CALIBRATION HARDWARE
RESEARCH AND DEVELOPMENT FOR SNO+

by

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Abstract

The SNO+ experiment is a kilo-tonne scale liquid scintillator detector located at SNOLAB in Sudbury, Ontario, Canada. As the successor to the Sudbury Neutrino Observatory, SNO+ will use linear alkylbenzene (LAB) as the scintillator to study neutrinos. During the solar phase, flux measurements will be made of low energy neutrinos originating in the Sun. In another phase, 800 kg of tellurium will loaded into the scintillator to search for neutrinoless double beta decay. Measurements will also be made of neutrinos coming from nearby nuclear reactors and from inside Earth’s mantle and crust.

To enable these multiple physics goals, a sensitive calibration procedure must be carried out in order to fully understand the detector. The optical and energy responses of the detector will be measured with calibration sources deployed throughout the acrylic vessel. These sources must be connected to the observatory deck above the vessel by gas capillaries, optical fibres, and signal wires housed in specially designed submersible umbilical cables. The design and fabrication of these umbilical cables is presented. Development work on a deployed radon calibration source will also be described.
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Chapter 1

Introduction

1.1 SNO and SNO+ Experiments

The Sudbury Neutrino Observatory (SNO) [1] was a large scale Cherenkov detector that used heavy water to detect the flux of $^8$B neutrinos from the Sun. Beginning in 1999 and concluding in 2006, SNO solved the solar neutrino problem: a discrepancy between the expected number of neutrinos originating from the Sun and flux measurements taken on Earth. Results from the SNO experiment have established the existence of neutrino oscillation, proving that neutrinos are massive and that their flavour eigenstates ($\nu_e$, $\nu_\mu$, $\nu_\tau$) are mixtures of their mass eigenstates ($\nu_1$, $\nu_2$, $\nu_3$) [2].

SNO+ is the successor to the SNO experiment where the heavy water (D$_2$O) will be replaced with a liquid scintillator, linear alkylbenzene (LAB). Most of the infrastructure from the SNO detector has been reused, namely the acrylic vessel (AV), water shielding cavity, and photomultiplier tubes (PMTs). By using liquid scintillator instead of heavy water, the light yield is increased by a factor of $\sim$50, allowing SNO+ to probe even lower neutrino energy regions. This increase in sensitivity is particularly important in making measurements of low energy solar neutrinos from
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the CNO and pep reactions. SNO+ also aims to investigate antineutrinos originating from the mantle and crust of the Earth, thereby analyzing the radiogenic heat production and radiochemical composition of the planet. Additionally, antineutrinos from nearby nuclear reactors in Ontario will be detected and further constraints on neutrino oscillation parameters will be made. A large liquid scintillator detector like SNO+ will be in great position to monitor neutrinos emitted from a supernova event, were one to occur during operation [3].

Another phase of the SNO+ experiment is planned to investigate neutrinoless double beta decay. In this phase, roughly 800 kg of double beta decay isotope $^{130}$Te will be loaded into the scintillator and the detector will search for neutrinoless double beta decay events to occur. SNO+ is scheduled to be filled with liquid scintillator in late 2014 and to become fully operational shortly thereafter.

1.2 Detector Geometry

The SNO+ detector is located in Vale’s Creighton mine near Sudbury, Ontario, Canada. It sits at a depth of 2km below ground, shielded from atmospheric particles by the equivalent of roughly 6000 meters of water. The main parts of the SNO detector repurposed for SNO+ are the 12m diameter AV, approximately 9500 PMTs, and 7400 tonnes of cavity water shielding.

Significant support modifications were necessary, however, with the change to liquid scintillator for SNO+. Because heavy water is, as the name suggests, heavier than the regular, light water in the cavity (1.11 g/cm$^3$ compared to 1.00 g/cm$^3$), hold-up ropes were installed along the AV in order to securely suspend the vessel. However, the liquid scintillator LAB has a density of 0.86 g/cm$^3$ and, therefore,
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the acrylic vessel will be buoyant. A system of hold-down ropes were designed and installed on the SNO+ acrylic vessel to keep it in a fixed position in the centre of the cavity. Figure 1.1 shows schematic diagrams of the SNO vessel and the additional hold-down rope modifications.

![Figure 1.1: Schematic diagrams of the SNO detector and the SNO+ hold-down ropes][4].

1.3 Liquid Scintillator

A scintillator is a material that produces light when a charged particle passes through it. Organic liquid scintillators for large-scale particle detectors typically are comprised of two or three elements: solvent, fluor, and wavelength shifter. The solvent makes up the bulk of the solution and becomes efficiently excited by the passage of charged
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particles. Excitations of the solvent are collected by the fluor via dipole interactions and then emitted as photons. Occasionally, a wavelength shifter is also added to the liquid scintillator solution. It collects the emission light from the fluor and re-emits it at a longer wavelength in order to avoid self-absorption and increase light output.

The scintillator solvent chosen for SNO+ is linear alkylbenzene (LAB) to which 2,5-diphenyloxazole (PPO) is added as the fluor in a concentration of 2 g/L. This concentration is set large enough for there to be small intermolecular spacing between the LAB and PPO molecules, allowing for efficient energy transfer between them.

LAB was chosen due to its compatibility with the detector materials inherited from SNO. Any degradation of the acrylic vessel or other components through contact with the scintillator is unacceptable. Likewise, any changes in the properties of the scintillator through exposure to unsuitable substances are to be avoided.

Several other liquid scintillators were considered for use in SNO+, namely diisopropynaphthalene (DIN) and pseudocumene diluted to 20% in mineral oil [5]. DIN was initially promising in that it had a slightly higher light output and higher density than LAB. However, a measured increase in light scattering in the acrylic-exposed DIN led to concerns that small acrylic particles may be leaching off and suspending in the scintillator. Pseudocumene is well-known to be an aggressive organic solvent that attacks acrylic. Appropriately diluted solutions of pseudocumene could, however, be compatible with acrylic for an extended period of time, and have been used for large-scale liquid scintillator detectors in the past. Accounts from the Palo Verde experiment raised concerns about the use of even diluted pseudocumene, however, as they suggested signs of degradation in both acrylic and the scintillator after prolonged exposure [6]. These issues with DIN and pseudocumene led to a series of
1.4. SUMMARY

Long-term acrylic compatibility studies with LAB, after which no significant changes were observed. Therefore, LAB was chosen as the liquid scintillator for SNO+ [7].

LAB is a major component in surfactants for detergents and, as such, is produced in large quantities and is readily available. CEPSA Quimica Bécancour, located in Quebec, has been chosen as the manufacturer for the SNO+ LAB. The nearby location and constant supply make LAB an economically viable choice.

The optical properties of LAB are also advantageous to large liquid scintillator experiments. The attenuation length due to scattering and absorption is roughly 20 m at a wavelength of 420 nm. This is longer than the 12 m diameter of the acrylic vessel. Further, the high light yield of LAB makes for good energy resolution and the ability to reach lower energy regions. The acrylic compatibility, relative inexpense, and good optical characteristics of linear alkylbenzene make it a good choice for the SNO+ liquid scintillator.

1.4 Summary

SNO+ is the successor the successful SNO experiment. It reuses important infrastructure from SNO including the acrylic vessel and surrounding photomultiplier tubes. SNO+ is a multipurpose detector which aims to study the physics of low energy solar neutrinos, geoneutrinos, reactor antineutrinos, supernovae, as well as search for neutrinoless double beta decay. A liquid scintillator, linear alkylbenzene, has been identified to be compatible with the existing detector components, namely the acrylic vessel, and offers an advantage of greatly increased light yield. Chapter 2 will discuss the SNO+ physics objectives in greater detail. Chapter 3 will detail the calibration program, developed by the SNO+ collaboration, that will be used to understand the
optical and energy response of the detector. Chapters 4 and 5 will present the original work of the author on the development of specific hardware components of the calibration system. Chapter 6 will conclude this thesis.

**Statement of Originality**

Chapter 4 will describe the original work of the author on the development of a fabrication process, including the custom instruments required, for producing the SNO+ umbilicals. The general design is adapted from previous SNO work. Assistance in construction of the umbilicals and fabrication instruments was provided by members of the SNO+ group at Queen’s. Chapter 5 contains work on designing and investigating a radon calibration source. The design, simulation, and scintillator spiking method described are the original work of the author. The measurements shown relating to alpha-beta discrimination in LAB were carried out previously by members of the SNO+ group at Queen’s.

The SNO+ experiment is made possible by the collaborative work of many. This thesis includes general information and development work related to the experiment and directly by the collaboration and is cited as such.
Chapter 2

SNO+ Physics Goals

SNO+ is a multipurpose experiment and its high sensitivity to low energy and rare events gives it the opportunity to make some interesting and competitive physics measurements. The SNO experiment was a great success and SNO+ is in the position to further that success by running in two different phases: a neutrinoless double beta decay phase and a solar neutrino phase. The different areas of interest to SNO+ are discussed in this chapter.

2.1 Solar Neutrinos

Energy production in the Sun proceeds by nuclear fusion reactions. Most of these are proton-proton (\( pp \)) chain reactions while chains of heavier elements, namely the CNO cycle, make up the remaining minority. Figure 2.1 shows the chain reactions and highlights the neutrinos released during each step.

The rates of these reactions and the energy production of the Sun are characterized by the Standard Solar Model (SSM) [8]. This model, based upon solar observations and experimental parameters, can be used to predict neutrino fluxes from the various steps in the \( pp \) chain and CNO cycle. A set of such predictions, plotted as a neutrino
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Figure 2.1: Solar reactions in the Sun: pp chain and CNO cycle [4].

energy spectrum, is shown in Figure 2.2. The figure shows that pp neutrinos are the most abundant but are low in energy while $^8$B neutrinos are less numerous but much higher in energy.

2.1.1 Solar Neutrino Problem

Before going any further, some brief historical background on neutrino-related discoveries should be discussed. Neutrinos were first proposed in 1930 by Pauli to explain the continuous energy spectrum of electrons emitted in beta decay. A milestone was reached when they were first successfully detected, coming from a fission reactor, in 1956 by Cowan and Reines [10]. Solar neutrinos were first detected by the Davis Chlorine Experiment in 1968 via the reaction in Eq. 2.1 [11].

$$\nu_e + ^{37}\text{Cl} \rightarrow ^{37}\text{Ar} + e^- \quad (2.1)$$

Measurements from the Davis Chlorine Experiment and others, such as SAGE
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Figure 2.2: Neutrino fluxes produced by the Sun. Neutrinos from the CNO cycle are in dashed blue lines while those from the $pp$ chain are in solid lines [9].

