Low Energy $^8\text{B}$ Solar Neutrinos in SNO+: Controlling and Constraining Radon Backgrounds

by

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Abstract

SNOLAB located in Sudbury, Canada, is hosting a new liquid scintillator experiment for studying neutrinos which is called SNO+. Many interesting physics topics such as measuring low energy solar neutrinos and searching for neutrinoless double beta decay are expected to be performed using the SNO+ detector. SNO+ is designed to measure the solar neutrino flux at a lower energy range than SNO, and therefore it is able to study LMA-MSW oscillations at this range of energy. This research is concerned with extracting low energy $^8$B solar neutrinos while studying the tagging and reduction of $^{214}$Bi by 99.8%, one of the main backgrounds in the energy range of interest. Ways to measure and control radon were also studied since it is the source of the $^{214}$Bi background. Scintillation material, zinc sulfide, was selected for use in fabrication of radon detectors known as Lucas cells. The fabrication of cover gas bags employed in the SNO+ experiment to react to mine air pressure fluctuations is described and the interior radon emanation of these bags was measured and calculated.
In the Name of God

the Most Compassionate

the Most Merciful
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Acronyms

ADC  Analogue to Digital Converter
AV  Acrylic Vessel
CC  Charge Current interaction
CTF  Counting Test Facility
HV  High Voltage
LAB  Linear Alkylbenzene
LDPE  Low Density Polyethylene
LMA  Large Mixing Angle
MC  Monte Carlo
MCA  Multichannel Analyzer
MSW  Mikheyev, Smirnov and Wolfenstein
NC  Neutral Current interaction
NCD  Neutral Current Detector
OPM  Optical Power Meter
PDF  Probability Density Function
PMNS  Pontecorvo-Maki-Nakagawa-Sakata
PMT  Photomultiplier Tube
PSUP  PMT support structure
SK  Super-Kamiokande
SNO  Sudbury Neutrino Observatory
SNOMAN  SNO Monte Carlo Analysis program
SSM  Standard Solar Model
Chapter 1

Introduction

One of the fundamental particles in the Standard Model of particle physics is the neutrino, a lepton with no electric charge. There are three different types (or flavours) of neutrinos, each related to a charged particle. These types are known as electron neutrino ($\nu_e$), muon neutrino ($\nu_\mu$) and tau neutrino ($\nu_\tau$). These neutrinos are weakly interacting with other particles which makes them difficult to detect.

There are different sources that produce neutrinos. The sun is one of the large sources of neutrinos, known as solar neutrinos. In order to detect and investigate solar neutrinos, large scale detectors have been designed and located underground in order to shield them against cosmic rays. The Sudbury Neutrino Observatory, SNO, is an example of these detectors located 2 km underground in an active mine in Sudbury, Ontario. The SNO detector consisted of a 12-m diameter acrylic vessel (AV) which was filled with ultra pure heavy water. Neutrino interactions in heavy water produced Čerenkov light that could be detected by the array of roughly 9,500 photomultiplier tubes (PMTs). The SNO experiment resolved the conflict between theoretical predictions of the rate of solar neutrinos and experimental observations
that existed for more than 30 years. The solution to this conflict was neutrino oscillations which means that neutrinos produced in the core of the sun as electron-type neutrinos can change flavour as they travel.

The SNO detector observed neutrinos from $^8$B decays in the sun. The energies of these neutrinos range from very low energy to about 15 MeV. The energy threshold in SNO was about 3.5 MeV. By detecting lower energy solar neutrinos more precise studies of neutrino oscillation parameters are possible. Therefore, it is planned to run a new experiment, known as SNO+, in the SNO detector after removing heavy water and filling the AV with linear alkylbenzene (LAB), an organic liquid scintillator. Using LAB will boost the light yield produced by neutrino interactions by roughly a factor of fifty compared to the SNO experiment. SNO+ is planned to run in two phases: neutrino-less double beta decay phase and solar neutrino phase. The pep and CNO neutrinos are among those low energy solar neutrinos that SNO+ plans to detect and investigate. Also, measuring the $^8$B solar neutrinos at lower energies along with pep and CNO neutrinos will boost our knowledge about neutrino oscillations.

An important challenge that any particle detection experiment is faced with is the backgrounds in the energy range of interest. A good knowledge of these backgrounds is required in order to measure and remove them as much as possible. One of the main backgrounds in the SNO+ experiment while studying the $^8$B solar neutrinos at lower energies is $^{214}$Bi. The main source of $^{214}$Bi background is radon entering the detector. Mine air contains high amounts of radon and any that leaks into the detector via permeation can be a background. Contamination in the AV, LAB and other components involved in the experiment can also introduce radon into the detector via emanation. It will be very crucial to avoid any radon permeation, contamination
and/or emanation. It is also important to measure any residual amount of radon in
the detector as precisely as possible. The SNO+ detector will be sealed to reduce the
amount of radon entering the detector from the mine air. In doing so, several cover
gas bags are being designed and will be used in this sealed system. These bags will
expand and contract in response to pressure changes between the mine air and the
gas space above the detector while acting as a barrier for radon entry. These bags
are fabricated from material with low permeability to radon and low emanation.

1.1 Research Objectives

It was stated that radon is an important background in the SNO+ experiment. There-
fore, its measurement and prevention from penetrating into the detector is a crucial
task in the experiment. A system used at Queen’s University for more than 20 years
is a radon emanation system used to measure the amount of radon emanation from
materials placed in a vacuum chamber. The system transfers the emanated radon
into a Lucas cell detector for counting the radon. This detector uses an inorganic
scintillation material such as zinc sulfide (ZnS) to detect radon as identified in [1]. As
the previous supplier of this material does not provide it any longer, it was required
to find a new supplier that can provide ZnS with satisfactory characteristics. Finding
a new ZnS supplier(s) and verifying the characteristics of their product was one of
my research objectives, and will be described in this thesis.

