{130}Te, but demanding a good energy resolution. Position resolution is also an important factor for the energy reconstruction, and can be important to avoid pile-up in case of high $2\nu\beta\beta$ rates. Solar ^{8}B neutrinos are also an irreducible background but its rate and distribution is known from SNO and Super-Kamiokande.

External γ-rays from the U/Th chains and ^{40}K from the rock can be suppressed by the ultrapure water shielding surrounding the AV; cosmic ray muons are suppressed to negligible levels by the underground location. Internal background from the U/Th in the water used in the process of diluting the Tellurium in the scintillator (TeLS) is assumed to be of the order of ~10^{-14} to 10^{-15}g of U/Th per g of TeLS as in SNO. Alpha (α) or beta (β) emitters, with short half-lives, or close to them in the decay chain, such as ^{214}Bi, ^{212}Bi, ^{208}Tl, ^{210}Po can be rejected by delayed coincidences. The radiopurity of the mixture TeLS requires several steps of purification. Cosmogenic activation on the surface is responsible for the production of unstable isotopes through cosmic ray interaction on the bulk material requiring a final purification step to be done at the SNOLAB underground laboratory.

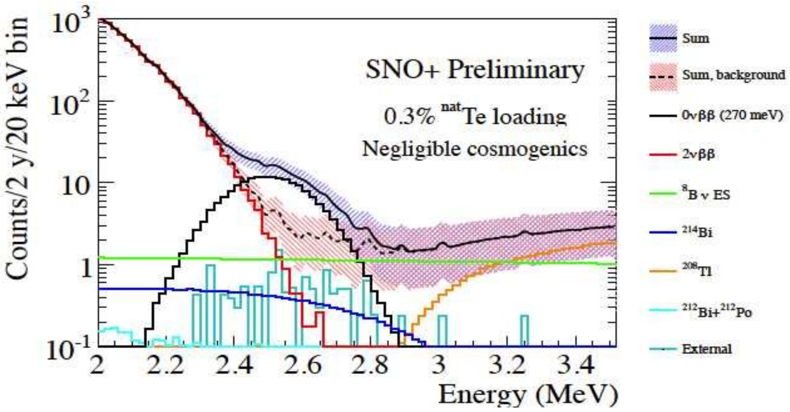

Figure 5. MC simulation of the SNO+ background and DBD (2νββ and 0νββ) signals.

In figure 5 is depicted a preliminary Monte Carlo simulation of the background in SNO+ and the neutrinoless double decay spectrum expected for a loading of 0.3% of natural Tellurium and for two years of SNO+ data taking. It is well visible the neutrinoless double beta decay peak superimposed to the end of the 2νββ-decay continuous spectrum. After five years of data taking the expected neutrino mass sensitivity is about 100meV, which could be improved by achieving higher loading of Tellurium in the scintillator.

4. Reactor and Earth Antineutrino searches with SNO+

Measurements of anti-neutrinos from nuclear reactors and the mapping of geoneutrinos reaching the SNO+ detector, contributing to the knowledge of the mantle composition and radiogenic heat production of the Earth, are additional goals of the SNO+ experiment.

The first observation of geoneutrinos, produced in the planet's crust and mantle (figure 6), are recent but are already being used to test Earth models; anti-neutrinos produced in nuclear reactors have been used in neutrino physics, namely for the study of neutrino oscillations [11]. In figure 7 it is shown a preliminary simulation of anti-neutrino oscillations seen at SNO+ where the peaks from neutrinos from different reactors in Canada are well visible.

Anti-neutrinos from reactors were detected for the first time by C. L. Cowan Jr., F. Reines et al (1956) through the interactions in liquid scintillator detectors like SNO+. The signature of the process, can be clearly identified by the delayed coincidence of the positron annihilation followed by a neutron capture in which the positron energy and the neutron initial direction follows the anti-neutrino kinematics. Anti neutrinos can then be identified with SNO+ even under the large event rate of DBD.

Also Supernovae explosions could be detectable with ^{130}Te loading, while low energy solar neutrinos will be searched with pure scintillator only.

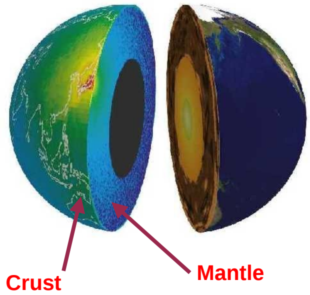

Figure 6. The Earth: crust and mantle are visible.

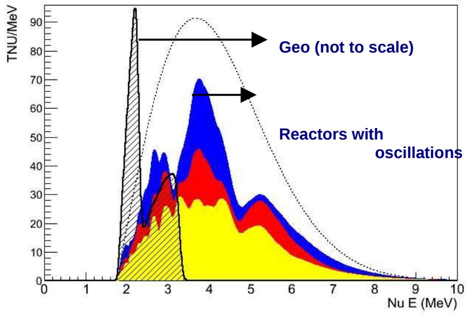

Figure 7. Simulation of anti-neutrino oscillations seen by SNO+.

5. Status and outlook

SNO +, a large volume liquid scintillator loaded with a large mass of ^{130}Te will probe the nature and magnitude of the effective neutrino mass with the sensitivity about 100 meV, and will measure anti-neutrinos from reactors and the Earth and also Solar and Supernova neutrinos. Water filling of the detector has started and SNO+ is almost ready for the water phase commissioning by the end of 2014. The new trigger and readout as well as the calibration systems are almost finished.

SNO+ scintillator phase is expected for 2015, initially with unloaded scintillator. First measurements of the background before loading it natural Tellurium are also planned. Neutrinoless DBD search will start with 0.3% Tellurium loading but could be later increased to 3%.

6. Acknowldgments

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