[12], GALLEX [13], Kamiokande [14], and Super-Kamiokande [15], had all shown discrepancies in the expected neutrino flux based on standard solar model predictions. The number of detected neutrinos was approximately one third to one half of the calculated SSM value. This was dubbed the solar neutrino problem. The solution was established when SNO confirmed the process of neutrino oscillations. Neutrinos were changing flavours between the point they were produced in the Sun and detected on Earth. SNO, with its 1000 tonnes of heavy water, was able to confirm speculations that neutrino oscillation was occurring by measuring $^8$B neutrinos through three
different interaction mechanisms: elastic scattering, charged current, and neutral current (Eqs. 2.2, 2.3, and 2.4, respectively). The neutral current interaction allowed SNO to measure the flux of all neutrino flavours while previous solar neutrino experiments were sensitive only to electron flavour. Thus, the neutrinos that had changed flavours enroute from Sun were undetectable by these other experiments.

\[
\nu_x + e^- \rightarrow \nu_x + e^-
\] (2.2)

\[
\nu_e + d \rightarrow p + p + e^-
\] (2.3)

\[
\nu_x + d \rightarrow \nu_x + n + p
\] (2.4)

Elastic scattering and charged current events are detected directly through the production of Cherenkov light from the recoiling electron. Neutral current events produced recoiling neutrons which were detected by the resulting gamma rays from neutron capture reactions in both D$_2$O and NaCl and from neutron-proton exchange interactions (namely, $^3$He+n → $^3$H+p) in deployed neutral current detectors [16].

The elastic scattering interaction can proceed with any of the three neutrino flavours but is more sensitive to electron neutrinos because of its larger cross section with electrons. The charged current interaction is exclusively sensitive to electron-type neutrinos while the neutral current interaction is equally sensitive to all three flavours. Therefore, a comparison of the fluxes detected from the charged and neutral current interactions allows one to determine what fraction of the total solar flux consists of electron neutrinos, indicating the remaining fraction had shifted into other flavours enroute from the Sun. The flux ratio of charged current to neutral current was found to be 0.317±0.016(stat.)±0.009(syst.) [2].
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2.1.2 Neutrino Oscillations

Vacuum Oscillations

The solar neutrino problem was solved by conclusively showing that neutrinos change flavour as they propagate through space, a phenomenon known as neutrino oscillation. This is because the flavour eigenstates, denoted $|\nu_\alpha\rangle$ ($\alpha = e, \mu, \tau$), are not identical to the mass eigenstates, $|\nu_k\rangle$ ($k = 1, 2, 3$), where an important consequence is that neutrinos have a finite mass. A neutrino with a well-defined flavour will not have a similarly well-defined mass. Flavour eigenstates can be expressed as a combination of the mass eigenstates as in Eq.2.5:

$$|\nu_\alpha\rangle = \sum_k U_{PMNS} |\nu_k\rangle,$$

(2.5)

where $U_{PMNS}$ is the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix, so-named for those who first developed the quantitative theory of neutrino oscillation [17][18]. $U_{PMNS}$ is a 3x3 unitary matrix and can be expressed in the three-neutrino case as the following [19]:

$$U_{PMNS} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}.$$

(2.6)

Here, $c_{ij} = \cos \theta_{ij}$ and $s_{ij} = \sin \theta_{ij}$. The $\theta_{ij}$ terms are the mixing angles for each mass sector. The phase factor $\delta$ is a CP-violating phase term.

An approximation of this model can be made for the two-neutrino case using a 2x2 rotation matrix:
\( U = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \), \quad (2.7)

where \( \theta \) is the mixing angle between the two mass eigenstates. Thus, we can express each flavour eigenstate, say \(|\nu_e>\) and \(|\nu_a>\) in the two-neutrino approximation, as a superposition of mass eigenstates \(|\nu_1>\) and \(|\nu_2>\):

\[
|\nu_e> = \cos \theta |\nu_1> + \sin \theta |\nu_2>
\]

\[
|\nu_a> = -\sin \theta |\nu_1> + \cos \theta |\nu_2> . \quad (2.8)
\]

A visual representation of the mixing of two-neutrino flavour and mass eigenstates is shown in Figure 2.3 [20]. Flavour eigenstates can be expressed as admixtures of mass eigenstates but so too can mass states be given as mixtures of flavour states. Here, \(|\nu_a>\) is a general non-electron flavour neutrino. This representation can be extended to the three-neutrino case with flavours \(e, \mu,\) and \(\tau\).

An important note about the portrait of the electron and non-electron neutrinos in Figure 2.3c) is that the flavour state of one contains elements of the other. That is, there is non-electron flavour appearing in the pure electron neutrino. The resolution of this paradox is that, in a given \(\nu_e\) state, the \(\nu_a\) components of the mass mixtures are equal and have opposite phases. Destructive interference cancels out the non-electron components and the electron neutrino has pure electron flavour as is expected.

During propagation, however, the phase difference changes and the complete destructive interference disappears. The time evolution of the propagating neutrino state leads to, for instance, non-electron components appearing in a neutrino that
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Figure 2.3: Representation of flavour and mass eigenstate mixing [20]. a) Flavour states $|\nu_e>$ and $|\nu_a>$ as a combination of mass states. The length of the box gives the admixture of mass states, where the sum of the boxes is normalized to 1. b) Mass states as a combination of flavour states where the electron neutrino flavour is red and the non-electron flavour is green. c) Illustration of electron and non-electron neutrinos. The two neutrino states are shown as admixtures of the eigenstates, which also show the flavour composition.

was originally pure electron flavour. In order to represent how the neutrino flavour varies with time, Eq.2.5 can be modified by introducing a time-dependent term:

$$|\nu_\alpha(t)\rangle = \sum_k U_{\alpha k} |\nu_k\rangle e^{-iE_k t},$$

(2.9)

where $E_k$ is the energy of the neutrino. Thus, the relations in Eq.2.8 can be rewritten as

$$|\nu_e\rangle = \cos \theta e^{-iE_1 t}|\nu_1\rangle + \sin \theta e^{-iE_2 t}|\nu_2\rangle$$

$$|\nu_a\rangle = -\sin \theta e^{-iE_1 t}|\nu_1\rangle + \cos \theta e^{-iE_2 t}|\nu_2\rangle.$$  

(2.10)

Eigenstates with different masses propagate with different speeds and each neutrino flavour is a mixture of the mass eigenstates. The preceding formulae show that
phase differences arise as a neutrino propagates. Therefore, the combination of mass eigenstates changes as the neutrino travels and the flavour observed at the time of detection may be different than the flavour when it was originally produced. We can use the survival probability, the likelihood of finding a neutrino in its original flavour, to understand the oscillation mechanism. Of particular interest to large-scale neutrino detectors is the survival probability $P_{ee}$ of electron neutrinos originating from the Sun after traveling a distance $L$:

$$P_{ee} = 1 - \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 L}{4E}\right),$$

(2.11)

where $\Delta m^2 = m_2^2 - m_1^2$, the difference in squared neutrino masses, $E$ is the neutrino energy, and $L = ct$ is the distance traveled between the source and where it was detected in time $t$. The frequency of the oscillating survival probability depends on the mass difference between states and the energy of the neutrino. It follows that oscillation can only occur if neutrinos are massive and there is a non-zero difference between mass eigenstates.

**Matter Oscillations**

The above discussion pertains to the oscillations of neutrinos propagating in vacuum. There is, however, an additional effect that becomes relevant when neutrinos are propagating through matter. The effect is called the MSW effect, after being first postulated by Wolfenstein [21] and shortly after by Mikheyev and Smirnov [22].

The presence of electrons in matter affects the oscillations and survival probabilities of neutrinos. Further, not all neutrino types are affected equally. Electron neutrinos interact differently than muon or tau neutrinos due to the possibility for
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charged current interactions with electrons (as in Eq.2.3). It is as if the neutrino-
matter interaction adds an "effective mass" to the mass of the electron neutrino. The
Hamiltonian now features an additional potential [23]:

\[
H_0 \rightarrow H = H_0 + V, \quad (2.12)
\]

\[
V = \frac{\sqrt{2}G_F n_e}{2}, \quad (2.13)
\]

where \(H_0\) is the Hamiltonian in vacuum, \(G_F\) is the Fermi coupling constant, and \(n_e\)
is the number density of electrons. It follows that we now have a matter-specific
mixing angle \(\theta_m\) and matter-specific eigenstates \(|\nu_{1m}\rangle\) and \(|\nu_{2m}\rangle\), which make up
the flavour states similar to the relations in Eq.2.8:

\[
|\nu_e\rangle = \cos \theta_m |\nu_{1m}\rangle + \sin \theta_m |\nu_{2m}\rangle,
\]

\[
|\nu_a\rangle = -\sin \theta_m |\nu_{1m}\rangle + \cos \theta_m |\nu_{2m}\rangle. \quad (2.14)
\]

For a full derivation of the matter oscillation phenomena the reader is referred to
[23]. The important results are highlighted here.

For neutrino interactions in matter of non-uniform density, the situation becomes
even more interesting. Such is the case for neutrinos emerging from the Sun. Electron-
flavour neutrinos are born in the core of the sun, travel through the changing densities
of the various radial regions of the sun, and exit at the outer edge. A model that
has gained wide favour and is supported by results from neutrino experiments is the
Large Mixing Angle Mikheyev-Smirnov-Wolfenstein (LMA-MSW) model [24]. Characteristic of the LMA-MSW model is that oscillations are dominated at low energies (<1MeV) by vacuum oscillations and at high energies (>5MeV) by MSW matter oscillations. Figure 2.4 shows the electron neutrino survival probability curve predicted by the LMA-MSW model along with measurements from solar neutrino experiments.

Figure 2.4: Solar electron neutrino probability measurements compared to LMA-MSW predictions (dashed line) for $^8B$ neutrinos [2].