My research also involved finding methods to screen out noise from the output
data obtained from the Lucas cell. This will also be described in this thesis.

Cover gas bags are an important part of the SNO+ experiment as they act as
a barrier between mine air and the detector. It is also required to measure the
radon emanated from the interior surface of these bags in order to understand their contribution to the total radon background in the cover gas and hence the detector. I will describe my measurements of this radon emanation in this thesis.

Studying $^8$B solar neutrinos at lower energies was another research objective. One of the main potential backgrounds for the low energy $^8$B solar neutrinos comes from radon. After radon enters the detector there will be decays from $^{214}$Bi and these occur in the energy range of interest for the lower energy $^8$B solar neutrinos. In this regard, it is required to study the ability to recognize and tag $^{214}$Bi decays in the detector. This was another research objective.

Specifically, the research work described in this thesis can be summarized as:

1. finding and evaluating an inorganic scintillator for Lucas cells
2. proposing a data analysis method to process data obtained from the Lucas cell
3. fabrication of cover gas bags and measuring their interior radon emanation
4. extracting and studying $^8$B solar neutrino signal from fake data sets and comparing it with some existing neutrino oscillation models
5. studying $^{214}$Bi tagging to deal with the potential background to the $^8$B solar neutrinos from radon in the detector.

1.2 Thesis Outline

This thesis is organized as follows. In Chapter 2, a general introduction about solar neutrinos is presented. Furthermore, some experiments accomplished so far to detect and study solar neutrinos are described. Chapter 3 introduces the SNO+ experiment and the objectives behind it. In Chapter 4, a brief description of Lucas cell fabrication is given. The results obtained from evaluating two types of ZnS from two suppliers
are also presented along with a discussion on choosing the better product. The data analysis method is also explained in this chapter. Chapter 5 deals with the fabrication of cover gas bags and measuring radon emanation from their interior surface. Chapter 6 presents studies of $^8$B solar neutrinos in a lower energy range. Chapter 7 concludes this thesis.
Chapter 2

Solar Neutrinos

The neutrino, a member of the Standard Model of particle physics, is a fundamental particle with no electric charge. This particle was first proposed by Pauli in 1930 to explain the continuous energy spectrum of electrons emitted by beta decay \(^2\). Since then there were a lot of attempts to understand the properties of this particle and also to detect it. Our very own sun is one of the sources producing neutrinos in large quantities. Neutrinos from the sun, also known as solar neutrinos, can be detected by experiments placed in underground laboratories. Solar neutrinos can be used to investigate the properties of the neutrino and the sun itself. The aim of this chapter is to briefly explain the properties of neutrinos and describe some solar neutrino experiments.

2.1 Neutrinos in Standard Model of Particle Physics

The particles of nature and their interactions are explained by the Standard Model of particle physics. In this model, elementary particles of spin-half, known as fermions,
are divided into two groups: quarks and leptons. These are further grouped into three generations according to their mass. The interactions between these particles are mediated by integer-spin particles known as bosons. The electromagnetic interaction between charged particles is mediated by the massless photons. The massless gluons mediate the strong interaction. The weak interaction is mediated by \( W^+ \), \( W^- \) and \( Z \), which are three massive bosons.

Neutrinos belong to the lepton family. There are three types of neutrino, each related to a charged particle as shown in Table 2.1. Since neutrinos do not carry any electric charge, they only interact via the weak interaction with the exchange of heavy particles such as \( W^\pm \) or \( Z \) bosons. Neutrinos were described as massless particles in the Standard Model until solar and atmospheric neutrino experiments proved that neutrinos have a tiny mass. This contradiction will be discussed later in this chapter.

### 2.2 Solar Neutrinos

The energy emitted by the sun is produced by nuclear fusion reactions, i.e. the fusion of protons into alpha particles \(^4\). As shown in Figure 2.1 and 2.2, these reactions can be classified in two series, the proton-proton (\( pp \)) chain and Carbon-Nitrogen-Oxygen (CNO) cycle. The dominant process in the sun which produces most of its energy

<table>
<thead>
<tr>
<th>generations</th>
<th>I ( \nu_e )</th>
<th>II ( \nu_\mu )</th>
<th>III ( \nu_\tau )</th>
<th>charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>neutrino</td>
<td>( \nu_e )</td>
<td>( \nu_\mu )</td>
<td>( \nu_\tau )</td>
<td>0</td>
</tr>
<tr>
<td>charged particle</td>
<td>electron(e)</td>
<td>muon(( \mu ))</td>
<td>tau(( \tau ))</td>
<td>-1</td>
</tr>
</tbody>
</table>

Table 2.1: Neutrinos and corresponding charged particles
Figure 2.1: $pp$ chain in the sun. Different neutrinos are produced in this chain. This figure is taken from [3].
is the $pp$ chain of reactions. As shown in these figures, neutrinos are produced in several reactions via the weak interaction. These solar neutrinos are all electron-type neutrinos.

The Standard Solar Model (SSM) is a detailed model of the sun based on solar observations and measurements. This model can be used to predict the number of solar neutrinos. By the early 1960's, the fluxes and energy spectra of the solar neutrinos were predicted by John Bahcall, as shown in Figure 2.3. As it can be seen from this figure, the $pp$ neutrinos are more abundant than other neutrinos, but their energy is low. On the other hand, the $^8$B neutrinos are high energy but low flux.