In the LMA-MSW model, the mixing angle and mass difference, in matter, are respectively defined as [25]
\[
\sin^2 2\theta_m = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - \beta)^2}
\] (2.15)

and

\[
\Delta m^2_m = \Delta m^2 \sqrt{\sin^2 2\theta + (\cos 2\theta - \beta)^2},
\] (2.16)

where

\[
\beta = \frac{2\sqrt{2} G_F n_e E_\nu}{\Delta m^2}.
\] (2.17)

\(\beta\) is a quantity representing the ratio of matter to vacuum oscillation effects. It is a parameter relating the relative importance of the MSW term in the Hamiltonian. In cases of large neutrino energy or electron density, we have \(\beta > 1\), indicating that the MSW effect dominates the oscillation. Here, the electron flavour survival probability can be approximated as

\[
P_{ee}(\beta > 1) = \sin^2 \theta.
\] (2.18)

For \(\beta < \cos 2\theta\), the MSW effect is negligible and vacuum oscillation mechanisms dominate. The survival probability can then be approximated as

\[
P_{ee}(\beta < \cos 2\theta) = 1 - \frac{1}{2} \sin^2 2\theta.
\] (2.19)

### 2.1.3 Low Energy Solar Neutrinos

SNO+ has the opportunity to further the understanding of neutrino oscillations by focusing on \(pep\) and CNO neutrinos. During the solar phase of the experiment,
SNO+ will make flux measurements of \textit{pep} and CNO neutrinos. Studying \textit{pep} flux is interesting because, at 1.44MeV, the \textit{pep} neutrino energy falls in the transition region between vacuum and matter oscillation mechanisms (that is, $\cos 2\theta < \beta < 1$). At low neutrino energies, even within the Sun, neutrino propagation is essentially governed by vacuum oscillations. For higher energies, the MSW effect becomes dominant. As can be seen in Figure 2.4, differences in neutrino energy greatly influence the flavour survival probability. Measuring the flux of \textit{pep} neutrinos in this transition region will allow constraints to be set on models of the neutrino-matter interaction or possibly shed light on new physics if the survival probability diverges from the LMA-MSW predictions.

The measurement of CNO contributions to the solar neutrino flux is also an interesting observation SNO+ aims to make. The density of heavier elements, namely carbon, nitrogen, and oxygen, in the interior of the Sun will in part determine the number of neutrinos produced by the CNO cycle. SNO+, with its ability to measure low energy neutrinos, including CNO neutrinos (see Figure 2.2), will be able to place constraints on the heavy elemental composition of the sun and the CNO contributions to the total solar energy production.

2.2 Neutrinoless Double Beta Decay

An important question that remains in neutrino physics today is whether neutrinos are Majorana or Dirac particles. Dirac particles are familiar in that the particles are distinct from the antiparticles. Majorana particles, however, make no distinction between particles and antiparticles. They are identical except for their helicities.
A way to discern the Dirac or Majorana nature of neutrinos is through the detection of neutrinoless double beta decay, an observation that SNO+ aims to make for the first time. A typical double beta decay proceeds as in Eq.2.20; a nucleus decays by two neutrons transforming into two protons while emitting two electrons and two neutrinos simultaneously. This process has been observed in a number of isotopes.

\[
N(A, Z) \rightarrow N(A, Z - 2) + 2e^- + 2\bar{\nu}_e \quad (2.20)
\]

If neutrinos are Majorana particles, however, another option for this decay is possible where only the two electrons are emitted (Eq.2.21). Here, the anti-neutrino emitted by one of the neutrons is absorbed as a neutrino by the other.

\[
N(A, Z) \rightarrow N(A, Z - 2) + 2e^- \quad (2.21)
\]

In addition to proving that neutrinos are Majorana particles, the observation of neutrinoless double beta decay would also provide a measurement of the absolute neutrino mass. This is because the decay rate is proportional to the effective Majorana neutrino mass [26]:

\[
\langle m_\nu \rangle = \sum_k m_k U_{ak}^2, \quad (2.22)
\]

where \( m_k \) are the masses of the three neutrino mass eigenstates and \( U_{ak}^2 \) are the elements of the mixing matrix between the mass and flavour eigenstates.

A difficulty in making such a measurement is that the neutrinoless double beta decay rate is so small. Indeed, even the two-neutrino double beta decay forms a background to the measurement. As shown in Figure 2.5, the challenge is to resolve
the mono-energetic peak of the electron pairs in neutrinoless double beta decay from the continuum of electron pairs in two-neutrino double beta decay.

![Illustration of expected spectra for double beta decay in general.](image)

Figure 2.5: Illustration of expected spectra for double beta decay in general. The sum of electron kinetic energies $K_e$ has been normalized to 1 with $Q$ (the beta decay endpoint). The small neutrinoless beta decay peak at the endpoint must be distinguished from the large, continuous two-neutrino background. The plot on the top right zooms in on the endpoint, emphasizing the overlap between the two signals [26].

SNO+ plans to search for neutrinoless double beta decay using the isotope $^{130}\text{Te}$. The $Q$-value of $^{130}\text{Te}$ is 2.53 MeV and the natural abundance of $^{130}\text{Te}$ is roughly 34%. This high natural abundance allows a large amount of the isotope to be loaded into the scintillator without the complication or expense of using enriched tellurium. A
2.3. REACTOR NEUTRINOS

0.3% loading of tellurium into the 780 tonnes of liquid scintillator corresponds to approximately 800 kg of the double beta decay isotope. A simulation of the expected energy spectrum in SNO+ at the double beta decay endpoint is shown in Figure 2.6. It is apparent that two-neutrino double beta decay is the dominant source of background after other backgrounds, such as $^{214}$Bi, $^{208}$Tl, and $^{212}$Bi/$^{212}$Po, have been tagged and suppressed as efficiently as possible.

![Energy spectrum](image)

Figure 2.6: Simulated energy spectrum at the 2.54 MeV $^{130}$Te Q-value after 2 years of data taking. A 3.5 m fiducial volume cut is used and external and internal backgrounds have been identified and, where possible, removed [27].

2.3 Reactor Neutrinos

A large number of electron antineutrinos are produced from the beta decays of fission products in nuclear reactors. The number of these antineutrinos produced is
proportional to the thermal power produced by the reactor. Therefore, the neutrino flux coming into the detector can be accurately predicted. Furthermore, because the composition of the nuclear fuel is well-known, so too is the shape of the neutrino spectrum from the reactor. Thus, measurements of the neutrino flux and energy spectrum at SNO+ can be compared to those measurements at the reactors themselves. This should provide a useful means to study neutrino oscillations.

Anti-neutrinos are detected through the inverse beta reaction with free protons:

$$\bar{\nu}_e + p \rightarrow e^+ + n - 1.8 \text{ MeV}. \quad (2.23)$$

The kinetic energy of the positron is 1.8 MeV less than the energy of the incoming antineutrino, due to the required threshold of the reaction. Almost immediately after production, the positron will annihilate with a nearby electron, depositing its kinetic energy plus twice the electron rest mass. The neutron will be detected shortly thereafter. This provides a good coincidence signature for separating the signal from backgrounds.

Anti-neutrinos from the reactors will propagate and undergo what are essentially vacuum oscillations. As such, reactor neutrinos will experience the same survival probability as in Eq.2.11. The neutrino energy $E$ is well-known as is the oscillation length $L$, which is the distance between the reactor and the detector. Dominant sources for reactor anti-neutrinos in SNO+ are from nuclear generating stations in Bruce, Pickering, and Darlington, Ontario. The KamLAND liquid scintillator experiment has measured oscillation parameters with nearby reactors in Japan [28]. Due to the proximity of nuclear reactors in Ontario, SNO+ is in good position to observe any spectral distortions and measure oscillation parameters in a complimentary way.
to KamLAND.

2.4 Geoneutrinos

Anti-neutrinos are also produced via the natural beta decay of radioisotopes in Earth’s mantle and crust. These are called geoneutrinos and come mainly from $^{40}$K and the decay chains of $^{238}$U and $^{232}$Th. A measure of the flux of these geoneutrinos can give a handle on the amount of radioactivity inside the Earth. There is a connection between the geoneutrino luminosity (antineutrinos produced in the Earth per unit time) for a given element, the radiogenic heat production rate, and the mass of that given element [29]. The radiogenic contributions to heat flow from the Earth are thought to be large (60-100%) but the uncertainties are also large. A direct and precise determination of the radiogenic component of heat flow is possible with a measure of geoneutrino flux and energy.

The first instance of geoneutrino detection and their usefulness to experimental geophysics came from the first data from KamLAND in [30]. Reactor antineutrinos form a background to the geoneutrino measurement, which proved to be a problem for KamLAND. SNO+, however, will have a smaller background of reactor antineutrinos and should be able to provide new information that can add to our ability to understand the deep Earth portion of the geoneutrino flux.

2.5 Summary

SNO+ will make many important and interesting measurements during its two operating phases. During the solar phase, flux measurements of pep and CNO neutrinos
from Sun will lead to knowledge of the Sun’s chemical composition and heat production as well as place constraints on models of neutrino oscillation. During the neutrinoless double beta decay phase, SNO+ will load $^{130}$Te into the liquid scintillator to search for the rare decay in order to determine whether neutrinos are Majorana particles. Measurements of flux and energy distribution of nuclear reactor antineutrinos will also be made in order to study the oscillation mechanism. Geoneutrino measurements will help narrow down models of heat flow and radiochemical composition of the Earth.

Before SNO+ can embark on its multiple physics goals, an extensive calibration program must be carried out in order to properly understand the optical and energy response of the detector. A number of calibration systems have been developed in order to properly characterize the response of the detector PMTs. In the following chapters, the calibration systems and procedures to be used in SNO+ will be presented. The research and development work on some systems in particular will be detailed.
Chapter 3

Calibration Hardware

An extensive and elaborate calibration program has been developed in order to understand the SNO+ detector. A series of calibrations and calculations are needed to bridge the gap between the raw PMT measurements of charge and time to a complete description of the interactions with respect to energy, position, and particles involved. Multiple calibration systems will be used to tune the parameters involved in modelling the detector and determining how well the model simulations reproduce data. A combination of calibration measurements and comprehensive Monte Carlo simulations makes it possible for SNO+ to properly interpret the raw data coming in and understand the physics processes involved. This chapter will briefly present the detector parameters of interest, the various calibration systems to be used in SNO+, and the infrastructure needed to support them.

The parameters set to be measured by the calibration systems can be separated into four categories: electronics parameters, PMT parameters, optics parameters, and detector geometry parameters. Electronics parameters are verified with every calibration run and include factors such as PMT voltages, channel thresholds, and noise amplitudes. PMT parameters include cable timing delays and light collection
3.1. CALIBRATION INFRASTRUCTURE

Efficiencies, among others. Optics parameters pertain to characteristics of the liquid scintillator and acrylic vessel such as light scattering, absorption, and yield. Detector parameters are geographical position measurements of PMTs, AV, hold-down/hold-up ropes, and other pieces of infrastructure. These parameters mentioned are not exhaustive but merely illustrative of the inputs used to reproduce the detector configuration for each Monte Carlo run. A complete listing can be found in [31].

3.1 Calibration Infrastructure

Before detailing any specific radioactive sources or other calibration systems, the complementary hardware components necessary for deployment must be discussed. A number of these components have been adapted from SNO for use in liquid scintillator. These include the umbilical retrieval mechanisms, umbilicals, manipulator side ropes, source storage box, source connections device, and universal interface. Figure 3.1 contains a two-dimensional representation of the detector and calibration hardware components.

3.1.1 Source Manipulation Systems

The response of the detector is position-dependent where the analysis of PMT timing measurements for events allows for reconstruction of interactions inside the acrylic vessel. As such, manipulator systems for deploying calibration sources throughout the detector have been developed. These manipulator systems, the umbilical retrieval mechanisms (URMs) and side rope motor boxes, allow encapsulated sources to be positioned along two orthogonal planes inside the liquid scintillator with an accuracy of better than 5 cm.
Each URM includes a set of pulleys for storing and reeling out an umbilical cable and central support rope with the deployed source. The umbilicals are specially designed, submersible cables which house services for the operation of all calibration sources; these will be discussed in depth in Chapter 4. The central support rope manipulates the vertical position of the source and is made of Tensylon, a brand of
3.1. CALIBRATION INFRASTRUCTURE

ultra high molecular weight polyethylene [33]. It is intended that the umbilical cable does not take any load from the source so as to protect the internal services from breakage.

Figure 3.2 shows a cut-away diagram of the URM assembly (without the umbilical or support rope installed). The umbilical cable is stored on a set of pulleys while the rope is wrapped around a threaded cylindrical drum above the deployment port. Both the umbilical and rope are fitted with encoder wheels that measure how much length has been reeled in or out. The entire URM is sealed in order to avoid contamination of the cable and ropes with air from the deck.

![Figure 3.2: Cut-away diagram of an Umbilical Retrieval Mechanisms (URM) [34].](image)

3.1.2 Universal Interface

In addition to the central support rope in the URM, there are four more Tensylon side ropes that attach to the deployed source. They allow the source to be positioned along two orthogonal planes by varying the tensions and lengths. The four side rope
motor boxes are equipped with encoders to measure the amount of rope movement and load cells to monitor the tension. Each rope travels through a set of anchor blocks on the inner AV wall. The motor boxes are attached to a sealed universal interface (UI), which is the connection between the AV neck and the observatory deck above the vessel. It is intended to isolate the vessel and liquid scintillator from contamination from the laboratory air. Figure 3.3 shows a drawing of the UI with four attached side rope motor boxes.

Figure 3.3: Illustration of the universal interface (UI) with the four side rope motor boxes [35].

In addition to the side rope motor boxes, the UI also has four ports for connecting
3.1. CALIBRATION INFRASTRUCTURE

URMs, pipes for introducing liquid into the AV, and glove ports for handling sources [36]. A flexible membrane known as the sliding floor is installed at the lower portion of the UI to allow for movement of the AV (6” horizontally, 8” downward, and 2” upward).

3.1.3 Source Storage and Connection Device

Calibration sources that are used often are stored in a special storage box (see Figure 3.4) on the observatory deck. They can be kept in an isolated, low background environment so as to avoid any surface contamination from laboratory air. It is imperative to keep any material that enters the AV as clean as possible because any added radioactive background could be disastrous for the experiment. Gate valves and glove ports are installed on the storage box for easily transporting sources into

Figure 3.4: Schematic of the source storage box [37].
3.2. POINT SOURCES

the URMs.

A quick-connect system was also developed for easily switching between sources in the URMs [38]. The two-part system contains connections for all of the optical fibres, hook-up wires, and gas capillaries that are housed in the umbilical. One section is permanently attached to one end of the umbilical while each individual calibration source includes the other complementary part. Figure 3.5 shows images of the two-part source connection device.

![Source connection device](image)

Figure 3.5: Source connection device with both parts attached (left) and an inside view of the adaptors (right) [38].

3.2 Point Sources

Multiple radioactive sources, emitting a variety of particles at a variety of energies, are under development for use with the SNO+ liquid scintillator. Deployed optical sources are also being developed. Table 3.1 summarizes the sources that will be available for calibration.
3.2. POINT SOURCES

<table>
<thead>
<tr>
<th>Source</th>
<th>Energy (MeV)</th>
<th>Particle(s) Emitted</th>
<th>Tagged? (Yes/No)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{57}$Co</td>
<td>0.136</td>
<td>$2 \gamma$: 0.014, 0.122 MeV</td>
<td>No</td>
</tr>
<tr>
<td>$^{60}$Co</td>
<td>2.5</td>
<td>$2 \gamma$: 1.17, 1.33 MeV</td>
<td>Yes</td>
</tr>
<tr>
<td>$^{90}$Y</td>
<td>2.28</td>
<td>$\beta^-$</td>
<td>No</td>
</tr>
<tr>
<td>$^{48}$Sc</td>
<td>3.33</td>
<td>$3 \gamma$: 0.98, 1.04, 1.31 MeV</td>
<td>No</td>
</tr>
<tr>
<td>$^{24}$Na</td>
<td>4.12</td>
<td>$2 \gamma$: 1.37, 2.75 MeV</td>
<td>Yes</td>
</tr>
<tr>
<td>$^{16}$N</td>
<td>6.1</td>
<td>$\gamma$</td>
<td>Yes</td>
</tr>
<tr>
<td>$^{222}$Rn</td>
<td>5.59</td>
<td>$\alpha$</td>
<td>No (coincidence)</td>
</tr>
<tr>
<td></td>
<td>3.27</td>
<td>$\beta^-$ (from $^{214}$Bi)</td>
<td>No (coincidence)</td>
</tr>
<tr>
<td></td>
<td>7.83</td>
<td>$\alpha$ (from $^{214}$Po)</td>
<td>No (coincidence)</td>
</tr>
<tr>
<td>AmBe</td>
<td>4.4</td>
<td>$\gamma$</td>
<td>No (coincidence)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>neutron</td>
<td>No (coincidence)</td>
</tr>
<tr>
<td>Laserball</td>
<td>Various</td>
<td>$\gamma$</td>
<td>No</td>
</tr>
<tr>
<td>Cherenkov ($^6$Li)</td>
<td>$\gamma$ (UV-optical)</td>
<td>Yes</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1: Calibration sources for SNO+. The energy listed in the second column refers to total deposited energy in a single event (sum of multiple $\gamma$ particles where applicable). For $\beta$ decays, the end-point energy is given. For sources with long decay chains, those decays important for calibration purposes are listed only \[31\].

Of interest are the energy response of the PMTs and the light yield of the scintillator. Measurements will be taken at multiple energies with multiple sources. Taking data at different energies allows an energy scale to be established and any nonlinearities to be identified. Sources are chosen with emissions spanning a large range of energies, both with single particles and multiple particles summing to a given energy. A test of the energy response near the double beta decay endpoint of $^{130}$Te is particularly useful and can be achieved with the 2.75 MeV $\gamma$ from the $^{24}$Na source \[31\].

The time stability of the detector over an extended period is another important calibration check. This is done by deploying the same source repeatedly throughout
3.3. **CHERENKOV SOURCE**

The operating life of the detector. The $^{60}$Co source is chosen as a stable tool to accomplish this. Any changes in the energy response with time will signal the need for more investigation into the stability of the scintillator or other detector components.

Also included in Table 3.1 is whether each source is tagged or not. Tagging involves installing a small PMT inside the calibration source itself. Comparing the timing of the source PMT and the detector PMT array allow for clean identification of source decays. When deployed in the detector, any data collected will be a sum of the events originating from the source and background events in the detector. The tag allows unwanted background events to be cut from the data, providing a clean calibration data sample. Tagging can also be useful in understanding the tails of the energy and position distribution pulses. In some instances, namely the $^{222}$Rn and AmBe sources, coincidence analysis can be used to tag the source decays. The decay chains of these sources involve decays which proceed with very short half-lives (on the order of ns). Thus, a short timing trigger window can be set to catch two coincident decays and properly identify source-related events.

### 3.3 Cherenkov Source

One of the specialized calibration tools mentioned in Table 3.1 is the Cherenkov source. When charged particles pass through a medium at a speed greater than the speed of light in that medium, Cherenkov light is produced. Cherenkov light is emitted in a cone opening along the direction of the particle’s velocity, where the angle of the cone is related to the velocity, and therefore energy, of the particle.

In SNO, Cherenkov rings were detected in the PMTs and used to identify recoiling electrons from scattering and charged current reactions (Eqs. 2.2 and 2.3). In SNO+,
these Cherenkov events are hidden underneath the dominant isotropic scintillation light.

However, a Cherenkov source using gaseous $^8$Li has been developed for SNO+ with the ability to generate Cherenkov light without being obscured by scintillation light. The $^8$Li gas travels down an umbilical and $\beta$ decays in a thick acrylic sphere. The $\beta$ particles produce Cherenkov light while travelling through the sphere but few escape into the liquid scintillator volume. Though the Cherenkov light of individual $\beta$ particles is directional, the source emits particles isotropically (neglecting the shadowing of the mounting hardware). $^8$Li decays into $^8$Be and these daughters quickly decay further by $\alpha$ emission; these $\alpha$ particles are tagged by an internal PMT [39].