The neutrino interaction cross section is small due to weak interactions but increases with the energy. This makes the $^8$B solar neutrinos one of the best candidate for detection. Large detectors are used to provide a large number of target atoms or target electrons that can participate in an interaction. These detectors are located underground to shield against cosmic rays. Some of the solar neutrino experiments will be discussed in the next section.

### 2.3 The Solar Neutrino Problem

The results obtained from the early experiments carried out to detect and study solar neutrinos were not in agreement with solar model predictions. This is discussed in this section by explaining some of these experiments.
Figure 2.2: CNO cycle in the sun [6].

Figure 2.3: Solar neutrino spectra for different reactions in the sun [4].
2.3.1 Radiochemical Experiments

The first solar neutrino experiment was a radiochemical experiment done by Ray Davis and collaborators in the Homestake Mine in South Dakota starting in 1967 [7]. They used 615 tonnes of perchloroethylene $\text{C}_2\text{Cl}_4$, located 1,478 m underground, as the target for solar neutrino interaction. Solar neutrinos interacted via charged-current weak interactions with $^{37}\text{Cl}$ as follows:

$$\nu_e + ^{37}\text{Cl} \rightarrow ^{37}\text{Ar} + e^{-}.$$ 

After being exposed to solar neutrinos for some period of time, the experiment would try to collect all the $^{37}\text{Ar}$ atoms produced by these charged-current reactions and count them with a proportional counter. The extracted number of $^{37}\text{Ar}$ atoms would be proportional to the integrated solar neutrino flux. While the threshold of this experiment (also known as the Chlorine experiment) allowed it to be sensitive to $^{7}\text{Be}$ and $\text{pep}$ solar neutrinos in the $\text{pp}$ chain, the sensitivity to $^{8}\text{B}$ solar neutrinos was dominant. The results of the Chlorine experiment were announced in 1968 in which the rate of solar neutrinos was significantly lower than that of the SSM. This experiment continued for about 30 years and the final results showed that the solar neutrino flux was $0.34\pm0.03$ times the value predicted by the SSM [7]. Following this experiment, subsequent radiochemical experiments [8], [9] and [10] were performed with gallium (sensitive mainly to neutrinos from the $\text{pp}$ reactions) to try to understand this unexpected result. The combination of the results of the gallium experiments was $0.579\pm0.050$ [11] times the value predicted by the SSM.
2.3.2 Water Čerenkov Experiments

Water Čerenkov experiments also detected solar neutrinos via the elastic scattering of neutrinos with target electrons that can be expressed as:

$$\nu_x + e^- \rightarrow \nu_x + e^-.$$ 

Scattered electrons radiate Čerenkov light that is detected by photomultiplier tubes (PMT). These experiments are sensitive to all types of active neutrinos. However, since the cross section for the electron neutrino is approximately six times higher than other neutrinos, these experiments predominantly detected electron neutrinos.

Kamiokande [12], located 1,000 m underground in Kamioka mine near Mozumi, Japan, was the first water Čerenkov detector. They started taking data in 1985 with 2,140 tonnes of pure water as an active detector. Čerenkov light was detected by 1,000 50-cm PMTs. The results of the measured flux of solar neutrinos in the Kamiokande experiment was approximately 50% of the SSM [12].

In 1996, an improved version of Kamiokande, Super-Kamiokande (Super-K) [13] started taking data. Super-K has a much larger volume active detector along with more PMTs. It has 50,000 tonnes of ultra-pure water as an active detector, and the cylindrical detector holding the water was surrounded by 11,146 PMTs (50 cm).

Water Čerenkov experiments have an analysis threshold determined by the minimum number of PMTs that need to fire for an event to be easily recognized and reconstructed. Based on the number of PMTs in the Super-K experiment, it has an energy threshold of around 5 MeV. Therefore, Super-K is only sensitive to $^8$B neutrinos. The result, obtained from 1,258 days of data taking, was that the measured flux of $^8$B neutrinos was approximately $0.451 \pm 0.015$ [14] times the SSM. Both Kamiokande and Super-K confirmed the discrepancy observed by the Chlorine experiment.
The flux of neutrinos measured by these experiments was significantly lower than the predicted solar neutrino flux by the Standard Solar Model. The difference between the measured and predicted solar neutrino fluxes became generally known as the “Solar Neutrino Problem” [4]. The solution to this problem will be discussed in the next section.

2.4 Neutrino Oscillations

One solution to the discrepancy between the measured and predicted solar neutrino fluxes suggests a new behavior for the neutrino. In this solution, an electron neutrino produced in the sun changes into other neutrino flavors before it is detected by the earth-based experiments. This is called neutrino oscillations. Since all the experiments that experienced this discrepancy were solely sensitive to electron-type neutrinos, if neutrinos oscillated, the other flavours would not be detected and the fluxes measured by those experiments would be lower than predicted by solar models. Both vacuum and matter oscillations will be briefly described below.

2.4.1 Vacuum Oscillation

Neutrinos are produced via the weak interaction as one of the flavour eigenstates that can be denoted as $|\nu_\alpha\rangle$ ($\alpha = e, \mu, \tau$). If neutrinos have a finite mass, the eigenstates of the free Hamiltonian, i.e. mass eigenstates, can be expressed as $|\nu_k\rangle$ ($k=1,2,3$). A flavour eigenstate does not have to be identical to a mass eigenstate, similar to the mixing in the quark sector. In other words, a neutrino with a well-defined flavour does not have to have a well-defined mass and vice versa. Then flavour eigenstates
can be expressed as the linear combination of the mass eigenstates:

$$|\nu_\alpha\rangle = U_{PMNS} |\nu_k\rangle$$  \hspace{1cm} (2.1)$$

where $U_{PMNS}$ is the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix, which is a unitary matrix. Following the convention of $[15]$, this matrix can be expressed as:

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$  \hspace{1cm} (2.2)$$

where $c_{ij} = \cos \theta_{ij}$ and $s_{ij} = \sin \theta_{ij}$. The $\theta_{ij}$'s are the mixing angles for each sector and $\delta$ is CP-violating phase.