The advantage of this Cherenkov source is that the response of the PMTs can be measured independently of the scintillator properties. Because there is no direct scintillation light produced, measurements of the detector efficiency can be decoupled from the scintillator light yield [40].

### 3.4 Optical Calibration

Another specialized deployed source is the laserball. This calibration tool was also previously used in SNO and has been adapted for use in SNO+ [41]. It is used to understand the absorption and scattering of light in the three media of the detector (ie. liquid scintillator, acrylic, and H$_2$O) as well as the angular response and timing characteristics of the PMTs.

The laserball consists of a 109 mm diameter quartz flask filled with silicone gel in which 50 $\mu$m diameter air-filled hollow glass beads are uniformly suspended. Optical
3.5. CAMERAS

fibres are carried to the source via a laserball-specific umbilical cable and terminate at the centre of the quartz flask such that refractions and reflections inside the sphere result in a quasi-isotropic light distribution. The light is made more isotropic for SNO+ by minimizing the shadowing caused by the mounting hardware [42]. A laser system on the deck injects light into the optical fibres at wavelengths ranging from 380 m to 490 nm.

Optical calibration is also accomplished in SNO+ by a set of permanently installed light injection fibres outside the AV. The External LED/Laser Light Injection Entity (ELLIE) system is an array of directional light emitting quartz fibres mounted on the PMT support structure (PSUP) [43].

The emission light can be wide-angle to measure attenuation or collimated to investigate scattering. An example of chosen collimated beam positions at different angles and path lengths is shown in Figure 3.6. Different angles and path lengths can be chosen to measure refractions and reflections at the interfaces between the scintillator, AV, and H$_2$O. Like the laserball, the LEDs and laser systems are housed on the deck and the fibres extend to their positions on the PSUP. Advantages of these external light injection systems are that they pose no risk to contaminating the detector (as deployed sources inside the vessel do) and that they can be used in-situ throughout the data-taking period of the experiment.

3.5 Cameras

An important tool for measuring detector geometry parameters is a set of cameras symmetrically mounted in six positions on the PSUP. These cameras will take photographs throughout the running phase to monitor the hold-down ropes and any
3.6 Internal Sources

Even with very efficient purification and cleaning methods, some amounts of backgrounds are intrinsic and unavoidable in a large-scale liquid scintillator detector. However, it is possible to use the inevitable backgrounds as an advantage to the calibration of the detector. An understanding of the backgrounds present and their sources can provide information on parameters such as energy scale, timing response, and alpha-beta coincidence tagging. The analysis of physics data also benefits from

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Figure 3.6: Collimated ELLIE beam positions across the detector. Relative path lengths are indicated by the beam colour where red is the longest and blue is the shortest. The fibres are mounted on the PMT support structure which sits 2 m outside the AV radius [44].
3.6. INTERNAL SOURCES

Figure 3.7: Camera system for SNO+. On the left is a photo of one of the cameras mounted on the PSUP in a sealed steel enclosure with an acrylic dome. On the right is a schematic diagram of the camera positions on the PSUP [45].

a thorough identification of backgrounds because they can be removed in favour of the physics interactions of interest.

The decay chains of $^{238}$U and $^{232}$Th (see Figure 3.8 on page 39) are a large source of background due to their high concentrations in mine dust. Any kind of detector operation, be it maintenance, scintillator refilling, or deployment of calibration sources, may expose the liquid scintillator to contamination of these chains. Likewise goes for $^{222}$Rn, which is present in relatively significant concentrations in mine air and can plate out onto objects in the laboratory.

These chains both contain short-lived sequences, namely $^{214}$Bi-Po and $^{212}$Bi-Po, where a $\beta$ particle is emitted and quickly followed by an $\alpha$. Using appropriately sized timing trigger windows, these decays can be detected in coincidence, allowing estimates to be made of $^{238}$U and $^{232}$Th concentrations and tests of event position.
3.7. SUMMARY

reconstruction. The long-lived $^{210}$Pb daughters also provide a stable $\alpha$ peak which can be used for energy scale calibration and quenching characterization.

Electron-capture decays from residual $^{40}$K concentrations result in 1.5 MeV $\gamma$ particles, which can provide a test of low-energy nonlinearities in the detector response. Finally, the $\beta$ spectrum of $^{14}$C ($Q_\beta = 156$ keV) may be fitted to investigate low-energy light yield.

3.7 Summary

This chapter has detailed the extensive series of calibrations planned for SNO+. These many calibration systems are necessary tools for understanding the response of the detector and being able to properly identify the interactions that take place. Radioactive sources are deployed at various positions inside the detector to measure parameters associated with energy response, optical properties of the scintillator, and the exact positions of hardware components. Redundancy is essential to these measurements as multiple tools are used to verify that values are accurate. Cameras and optical fibres are mounted externally on the PMT support structure to provide continuous in-situ calibration checks while the detector is taking data. The following two chapters will discuss in detail the development of calibration hardware components for SNO+: umbilical cables, providing connections to deployed sources, are covered in Chapter 4 and one of these sources, utilizing the decays of $^{222}$Rn, is examined in Chapter 5.
Figure 3.8: $^{238}$U and $^{232}$Th decay chains. Energies listed are in MeV [46].
The optical and energy responses of the SNO+ detector will be measured in situ using the various calibration devices mentioned in the previous chapter. Those calibration devices deployed internally must be connected to the observatory deck above the acrylic vessel by gas capillaries, optical fibres, and signal wires which are encased in specially designed submersible umbilical cables. Specific calibration systems will have their own dedicated umbilicals housing special services (optical fibres with the laser-ball, for example) while most sources will be deployed with a single, basic umbilical design.

Umbilicals were also designed for use in SNO [32]. However, the change to liquid scintillator in SNO+ forced the collaboration to reevaluate the materials chosen and develop new procedures for fabricating the umbilicals. This chapter describes the details of the design and fabrication of the umbilicals for all SNO+ calibration sources.

4.1 Design Requirements

Design requirements for the umbilicals include:
4.1. DESIGN REQUIREMENTS

- Radioactive cleanliness: in order for safe deployment in SNO+, umbilicals must not introduce any significant $^{222}$Rn contamination into the detector (an umbilical $^{222}$Rn emanation level of 10 atoms/day/m$^2$ would result in a rate of at least 0.0015 atoms/day of $^{210}$Pb in the detector)

- Compatibility with linear alkylbenzene to not compromise the scintillator

- Impermeability to liquid scintillator to protect the cable components and sources themselves

- Length of at least 25m in order to reach the furthest available positions inside the acrylic vessel

- Robust enough so no significant strain develops during deployment

- Flexibility and small bending radius for use with the source manipulation system

Components were chosen for the umbilical to be as compact as possible in order to comply with the size constraints imposed by the pulley system of the Umbilical Retrieval Modules (URMs) [34]. The umbilicals are also designed in order to accommodate the needs of each source in terms of high voltage power, fibre optic connections, gas flow, and signal transmission.

A cross-section of the design for the laserball umbilical is shown in Figure 4.1 and a short length of an umbilical is pictured in Figure 4.2. The cable consists of a 25 m long polyurethane tube with an outer diameter (OD) of 1/2” (12.7mm) encapsulating a 1/4” (6.35mm) OD tube of polyethylene. This inner polyethylene tube is helically wrapped with four thin, Teflon-insulated hook-up wires and a single, thin coaxial cable. The four wires and coaxial cable ensure the polyethylene sits in the centre
4.1. DESIGN REQUIREMENTS

Figure 4.1: Cross-sectional view of the laserball umbilical.

of the umbilical. The helical wrapping allows longitudinal tensile and compressive forces to be dissipated locally as the umbilical is deployed over the pulleys of the URM. Further, the centring of the polyethylene and helical wrapping also reduce the minimum bending radius of the umbilical, ensuring it can be easily stored on and deployed with the 205mm diameter pulleys.

Finally, the space between the central polyethylene and outer polyurethane jacket is filled with a two-part potting compound in order to mechanically support the umbilical by protecting the inner components from radial (crushing) and longitudinal (stretching) forces. The umbilical is not intended to support the weight of the deployed calibration sources; however, were the side ropes to fail during a deployment,
the umbilical should be strong enough to independently retrieve any source which is attached to it.

![Image](image108x469to540x619)

Figure 4.2: Close-up section of 1/2” (12.7 mm) OD umbilical. The thin coaxial cable and hook-up wires have been helically wrapped around the central polyethylene tube.

An addition to this basic design for the laserball-specific umbilical is to feed a set of optical fibres, housed in a small Teflon tube, into the central chamber inside the polyethylene. Multiple fibres are used for redundancy in case of breakage and to preserve light intensity as laser light is injected into the laserball through the umbilical. These fibres are kept loose inside the Teflon, allowing them to move freely and avoid taking any load relative to the movement of the umbilical.

For sources involving gaseous radionuclides (namely $^8$Li and $^{16}$N), the fibre bundle is replaced by a set of gas capillaries. Concentric flow and return lines are in place for the gas to flow to the source and decay before retreating back through the umbilical.

### 4.1.1 Materials Selection

The umbilicals that were previously employed in the SNO experiment were found to be incompatible with the SNO+ liquid scintillator. As such, new materials needed
to be chosen that would not break down from exposure to LAB or compromise the scintillator [47]. This section describes the materials chosen for the SNO+ umbilicals and compares them to the SNO umbilical components.

**Tubing**

Tygothane polyurethane tubing is used for the outer jacket of the umbilical. It is resistant to abrasion and highly impermeable, making Tygothane a suitable choice for housing the inner umbilical components without risk of damage. It is important to note that Tygothane is an ester-based polyurethane and may degrade when exposed to water. As such, the umbilicals developed here will be deployed only in the liquid-scintillator phase of SNO+.

<table>
<thead>
<tr>
<th>Tygothane (SNO+)</th>
<th>Polyurethane Tubing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Compatible with LAB</td>
</tr>
<tr>
<td></td>
<td>Translucent,</td>
</tr>
<tr>
<td></td>
<td>Hard: 82 Durometer (Shore A),</td>
</tr>
<tr>
<td></td>
<td>ID: 3/8” (9.525 mm), OD: 1/2” (12.7 mm).</td>
</tr>
<tr>
<td></td>
<td>McMaster-Carr part #: 5549K36</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Silicone (SNO)</th>
<th>Silicone Rubber Tubing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NOT Compatible with LAB</td>
</tr>
<tr>
<td></td>
<td>Translucent</td>
</tr>
<tr>
<td></td>
<td>Medium hard: 50 Durometer (Shore A),</td>
</tr>
<tr>
<td></td>
<td>ID: 3/8” (9.525 mm), OD: 1/2” (12.7 mm).</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LDPE (SNO+)</th>
<th>Low Density Polyethylene Tubing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Compatible with LAB</td>
</tr>
<tr>
<td></td>
<td>Multiple colours,</td>
</tr>
<tr>
<td></td>
<td>Medium hard: 50 Durometer (Shore A),</td>
</tr>
<tr>
<td></td>
<td>ID: 0.17” (4.318 mm), OD: 1/4” (6.35).</td>
</tr>
<tr>
<td></td>
<td>Maximum 200 psi (1.379 MPa),</td>
</tr>
<tr>
<td></td>
<td>Bending radius 1.25” (31.75 mm)</td>
</tr>
<tr>
<td></td>
<td>McMaster-Carr part #: 5384K53</td>
</tr>
</tbody>
</table>

Table 4.1: Tubing used for the SNO+ and SNO umbilicals.
Low density polyethylene (LDPE) is used for the smaller, central tube. It is flexible enough to fit the bending radius of the URM pulleys but still provides adequate support to the external helically wrapped wires and internal optical fibres. While polyethylene is compatible with LAB, compatibility is not a necessary requirement because the inner umbilical components should ideally never come in contact with the liquid scintillator.

Table 4.1 contains specifications for the SNO+ umbilical tubing. The table also contains SNO tubing details for comparison. Of note is that Tygothane is significantly harder than silicone. Because of this difference, the fabrication procedure developed for the SNO silicone umbilical was not possible with Tygothane. This will be described in section 4.2. Tygothane outer jackets of 5/8” (15.875 mm) OD were also tested as they still comply with the maximum cable diameter on the URM pulleys [34]. McMaster-Carr was the supplier for all umbilical tubing.

**Electical Wiring**

<table>
<thead>
<tr>
<th>Coaxial Cable</th>
<th>30AWG (stranded 7x38AWG) conductor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Impedance: 50 Ω</td>
</tr>
<tr>
<td></td>
<td>Maximum operating voltage: 750 V RMS</td>
</tr>
<tr>
<td></td>
<td>Overall nominal diameter: 1.803 mm</td>
</tr>
<tr>
<td></td>
<td>Nominal diameter without Teflon jacket: 0.965 mm</td>
</tr>
<tr>
<td></td>
<td>Belden part #: 83265 [48]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Hook-up Wires</th>
<th>16AWG (stranded 19x36AWG)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Impedance: 23.9 Ω</td>
</tr>
<tr>
<td></td>
<td>Maximum operating voltage: 600 V RMS</td>
</tr>
<tr>
<td></td>
<td>Overall nominal diameter: 1.143 mm</td>
</tr>
<tr>
<td></td>
<td>Multiple colours</td>
</tr>
<tr>
<td></td>
<td>Pro-Power part #: PPWN2419 [49]</td>
</tr>
</tbody>
</table>

Table 4.2: Wiring used for the SNO+ umbilicals.
The electrical wiring chosen for the umbilicals were to be as thin as possible while adequately meeting the voltage and current requirements of various calibration sources [50]. It was imperative to keep the working outer diameter of the LDPE tube and helically wrapped wires as small as possible in order to achieve successful insertion into the full 25 m Tygothane jacket. Stranded wires were chosen for all electrical components because they are more flexible and resistant to damage than solid-core wires. Teflon insulated hook-up wires were chosen because they tend to be thinner than wires insulated by other plastic products. Detailed specifications of the umbilical wiring components are found in Table 4.2.

Figure 4.3: Wire-stripping device. The coaxial cable is run through the small hole where a razor blade is positioned to cut the outer jacket without damaging the cable itself.

To minimize the nominal outer diameter of the coaxial cables, the outer Teflon jacket was removed using a custom wire-stripping device (shown in Figure 4.3). The cable is run through a small hole where a razor blade has been positioned to cut and
remove the outer jacket without damaging the cable itself. This decreased the cable diameter by roughly 50%. Once the jacket is removed, the cable is respooled and ready for the fabrication process in section 4.2.

All wiring components were acquired from Newark element14 electronics supply.

**Potting Compound**

The silicone rubber product used to pot the SNO umbilicals was no longer available but a similar alternative was chosen. Clear Flex 50, a two-part clear urethane liquid rubber compound, was selected for the SNO+ umbilicals. Mixing guns that satisfy the volume and flow requirements to pot full 25 m cables were not commercially available so a custom injection system was developed (this will be discussed in section 4.2). Properties of both SNO+ and SNO potting materials can be found in Table 4.3.

<table>
<thead>
<tr>
<th>Clear Flex 50 (SNO+)</th>
<th>Water Clear Urethane Rubber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear, colourless, A+B fluids in 1:2 mixture by weight, Pot life: 25 minutes; Cure time: 16 hours, Shore A hardness: 50A, Index of refraction: 1.48649, Specific gravity: 1.04. [51]</td>
<td></td>
</tr>
</tbody>
</table>


Table 4.3: Potting material for the SNO+ umbilicals. All values quoted at 25°C.

**4.2 Fabrication Procedure**

A three-phase fabrication procedure was developed and is presented in this section.
4.2. FABRICATION PROCEDURE

4.2.1 Inner Umbilical Wrapping

![Cable-wrapping device.](image)

The first step in the fabrication procedure is to helically wrap the coaxial cable (with its Teflon jacket removed) and four hook-up wires around the polyethylene tube. After the coaxial cable is prepared, it and the other spools of hook-up wires are loaded onto the mounting plate of the cable wrapping device shown in Figure 4.4. The wires are threaded through a small guiding plate in order to unwind smoothly and avoid tangling with each other. The LDPE tubing is fed through a central tube in the wrapping jig while the wires are taped in a helical pattern as the spool mounting plate rotates around the polyethylene.
4.2. FABRICATION PROCEDURE

Coils of the helix are evenly spaced every 2" and firmly secured to the polyethylene with pieces of tape. Clear packing tape was used because it is thin, smooth, and adheres well to the LDPE. Other types of tape were tested and failed to properly secure the wires during insertion into the Tygothane outer jacket. It was found that coiling the wires any closer together than every 2" would lead to problems with the wires binding in the second phase of the fabrication procedure. Similar problems occurred for spacings larger than 2" where the wires would detach and bunch inside the Tygothane. Both cases result in failure to insert the full polyethylene tube into the Tygothane.

4.2.2 Insertion Into Outer Jacket

Figure 4.5: Single-weave cable pulling grip from McMaster-Carr (part #: 7283K1). It is modified by milling down the metal bracket adjacent to the cable loop and fastening the end cables together to minimize its radius.

Once the coaxial cable and hook-up wires are secured to the polyethylene, the umbilical is ready for the second step of the fabrication procedure. This stage takes place in a long, straight hallway where the umbilical can be fully extended. Heavy rope is fed through the Tygothane and tightly fastened at one end of the hallway. The opposite end is attached to the cable pulling grip pictured in Figure 4.5. The cable puller must be modified by milling down the metal bracket directly adjacent to the
cable loop in order to minimize its radius and reduce friction inside the Tygothane jacket. For similar reasons, the wires beside the metal bracket must be stripped of their insulation and fastened together to a minimal size. It is important to minimize the friction with the inner Tygothane jacket to prevent the LDPE from tearing during insertion.

The mesh end of the cable pulling grip is attached to roughly 6” of unwrapped polyethylene at the end and tension is placed on the rope. With the rope and LDPE held taut, the outer Tygothane tubing must be pushed over the cable puller while the polyethylene is fed into the Tygothane. Attempting to pull the Tygothane over the inner umbilical will result in failure as pulling will cause the Tygothanes diameter to contract as it stretches, leading to increased friction between it and the inner umbilical.

The quality of wrapping around the polyethylene and care taken in pushing the Tygothane over the cable puller are important to the success of this fabrication procedure. If the wrapping has been done loosely or unevenly the wires and tape will bundle inside the Tygothane, creating insurmountable amounts of friction and ultimately resulting in tearing of the LDPE. Once this process is successful, however, the umbilical is ready for potting.

4.2.3 Potting Method

The space between the polyethylene and Tygothane tubes is filled with Clear Flex 50 urethane rubber to increase the mechanical stability of the cable and protect the inner components while running over the drive pulleys of the URM. There are no mixing guns commercially available that can adequately hold or flow the volume of
potting material needed to fill the umbilicals. As such, a custom injection system was
developed.

![Diagram of the custom acrylic piston.](image)

The piston was fabricated out of clear acrylic because the material is easily ma-
chined and bonded together. Its transparency allows the user to observe the position
and movement of the piston head as well as ensure no internal leaks are present dur-
ing operation. A schematic diagram of the piston design is shown in Figure 4.6. The
main components of the piston were machined from clear acrylic except for the two
steel pipe fittings on top (used to supply pressure on either side of the piston head),
the stainless steel nozzle on the injection end, and the Delrin plastic piston head. An
aluminum rod is also present on the rear end of the piston to inhibit the head from
binding on the sides of the chamber. The acrylic fittings and flanges were annealed
before bonding in order to increase their durability and prevent fracture while under
pressure. Photos of the fabricated piston can be seen in Figure 4.7.

As a safety precaution, water was chosen as the driving pressure source in the
piston. Water has a much lower compressibility than any gas and, in the event of
a fracture in the acrylic while under pressure, there is a smaller chance of injury
resulting from the violent expansion as the pressurized fluid is released.
Only the area between the LDPE and Tygothane are filled with the potting material. The central area inside the polyethylene must be kept clear for the insertion of optical fibres or gas capillaries after the potting procedure. T-joints are used on both ends of the umbilical in order to isolate the medial area between the two tubes (see Figure 4.8). One end of the T-joint is connected to the nozzle of the injection piston while the other T-joint end is fastened to a vacuum roughing pump. The vacuum pump is necessary to degas the Clear Flex 50 and also help flow the potting material through the umbilical.