A simplified case for neutrino mixing is one where only two different neutrinos are involved. The two-neutrino mixing can be described by:

$$\begin{pmatrix} \nu_e \\ \nu_x \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$  \hspace{1cm} (2.3)$$

where $\nu_x$ is an admixture of $\nu_\mu$ and $\nu_\tau$ and the $2 \times 2$ matrix is just a rotation matrix where $\theta$, the rotation angle is referred to as the mixing angle. This can be expanded as:

$$|\nu_e\rangle = \cos \theta |\nu_1\rangle + \sin \theta |\nu_2\rangle$$  \hspace{1cm} (2.4)$$

$$|\nu_x\rangle = -\sin \theta |\nu_1\rangle + \cos \theta |\nu_2\rangle$$

This relation may be inverted to express the mass eigenstate as a superposition of the flavour eigenstates as:

$$|\nu_1\rangle = \cos \theta |\nu_e\rangle - \sin \theta |\nu_x\rangle$$  \hspace{1cm} (2.5)$$

$$|\nu_2\rangle = \sin \theta |\nu_e\rangle + \cos \theta |\nu_x\rangle$$

Neutrinos propagate as the mass eigenstates and the time dependence of the mass
The eigenstate is given by:
\[
|\nu_j(t)\rangle = |\nu(0)_j\rangle e^{-iE_j t}; j = 1, 2
\]
(2.6)
where \(E_j\) is the neutrino energy for the mass eigenstate (1 or 2). Neutrinos with different masses travel with different speed. Therefore the combination of mass eigenstates changes over time as the neutrino propagates. The observed flavour is determined by the admixture of the mass eigenstate at the time of detection. Equations 2.4, 2.5 and 2.6 can be used to determine the survival probability of an electron neutrino, \(P_{\text{ee}}\), which is the probability of detecting an electron neutrino as the same flavour after traveling a distance \(L\). The \(P_{\text{ee}}\) which also describes an oscillation of the neutrino flavour is given by:
\[
P_{\text{ee}} = 1 - \sin^2(2\theta) \sin^2\left[\frac{\Delta m^2 L}{4E}\right]
\]
(2.7)
where \(\Delta m^2 = m_2^2 - m_1^2\) is the difference of the neutrino masses squared, \(L\) is the distance that the neutrino travels between the source and detection point, and \(E\) is the energy of the neutrino. As can be seen, \(P_{\text{ee}}\) oscillates and the frequency of the oscillation depends on the mass difference and energy of the neutrino. This implies that neutrino oscillations can happen only if neutrinos do have a finite mass and if the mass difference between states is not zero.

The distance that a neutrino travels and returns to its initial state is called the oscillation length \(L_\nu\), which is defined as:
\[
L_\nu = \frac{4\pi E}{\Delta m^2}.
\]
(2.8)
Inserting the oscillation length in Equation 2.7, the \(P_{\text{ee}}\) can be written as:
\[
P_{\text{ee}} = 1 - \sin^2(2\theta) \sin^2\left[\frac{\pi L}{L_\nu}\right]
\]
(2.9)
In this equation the frequency of oscillation depends on \(\frac{L}{L_\nu}\). For \(L \ll L_\nu\), the oscillation
does not have time to occur and the survival probability is equal to 1. In the case where \( L \gg L_v \), i.e. the distance between the source and detection point is much larger than the vacuum oscillation length, the average of oscillations becomes of interest. As the average of \( \sin^2\left(\frac{\pi L}{L_v}\right) \) is \( \frac{1}{2} \), therefore:

\[
P_{ee} = 1 - \frac{1}{2} \sin^2(2\theta)
\]

In the averaged survival probability case, \( P_{ee} \) cannot be less than 0.5. The Chlorine and Super-K experiments found a ratio of observed flux over predicted less than 0.5 (and different ratios), while the gallium experiments found a ratio of observed/predicted flux above 0.5. This suggests that the simple case of vacuum oscillations would be difficult to invoke to explain the observed deficits in the solar neutrino experiments (a “just-so” scenario would have been required with only vacuum oscillations).

### 2.4.2 Matter Oscillation

When neutrinos propagate through matter, an additional oscillation effect occurs because all neutrinos do not have identical interactions with matter. This idea was first postulated by Wolfenstein [16] and then by Mikheyev and Smirnov [17], and is called the MSW effect. In propagating through ordinary matter that contains electrons, electron neutrinos have an additional charged-current weak interaction with those electrons that affects their forward propagation. This means that electron neutrinos experience an additional potential in the Hamiltonian for propagation that can be expressed as [18]:

\[
V = \frac{\sqrt{2}G_F n_e}{2}
\]
where $G_F$ is the Fermi constant and $n_e$ is the number of electrons per unit volume in the medium. The additional potential results in the electron neutrino gaining an effective mass which consequently can affect neutrino oscillations. The matter oscillation eigenstates can be written as:

$$|\nu_{1m}\rangle = \cos \theta_m |\nu_e\rangle + \sin \theta_m |\nu_x\rangle$$
$$|\nu_{2m}\rangle = -\sin \theta_m |\nu_e\rangle + \cos \theta_m |\nu_x\rangle$$

where $|\nu_{1m}\rangle$ and $|\nu_{2m}\rangle$ are the matter mass eigenstates and $\theta_m$ is the matter mixing angle. It is noteworthy that these quantities are different from those in the vacuum oscillation. The mixing angle and mass-squared splitting in matter oscillations are defined as [19], [20]:

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{(\cos 2\theta - \beta)^2 + \sin^2 2\theta}$$

$$\Delta m^2_M = \Delta m^2 \sqrt{\sin^2 2\theta + (\cos 2\theta - \beta)^2}$$

where

$$\beta = \frac{2\sqrt{2}G_F n_e E}{\Delta m^2}.$$ 

By replacing the $\theta$ with $\theta_m$ and $\Delta m^2$ with $\Delta m^2_M$ in Equation 2.7, the form of the neutrino oscillation survival probability equation remains the same as Equation 2.7. The $\beta$ measures the relative importance of the matter effect and depends on the neutrino energy, the matter density, the strength of the neutrino-matter interaction and the mass difference. If in Equation (2.13), $\cos 2\theta = \beta$, then $\sin 2\theta_m$ takes its maximum value which is one. Therefore at $\theta_m = 45^\circ$ a resonance occurs and the matter mixing angle is large regardless of the size of the vacuum mixing angle.

Neutrino oscillations in matter are even more interesting if the neutrinos propagate
through variable electron density, as they do emerging from the sun. Neutrinos are
born as electron neutrinos in the core of the sun and travel to the outer edge of the sun
through matter while its density changes significantly. In the solar core, the electron
density is known. For certain values of the neutrino energy and $\Delta m^2$, there can be
the resonance condition described above, leading to $\theta_m$ taking on its maximum value.
This condition causes electron neutrinos to be born as the massive eigenstate, $\nu_{2m}$. If
the electron density, $n_e$, changes slowly enough with $r$ (where $r$ is the distance from
the center of the sun), then the propagation of neutrinos from the core to the outer
edge is adiabatic. When the adiabatic condition is met, neutrinos can remain in the
$\nu_2$ state and exit from the sun as the heavier mass eigenstate. Now their survival
probability (flavour detection probability) will equal $P_{ee} = \sin^2 \theta$. Experiments such
as SNO have shown the adiabatic condition in the sun to be correct, for which the
transition between mass eigenstates is negligible because of slowly changing density,
and are strongly in favour of large mixing angle (LMA-MSW) mixing parameters [21].

From the Equation (2.15), it can be seen that the importance of MSW effects
grows with neutrino energy. Therefore the influence of the solar matter effect is
more significant for those neutrinos with higher energy. Based on LMA-MSW, the
survival probability of solar electron neutrinos (with $\theta_{12}$) changes as shown in Figure
2.4. For low energy neutrinos where $\beta < \cos 2\theta_{12}$ the matter effect is negligible and
essentially vacuum oscillations occur. Therefore at this region, the survival probability
is $1 - \frac{1}{2} \sin^2 (2\theta_{12})$ (vacuum). For high energy neutrinos (where $\beta > 1$) the oscillation
is dominated by matter effects (MSW effect), and the survival probability is $\sin^2 \theta_{12}$
and roughly independent of energy. There is a transition between these two effects in
the intermediate region as shown in Figure 2.4. In this transition region the details
of the neutrino-matter interaction are important and the survival probability can be strongly affected. In order to probe this effect, neutrinos with energy in this range are required. The $^8$B neutrino can be one of those candidates since its spectrum starts from a very low energy and stretches as far as 15 MeV. The result of the transition between vacuum and matter effects can be seen as a distortion in the $^8$B energy spectrum. In this thesis I present studies of the $^8$B neutrino spectrum down to 2.5 MeV in order to probe the effect of this transition.

\section{2.5 Sudbury Neutrino Observatory}

The Solar Neutrino Problem and neutrino oscillations (the solution to this problem) were discussed in the previous two sections. The first experiment that clearly demonstrate solar neutrino oscillations and resolved the Solar Neutrino Problem was the Sudbury Neutrino Observatory (SNO). This experiment was located in the Vale Creighton mine near Sudbury, Canada, at a depth of 2,039 m. SNO was a water Čerenkov experiment that used 1,000 tonnes of ultra pure heavy water ($D_2O$) as an active detector. The heavy water was in a 12-m diameter acrylic sphere which was surrounded by ordinary light water and about 9,500 PMTs (20-cm diameter) which were used to detect the Čerenkov light. Neutrinos interact with deuterons in heavy water via two interactions, charged-current (CC) and neutral-current (NC). The charged-current interaction can be expressed by:

$$\nu_e + d \rightarrow p + p + e^-$$  \hfill (2.16)
and is sensitive only to electron-type neutrinos and results in an energetic electron that produces Čerenkov light. The neutral-current interaction is expressed by:

\[ \nu_x + d \rightarrow \nu_x + n + p \quad \text{where} \quad x = e, \mu, \tau \]  \hspace{1cm} (2.17)

and is equally sensitive to all three types of active neutrinos. The signature of this interaction is a free neutron in the detector.

SNO used three different techniques to detect this free neutron, while taking data in three phases. In the first phase, run from November 1999 to May 2001, the acrylic vessel (AV) contained only pure D$_2$O. The neutrons produced in NC interactions were captured on the deuterium nuclei, which resulted in the production of a single monoenergetic $\gamma$ ray of 6.25 MeV. In the second phase, run from July 2001 to October 2003, 0.2% sodium chloride salt was added to the heavy water. Neutrons from NC were captured on Cl in the heavy water with higher capture cross section. The signature for neutron capture at this phase was a multiple gamma ray signal

![Figure 2.4: Electron neutrino survival probability as a function of energy based on the LMA-MSW oscillations [18].](image)
CHAPTER 2. SOLAR NEUTRINOS

(produced because of de-excitation of chlorine nuclei after neutron capture) with total energy of 8.6 MeV. In the third phase, run from November 2004 to November 2006, $^3$He proportional counters, also known as Neutral Current Detectors (NCDs), were deployed in the heavy water region. These NCDs provided separate detectors for the NC interactions to be detected which reduced the correlations between the CC and NC flux measurements.