It was found that water pressure of 80 psi was sufficient in being able to flow the urethane rubber potting material through a full 25 m length of 5/8” (15.875 mm) OD
4.3 Summary

In this chapter, details of the material choices, design, and fabrication procedures for the SNO+ umbilicals were presented. The umbilicals facilitate connections between deployed calibration sources and the observatory deck above the acrylic vessel. Liquid scintillator-compatible materials were chosen for SNO+ and a novel manufacturing technique was developed including the design and construction of a custom wrapping device and injection system. The umbilical cables are flexible, robust, and versatile; the basic umbilical design is easily modified to provide the necessary facilities for all SNO+ calibrations devices. These LAB-compatible umbilicals will be used with the umbilical in the 25 minute working life of Clear Flex 50. Difficulties were encountered in filling 1/2” (12.7 mm) OD umbilicals as roughly only 16m were fully potted while the remaining length suffered from air bubbles which could compromise the characteristics of the potting material or cause buoyancy problems during deployment. Alternative potting materials with longer working lives are being considered at this time.
multiple calibration systems deployed in the detector to characterize the optical and energy responses of the SNO+ PMT array.
Chapter 5

Radon Calibration Source

A number of deployed radioactive sources are under development for the calibration of SNO+ (a list is given in Table 3.1 on page 32). Some of those listed were previously used in SNO and are being adapted for use in liquid scintillator while others are newly developed for SNO+. One of the new sources being produced involves the use of $^{222}\text{Rn}$ to study multiple calibration parameters. This chapter will discuss the research and design work on a radon source for SNO+.

$^{222}\text{Rn}$ has a half-life of 3.82 days, which is long enough for the source to be used for multiple days but will decay quickly enough that the risk of long-term contamination is low, were the source to leak into the liquid scintillator. The basic design of the source consists of a sealed spherical quartz flask filled with a solution of LAB, with PPO fluor added at a concentration of 2 g/L, identical to the liquid scintillator in the acrylic vessel. The source solution will be spiked by bubbling gaseous radon through the scintillator. No electrical services from the deck for an internal PMT or other components will be necessary.

Of particular importance are the short-lived bismuth and polonium daughters in the middle of the chain. The dominant decay branch of $^{214}\text{Bi}$ involves a $\beta^-$ decay
\( Q_\beta = 3.27 \text{ MeV} \) to \(^{214}\text{Po}\), which has a short half-life of 164 \( \mu \text{s} \) and decays via emission of a 7.69 MeV \( \alpha \) particle. Figure 5.1 reproduces the \(^{222}\text{Rn}\) chain and highlights the important \(^{214}\text{Bi}-\text{Po}\) coincidence.

![Diagram of decay chain](image)

Figure 5.1: \(^{238}\text{U}\) decay chain, highlighting \(^{222}\text{Rn}\) and the \(^{214}\text{Bi}-\text{Po}\) coincidence. Energies (Q-value) listed are in MeV \([46]\).

Analysis of data from this decay sequence will help to optimize the pulse shape discrimination used to distinguish between particles of different types. This discrimination tool hinges on the analysis of timing profiles and the rate of de-excitation of the scintillator following a particle interaction. A timing profile is a measure of
scintillation light intensity from a single event as a function of time. The shape of
the timing profile is related to the ionization density of a charged particle travelling
through the scintillator. Signals due to heavily ionizing particles, such as alpha par-
ticles, decay slower than those produced by relativistic electrons. It follows that the
relative amount of light in the tail of pulses from alpha particles is greater than the
tail fraction of beta pulses. The differences in the shape of scintillation waveforms
can be used to discriminate between alpha and beta particles.

The timing profiles of alpha particles and electrons are shown in Figure 5.2. Mea-
measurements were taken using oxygenated and deoxygenated solutions of LAB and 2
g/L PPO [52]. The difference in pulse shape between alphas and electrons is appar-
ent in both samples as the alpha curves fall off more slowly. These differences are
enhanced in the deoxygenated scintillator where the quenching is reduced and, thus,
the longer-lived alpha processes are more easily identified.

The discrimination between alphas and electrons is even more apparent when
comparing peak-to-total ratios of their respective timing profiles. Figure 5.3 shows the
ratios for the same samples of oxygenated and deoxygenated scintillator. The peak-
to-total ratio is calculated as the integral of the peak region in the timing distribution
divided by the total integral.

In oxygenated LAB, approximately 99% of the alphas can be identified and re-
jected while retaining >99% of the electrons. In deoxygenated LAB, the discrimina-
tion is even more efficient where >99.9% of alphas can be rejected while retaining
>99.9% of the electrons. It is clear that the liquid scintillator should be kept as free
of oxygen as possible in order to optimize the study and execution of pulse shape
discrimination. This applies to both the scintillator in the whole detector and the
Figure 5.2: Timing profiles for alpha particles and electrons in oxygenated and deoxygenated samples of LAB + 2 g/L PPO. The peaks have been normalized in order to easily compare the relative tail fractions [52].

If the scintillator in the radon source is kept sufficiently oxygen free, it may be possible to use the radon source to calibrate the energy scale of the detector. Alpha peaks in the radon decay chain would be used but the presence of oxygen in the scintillator is associated with potentially problematic quenching effects. Heavy charged
Figure 5.3: Peak-to-total distributions for excitations due to alpha particles and electrons in oxygenated and deoxygenated samples of LAB + 2 g/L PPO [52].

Particles like alphas are densely ionizing and not all of the energy deposited is directly converted into light. For alphas in organic scintillators, the light output is roughly only 10% of that for electrons at the same energy. An alpha particle of 5 MeV will appear to have an energy of 500 keV, though the response tends to also be non-linear. In order to properly measure alpha particle energies, the oxygen in the scintillator must be kept to a minimum [53].

In particular, the 5.30 MeV alpha emission of $^{210}$Po is of interest. This alpha peak is important for understanding the concentrations of $^{210}$Pb and $^{210}$Bi, which are troublesome background sources that obfuscate the CNO neutrino flux measurement.
These backgrounds can be present in the detector due to intrinsic $^{238}\text{U}$ contamination, leaching of $^{210}\text{Pb}$ from the AV surface, or the ingress of $^{222}\text{Rn}$ during interactions with the scintillator. The last of these sources could be the most problematic, which is why exposure of the scintillator to air, where radon concentrations are high, should be minimized [54].

The anticipated amount of $^{210}\text{Po}$ is low and desired to be so low that extraction of its alpha peak, even with precise energy calibration, will likely be difficult. Extrapolating the alpha measurement to an estimate of $^{210}\text{Bi}$ and $^{210}\text{Pb}$ is also troublesome because there is no guarantee of secular equilibrium. $^{210}\text{Pb}$, with its 22.3 year half-life, is likely out of equilibrium with everything above it in the chain but should be in equilibrium with its $^{210}\text{Bi}$ daughter, which has a half-life of 5.01 days. The equilibrium may be broken again at $^{210}\text{Po}$, which has a half-life of 138 days. An analysis of any changes in the $^{210}\text{Po}$ decay rate over time should allow constraints to be set on the $^{210}\text{Bi}$ decay rate.

A further application for a radon source is to test the detector’s ability for accurate position reconstruction. The source may be deployed in various positions throughout the acrylic vessel and the analysis of PMT timing data will be cross checked with measurements from the side rope encoders and photographs from the camera system mounted on the PMT support structure.

To summarize, calibration measurements with the radon source will help to understand the response of the detector to different particles. In particular, an analysis of timing profile data from coincident $^{214}\text{Bi}$-Po decays will illustrate how the detector responds differently to beta and alpha particles. This understanding, coupled with
5.1. DESIGN

an appropriately sized trigger window, will allow these decays to be efficiently identified and, if desired, removed as a background from the detector operation data. The source will also produce alpha particles of known energies from the $^{222}$Rn decay chain. These alpha peaks may be used to understand the energy response of the detector. Finally, data from the placement of the source at various positions in the AV can test the position reconstruction of the detector.

5.1 Design

The basic design of the radon source consists of a spherical quartz flask, filled with radon-spiked scintillator, which is secured by stainless steel clamping hardware. Figure 5.4 contains a two-dimensional schematic of the source components and Figure 5.5 shows a three-dimensional rendering of the design. The spherical quartz flask has an outer radius of 54.5 mm, a wall thickness of 3 mm, and holds a scintillator volume of roughly 572 mL, not including the neck. The scintillator for the source will be taken from a sample port on the LAB process systems. Fused quartz is chosen for its good optical transmission properties when compared to borosilicate glass. The neck of the flask extends roughly 50 mm and a 5 mm wide lip is placed about two-thirds the distance up the neck. SCP Science, located in Baie D’Urfé, Québec, has been identified as a possible manufacturer for a quartz flask of these specifications.

After filling the volume with spiked scintillator, the flask is flame sealed at the top of the neck to minimize the possibility of any leaks which would contaminate the detector. Sealing quartz presents a challenge because the softening temperature of quartz is over 1600°C, nearly twice that of borosilicate glass. For this reason, it may be advantageous to produce the flask with only the spherical portion made of fused
Figure 5.4: Two-dimensional representation of radon source design. Length dimensions are given in mm. The height of the rod (shown in purple) is set in order to minimize shadowing from the adaptor to the source connection device.
Figure 5.5: Coloured three-dimensional rendering of the radon source design. One side of the clamp is left out to display the inner dimensions of the neck and clamp assembly. The sphere and neck are made of quartz while all other components are made of stainless steel.

quartz.

The lip on the neck gives a place for the stainless steel hardware to clamp on to, affixing the quartz flask to the source connection device and manipulator system. Two identical brackets (shown in red in Figures 5.4 and 5.5) clamp around the neck
and the lip contacts an internal ledge and the internal bracket surface. A central cylindrical adaptor (shown in green) is positioned between the two brackets, securing them together with screws. An O-ring groove is in place at the bottom of the brackets where a Teflon O-ring will provide a compressive seal for further securing the neck as well as preventing contamination if a leak appeared in the flame seal.