The SNO experiment was able to measure the total flux of all active neutrinos through the neutral-current interactions and the flux of electron type neutrino via the charged-current interactions. The comparison of the measured solar neutrino flux for CC and NC interactions indicated that only $0.34 \pm 0.04$ of the total flux of all active neutrinos that were detected by SNO were electron neutrinos \[22\]. Thus, SNO results identified the other contents of the solar neutrino flux ($\nu_\mu$ and/or $\nu_\tau$) besides the electron neutrinos, although all neutrinos were created in the sun as electron neutrinos. Furthermore, the flux of all neutrino flavours through the NC measurement was compared with the solar model predicted flux $(5.60 \pm 0.91) \times 10^6$ cm$^{-2}$s$^{-1}$ and they were in good agreement. In conclusion, the SNO results showed that solar neutrinos undergo flavour changes and solved the Solar Neutrino Problem.

As described in Section 2.4.1 and 2.4.2, neutrino oscillations can be described by two mixing parameters: $\theta$ and $\Delta m^2$. The results of SNO (which were strongly in favor of the LMA solution), combined with other experiments, gave the best-fit value for $\Delta m^2_{12} = 8.0^{+0.6}_{-0.4} \times 10^{-5}$ eV$^2$ and $\theta_{12} = 33.9^{+2.4}_{-2.2}$ degree \[22\].
2.6 Borexino

Another type of solar neutrino experiment is a liquid scintillator which detects the elastic scattering of a neutrino and electron:

\[ \nu_x + e^- \rightarrow \nu_x + e^- . \]

A liquid scintillator has higher light yield than a water Čerenkov experiment, i.e. produces more light when a charged particle deposits energy in it. This makes the liquid scintillator detector more sensitive to low energy solar neutrinos (energy less than 1 MeV).

Borexino, located in the Gran Sasso underground lab in Italy (3,500 metres water equivalent overburden), is the first detector which used liquid scintillator to detect solar neutrinos. The aim of the Borexino experiment was to detect the monoenergetic \(^7\text{Be}\) (0.862 MeV) solar neutrinos to explore the MSW effect in a lower energy range. In 1994, Borexino started with the prototype experiment which was called the Counting Test Facility (CTF). The CTF was designed to test some concepts important for Borexino success, to operate at such a low energy threshold, prior to its construction. The estimation of the radiopurity of liquid scintillator and background levels was one of those concepts. The results of CTF convinced the experimenters of the desired radiopurity and low background levels. The construction of the final design was started in 1994. In May 2007, the detector was filled with 300 tonnes of pseudocumene as liquid scintillator. The results of of the Borexino experiment were published in 2008 \cite{23}. The observed rate of \(^7\text{Be}\) solar neutrinos was \(49\pm3\pm4\) counts/day for 100 tonnes. The solar model predicted rate with no oscillation is 74 counts/day per 100 tonnes. Neutrino oscillations cause this discrepancy. When the best-fit LMA-MSW neutrino oscillation parameters are included, the predicted result would be \(48\pm4\)
counts/day per 100 tonnes which is in good agreement with the Borexino results. Therefore Borexino results confirmed the SNO results and are consistent with the LMA solution.
Chapter 3

SNO+ Experiment

SNOLAB located in Sudbury, Canada, is hosting a new liquid scintillator experiment for studying neutrinos which is called SNO+. SNO+ stands for SNO, plus liquid scintillator. SNO+ has the advantage of using the fundamental parts of the successful SNO experiment such as the 12 diameter acrylic vessel (AV), roughly 9,500 PMTS, PMT support structure (PSUP) and much of the existing electronics. This will be beneficial for constructing SNO+ with less expense and time. SNO+ (same as SNO) is taking advantage of many characteristics of SNOLAB, including the deep location (one of the deepest underground labs) which shields detectors against cosmic rays, and very clean environment. Different phases and the future plans of SNO+ will be discussed in this chapter. Furthermore, a brief explanation about the backgrounds associated with the SNO+ experiment will be given.
3.1 SNO+ and the Liquid Scintillator

The liquid scintillator which is used in large experiments usually has two or three components. The main component is a solvent and is used to fill the majority of the detector volume. The solvent is an organic liquid that typically contains benzene rings. It is efficiently excited by the passage of charged particles and produces scintillation light. To increase the light efficiency of the solvent such that it is detected by PMTs, a fluor is used. A typical fluor is 2,5-diphenyloxazole (PPO) which is used at a few grams per litre concentration. The fluor (PPO) collects the light produced by the solvent and emits them with high efficiency as light. A wavelength shifter is sometimes used to shift the wavelength of the light produced by the solvent and fluor to longer wavelengths in order to decrease the chance of re-absorption of the light.

Not all organic scintillators are suitable to be used in scintillator experiments. There are a number of criteria to be met for a liquid scintillator to be chosen in an experiment. Some of them are listed here.

A liquid scintillator should be compatible with detector components especially for long term use. Converting the absorbed energy efficiently to light, known as light yield, is another important criterion for the solvent. A solvent with higher light yield is more desirable. The third criterion is a long attenuation length in order to have less attenuation of the emitted light. Safety and cost are also important for choosing a liquid scintillator in an experiment.

It was decided to use linear alkylbenzene (LAB) as a liquid scintillator in SNO+ since it meets all the mentioned criteria. LAB shows a good compatibility with AV among several other scintillators \[24\]. The light yield of LAB is roughly 50 times higher than the Čerenkov light produced in SNO. LAB supplied from some
manufacturers has light attenuation length of roughly 20 m at 420 nm. LAB is used as a main ingredient in household and industrial detergents and it is a chemically mild liquid. Fortunately there is a plant in Quebec, owned by Petresa Canada (now CEPSA), which produces LAB with high purity. This means that SNO+ can get the desired LAB at relatively low price. The SNO+ detector will be filled with 780 tonnes of LAB. PPO will also be added at a concentration of 2 grams per litre, as the fluor.

Filling the AV with LAB causes a density mismatch between LAB and the surrounding light water. Since LAB is lighter than water, the acrylic vessel volume will be buoyant and a hold-down rope net needed to be designed (SNO used heavy water inside the AV which was heavier than the surrounding light, thus hold-up ropes were used). The design of the hold-down ropes is shown in Figure 3.1.

3.2 SNO+ Physics Goals

SNO+ is a multipurpose experiment. The high light yield of LAB gives this opportunity to SNO+ to measure the low energy solar neutrinos. Neutrinoless double beta decay, which is a topic of great interest in particle and nuclear physics, can be measured by SNO+ by loading the liquid scintillator with a double beta decay isotope. SNO+ can also measure the flux of the reactor anti-neutrinos produced by nuclear reactors. Geo neutrinos produced by the radioactive decay of elements in earth’s mantle and crust and supernova neutrinos produced by specific stellar explosions can also be studied.

SNO+ is planning to run in two phases: neutrinoless double beta decay phase and solar neutrino phase. First, neutrinoless double beta decay is run by adding an
isotope such as neodymium to the scinillator. Later, the solar neutrino phase will begin by removing the neodymium from the scintillator.

3.2.1 Low Energy Solar Neutrinos

SNO+ will be sensitive enough to measure the flux of low energy solar neutrinos, if backgrounds are low enough. Pushing the energy threshold to lower energy is appealing and may suggest new physics if the electron neutrino survival probability as a function of energy shows different behavior than the expected one for LMA-MSW neutrino oscillations. Of these low energy solar neutrinos, pep and CNO solar neutrinos are of particular interest. The $^8$B neutrino is also interesting to probe at low energy. The behavior of $^8$B neutrinos at high energy has been studied by SNO.
and Super-K. The behaviour at high energy suggest neutrino oscillation parameters that would correspond to LMA-MSW oscillations. Our curiosity concerning a new physics will be answered by studying $^8$B neutrinos at low energy and other low energy solar neutrinos such as \textit{pep} and CNO. The behavior of $^8$B is one of the topics of this thesis and more information can be found in Chapter 6.

One of the goals of the SNO+ solar phase is to look for the low energy \textit{pep} neutrinos. The \textit{pep} neutrinos are difficult to detect for some experiments because of the cosmogenic background (background produced by cosmic rays) especially $^{11}$C. However, this cosmogenic background is negligible for SNO+ due to the depth of SNOLAB. The study of the \textit{pep} neutrinos (1.44 MeV) is interesting since its energy lies within the transition region between vacuum and matter dominated oscillation regions for solar neutrino survival probability as shown in Figure 3.2 and 2.4. The neutrino survival probability in this transition region depends sensitively on the oscillation parameters and could be strongly affected by new physics. The energy of the transition depends strongly on the mass splitting. The behavior of the survival probability for \textit{pep} solar neutrinos in this transition region can open a door to new physics.

CNO solar neutrinos are also interesting since they provide information about the interior of the sun and solar physics. The density of metals (N, O and C) in the interior of the sun affects the contribution of the CNO cycle in the sun (Figure 2.2). It has been predicted that the contribution of the CNO cycle to the total energy production of the sun is just 1.5\%, and there is still a large uncertainty associated with that [27]. Therefore, the measurement of the CNO flux constrains the contribution of the CNO cycle to the total energy production of the sun and also provides useful information.
about the solar metallicity. SNO+ is planning to measure the CNO flux in its solar phase. The lower cosmogenic background and the large mass of the active detector of SNO+ allow this measurement.

3.2.2 Neutrinoless Double Beta Decay

Double beta decay is a rare process which can be explained as the combination of two beta decays when a single beta decay is energetically forbidden or strongly suppressed. The initial nucleus \((Z, A)\) undergoes double beta decay as

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

This process has been observed for some isotopes. There is a possibility for the double beta decay isotope to undergo the following decay

\[
(Z, A) \rightarrow (Z + 2, A) + 2e^- .
\]
which is known as neutrinoless double beta decay. This process can happen if the anti-neutrino emitted in one beta decay is “re-absorbed” as a neutrino in the second beta decay process. Such an observation could prove that the neutrino is a Majorana particle (a particle that is its own anti-particle) and would allow the determination of its mass. The signature for neutrinoless double beta decay is a small peak in the energy spectrum, at the endpoint of the continuous two neutrinos double beta decay spectrum.

SNO+ is planning to add $^{150}$Nd, the double beta decay isotope, to the liquid scintillator in its first phase. The Q-value, the nuclear transition energy, of $^{150}$Nd is 3.37 MeV which is higher than most of the potential backgrounds. The large Q-value and the large matrix element of $^{150}$Nd make it one of the best isotopes for this phase. The large matrix element contributes to a larger potential rate for the process. A 0.1% loading of neodymium, by weight in the SNO+ liquid scintillator, corresponds to 780 kg of Nd or 56 kg of $^{150}$Nd. While the rate of double beta decay would increase with more Nd dissolved in the liquid scintillator, the optical properties of the scintillator constrain the maximum amount of Nd that can be used. There is a possibility that SNO+ will be able to load the scintillator with enriched $^{150}$Nd. Enriching results in a larger target isotope mass for the neutrinoless double beta decay process to occur while keeping the desired optical properties of the scintillator.