Extending from the top of that central cylindrical piece is a rod (shown in purple) which screws into a 2.5” NPT adaptor (shown in light blue). This adaptor couples into the source connection device discussed in section 3.1.3. The length of the rod is such that the light shadowing from the NPT adaptor is minimized. This can be seen in Figure 5.4 where the 24° shadowing angle is determined by the bottom edge of the clamp.

### 5.2 Monte Carlo Studies

A set of simulations were made to investigate the expected response of the detector with the deployed radon source. The Monte Carlo package used was RAT, which stands for Reactor Analysis Tools. This abbreviation is a misnomer as the package is not limited to only reactor experiments. RAT is written in C++ and utilizes libraries and tools such as GEANT4[55] and GLG4sim[56].

RAT includes the geometry of the entire SNO+ detector as well as any deployed calibration sources. The package simulates physics processes including the energy loss of the primary particle, the production and tracking of secondary particles and optical photons, the PMT response, the detector electronics response, event triggering, and event reconstruction. Events are generated from input files which contain the necessary parameters for simulating decay events in the SNO+ detector. The
5.2. MONTE CARLO STUDIES

Event producer sets the total number of events to generate, decay particle type, decay energy, position, and decay rate. Processors then handle the simulated interactions as real events would be in the detector where timings, energies, and reconstructed positions are measured and stored.

RAT has problems processing decay chains with many daughters and long half-lives, such as in the $^{222}$Rn chain. These problems were remedied by simulating each step in the decay chain individually and later summing up their contributions. The decay of $^{214}$Bi and its daughters were, however, able to be accurately simulated together. This includes the coincidence with $^{214}$Po as well as the alpha decay to $^{210}$Tl, which has a branching fraction of only 0.021%.

The geometry of the radon source was modelled using GEANT4 tools and is pictured in Figure 5.6. A similar GEANT4-based model of the entire detector geometry is also in place in RAT. For these studies, the centre of the quartz sphere of the source was placed at the centre of the acrylic vessel.

The resulting spectrum from the simulation of the radon chain is displayed in Figure 5.7. The output analysis was carried out using ROOT, a data analysis framework developed by CERN [57]. 100000 total events were simulated across each step of the $^{222}$Rn decay chain though not all of these are present in the output files due to some events not meeting trigger criteria in RAT and others being rejected with a 3.5 m radius fiducial volume cut.

The dominant features of the spectrum come from the initial decay of $^{222}$Rn and the $^{214}$Bi-Po coincidence. Two large peaks are visible: the lower energy peak is the 5.49 MeV alpha particle from $^{222}$Rn while the higher energy peak is the 7.69 MeV alpha from $^{214}$Po. There is also a 6.00 MeV alpha from $^{218}$Po but this energy is close
enough that it cannot be distinguished from the $^{222}$Rn alpha. This peak appears wider than if it were just a single alpha at 5.49 MeV. The remaining feature is the smeared out beta spectrum and various associated gammas from the decay of $^{214}$Bi ($Q_\beta = 3.27$ MeV).

This simulation data shows that the radon source can be a valuable calibration tool for SNO+. Both beta and alpha particles have been detected and the coincident decays of $^{214}$Bi and $^{214}$Po can be identified. Alpha peaks from $^{222}$Rn/$^{218}$Po and $^{214}$Po...
5.3 SCINTILLATOR SPIKING METHOD

Figure 5.7: Simulated energy spectrum of the radon source. A fiducial volume cut with a radius of 3.5 m was used.

are clearly visible and can be used for calibrating the energy scale and response of the detector.

5.3 Scintillator Spiking Method

A number of procedures were considered for dissolving gaseous radon into a sample of scintillator for the source volume. The Borexino experiment used a method, for its 222Rn source, that trapped radon from the underground laboratory air with a cooled carbon absorbent and then transferred the concentrated radon into the scintillator liquid [58]. Methods like this offer the advantage of not needing to make special
precautions for the use of long-lived radium isotopes to produce the radon ($^{222}$Rn is the daughter of $^{226}$Ra).

The use of radium isotope is still a viable option for spiking the scintillator with radon. A simple spiking system has been designed with a stable radium source to investigate the possibility of dissolving gas into scintillator without the need for a separate system to trap and concentrate radon.

The system (pictured in Figure 5.8) utilizes a Pylon RN-1025 flow-through source, which contains a dry $^{226}$Ra source and consistently emanates $^{222}$Rn gas [59]. The output of the Pylon source is connected to a spigot submerged in a 200 mL sample of LAB where incoming radon gas can bubble through. An outgoing line from the scintillator sample loops back into the inlet of the Pylon source. A column of Drierite desiccant is positioned at the inlet to prevent any LAB vapour from flowing into the source [60]. Flow was circulated through the source and scintillator sample with a Masterflex L/S Digital Economy Drive peristaltic pump at a rate of about 0.1 mL/min [61]. For these tests, the 200 mL sample was exposed to this circulation system for 45 minutes.

In order for the calibration source to act as much like real radon events in SNO+, the scintillator in the source must be as similar to the detector scintillator as possible. The source sample will be taken from a sample port in the scintillator process system, the same system used to fill and purify the detector. The goal is to avoid contaminants like oxygen from dissolving into the scintillator. This is accomplished by evacuating and sealing the flask with a vacuum pump. Pure scintillator can then be sucked into the flask and connected to the radon spike system. It may also be possible to trap the gaseous radon in the flask first and then draw scintillator in, as was done in the
5.3. SCINTILLATOR SPIKING METHOD

Borexino experiment [62]. For the purposes of the spike test described above, such a vacuum system was not used and the sample was exposed to laboratory air.

Following a 45 minute exposure to the radon system pictured above, the 200 mL vial of scintillator was put in a dark room to be counted with a 5 cm-diameter Hamamatsu PMT operated at a voltage of 1.4 kV (shown in Figure 5.9). The PMT had been calibrated with the 661 keV $\gamma$ line from $^{137}$Cs. The resulting spectrum from the radon-spiked scintillator is shown in Figure 5.10. The main feature in the graph consists of the broad $^{222}$Rn and $^{218}$Po alpha peaks, which appear at a lower value than predicted in the simulated radon spectrum seen in Figure 5.7. Alpha quenching due to oxygen exposure is evident as the alpha peaks have been pushed to a lower energy value than expected. The resolution is poor as the alpha peaks have been smeared together. This result shows that, in order to avoid these quenching problems, it is
imperative to keep the liquid scintillator as free of oxygen as possible while being sampled from the scintillator process systems and spiked with radon.

Figure 5.9: 5 cm-diameter Hamamatsu PMT with a 200 mL sample of scintillator spiked with $^{222}$Rn.

5.4 Summary

The development work on a $^{222}$Rn source for SNO+ has been presented here. A radon source could be a useful tool for calibrating the pulse shape discrimination, energy scale, and position reconstruction of the detector. The fundamental design of the source involves a spherical quartz flask which has been filled with $^{222}$Rn-spiked
5.4. SUMMARY

Figure 5.10: Spectrum of $^{222}$Rn-spiked LAB + 2g/L PPO (blue). The sample was counted for 24 hours. The counting setup was calibrated with the Compton edge from the $^{137}$Cs 661 keV $\gamma$ (green).

scintillator. Precautions have been incorporated into the design to ensure that the flask is properly sealed, a safeguard against possible detector contamination, and that the mounting hardware can securely couple the flask to the source manipulator systems with minimal shadowing effects. A set of Monte Carlo simulations were designed and carried out to investigate the expected response of the detector to a deployed radon source. In order to dissolve the radon gas into a sample of scintillator, a circulation system was constructed with a long-lived radium source. The results from counting this system indicate that it is imperative that this scintillator mimics the scintillator in the detector as much as possible. Any exposure to laboratory air,
specifically oxygen, can negatively impact the characteristics of the scintillator. A vacuum system will need to be implemented in further iterations of the source to evacuate the flask during preparation.
Chapter 6

Summary and Conclusions

A design and fabrication procedure was developed for producing umbilical cables for SNO+. These umbilicals house optical fibres, gas capillaries, and signal wires which connect internally deployed calibration sources to the observatory deck above the acrylic vessel. A basic umbilical design will be used for most sources while specific sources will utilize their own dedicated umbilical with some minor modifications (optical fibres will be added for the laserball umbilical, for example). The umbilicals are compatible with linear alkylbenzene, impermeable to liquid scintillator, and robust enough so no strain on the internal connections develops during deployment. A three-phase fabrication procedure was developed for securely wrapping the cable connections around a central polyethylene tube, inserting that tube into an outer Tygothane jacket, and injecting potting material into the intervening space for mechanical support. The umbilicals will enable deployed sources to make the calibration measurements necessary for turning the raw PMT measurements of charge and time to a complete description of the physical processes inside the acrylic vessel.

One such internally deployed source has been designed and involves a scintillator-filled quartz flask which has been spiked with $^{222}$Rn. This radon source could be a
useful tool for calibrating the pulse shape discrimination, energy scale, and position reconstruction of the detector. Monte Carlo simulations were performed to investigate the expected response of the detector to the deployment of this source. A circulation system with a long-lived radium source was used to dissolve radon gas into a sample of liquid scintillator.

6.0.1 Future Work

Alternative potting materials are being investigated for use with the umbilicals at this time. It was found that the specially designed injection system was able to flow Clear Flex 50 urethane rubber through the full 25 m length of a 5/8” (15.875 mm) outer diameter umbilical in its 25 minute working life. Air pockets were present in the 1/2” (12.7 mm) outer diameter umbilical, however, which may compromise the strength of the umbilical or lead to buoyancy problems during deployment. Wacker SilGel 612A is being considered; this is the same material used to pot the SNO+ photomultiplier tubes and which has a working life of 158 minutes.

For the radon source, the circulation system presented here for preparing the $^{222}$Rn-spiked scintillator involved exposing the sample to laboratory air. This allows oxygen to dissolve into the scintillator and, as can be seen in Figure 5.10, leads to alpha quenching effects. A contaminant-free system for dissolving radon into a sample of liquid scintillator and sealing it into its quartz flask needs to be developed. Additionally, the design of the source itself may be modified before final construction. Making the flask neck smaller in diameter may make flame sealing easier and scaling down the size of the whole source may increase the precision of reconstructing the source position.
Bibliography


[57] ROOT. Available at root.cern.ch.