3.2.3 Reactor Anti-neutrinos

Nuclear power reactors produce electron anti-neutrinos via the beta decay of the fission products. Therefore, reactors are powerful and free sources of low energy electron anti-neutrinos ($E_\nu \sim \text{few MeV}$). The flux of anti-neutrinos from reactors
can be well known since it is related to the thermal power of the reactor which is carefully measured. These anti-neutrinos will be detected in the liquid scintillator via the inverse beta decay reaction

$$\bar{\nu}_e + p \rightarrow n + e^+.$$ 

The positron produces scintillation light and quickly annihilates (also producing scintillation light), while the neutron is thermalized and captured on another proton about 200 $\mu$s later, producing a 2.2 MeV $\gamma$. The coincidence of the prompt scintillation light from the positron and the delayed scintillation light from the neutron capture is a signature for the reactor anti-neutrino interaction.

As reactor anti-neutrinos propagate they undergo vacuum oscillations. If a detector is located at a distance on the order of the oscillation length for reactor anti-neutrinos, it will be able to observe neutrino oscillations.

The KamLAND experiment in Japan is located near several Japanese (and Korean) reactors at a typical distance of 180 km. At this distance it was sensitive to $\Delta m^2_{12}$ and the most precise measurement to date of $\Delta m^2_{12}$ was done by KamLAND [28].

SNO+ is going to detect anti-neutrinos mainly from nuclear power reactors in Ontario: the Bruce, Pickering and Darlington nuclear power generating stations will contribute the most to the signal in SNO+. The distance from these reactors to SNO+ is farther than the typical distance of reactors from KamLAND. Therefore, SNO+ is expected to see fewer events compared to KamLAND. However, the distances of these reactors from SNO+ is such that the sum of the oscillation-distorted energy spectra from the different reactors happens to produce energy peak structures which are sharper for SNO+ than KamLAND. This will allow SNO+ to measure $\Delta m^2_{12}$ as well as KamLAND.
3.2.4 Geo Neutrinos

The radioactive isotopes inside the crust and mantle of the earth, especially $^{40}$K and isotopes in the decay chain of $^{238}$U and $^{232}$Th, produce anti-neutrinos via beta decay. These anti-neutrinos are known as geo neutrinos. Geo neutrinos can provide useful information about the amount of radioactivity present deep inside the earth. This radioactivity is important since it is thought to be responsible for a large fraction (50%-100%) of the heat emitted by the earth [29].

The KamLAND experiment did the initial study of the geo neutrinos flux at Kamioka [30]. They provided important first results of geo neutrinos. But because of the low rate of geo neutrinos, the high background from the reactor neutrinos and the small amount of radioactive background inside the detector, their initial results were not precise enough to usefully constrain the amount of the heat production from the inferred $^{238}$U and $^{232}$Th that produced these geo neutrinos.

SNO+ is also able to measure the geo neutrino flux and this measurement should be easier for SNO+ than KamLAND. The predicted rate of geo neutrinos is significantly higher in SNO+ than KamLAND, due to differences in regional geology. In addition, the smaller rate of reactor anti-neutrinos (as one of the main background for geo neutrinos) and hopefully lower backgrounds from the detector, give SNO+ this ability to measure the flux of geo neutrinos.

3.2.5 Supernova Neutrinos

Supernova neutrinos are produced when a massive star undergoes gravitational collapse when its nuclear fuel is exhausted — producing a Type II supernova explosion as a result. When this happens more than 99% of the gravitational binding energy
is released as neutrinos \cite{31}. The number of neutrinos released by the supernova, over the span of a few seconds, is more than the total number of neutrinos emitted during the entire life of the star. These supernova neutrinos are predicted to have an average energy of 15 MeV and are distributed between three neutrino flavours, and include both neutrinos and anti-neutrinos \cite{32}. Because the neutrino flux is so large, a supernova at galactic distances can still be detected easily by a large volume liquid scintillator detector like SNO+. If a supernova explosion happens during the running time of SNO+, useful information can be obtained about neutrino physics and the supernova process itself through the detection of these neutrinos.

3.3 SNO+ Backgrounds

One of the priorities of the SNO+ experiment (like other experiments) is to understand, minimize and even remove backgrounds from its data. Radioactive backgrounds in SNO+ can be classified into two groups: internal and external. The internal backgrounds are those originating from inside the liquid scintillator volume. The external backgrounds are those produced in regions outside the scintillator volume (e.g. light water and acrylic vessel) that leak into or produce counts in the LAB volume.

Naturally occurring radioisotopes such as uranium-238 ($^{238}\text{U}$) and thorium-232 ($^{232}\text{Th}$), with half-lives of $4.47 \times 10^9$ years and $1.4 \times 10^{10}$ years respectively, are two main radioactive backgrounds in SNO+. Figures 3.3 and 3.4 show the decay chains of these two isotopes. As can be seen, many alphas and betas are produced through these chains with different energies and half-lives. Some of these backgrounds produce events in the detector in the energy range of interest. Therefore it is imperative to
understand these backgrounds and keep them away from the vicinity of the scintillator as much as possible. For example, it will be shown in Section 6.1.1 how $^{214}$Bi can be tagged and removed by 99.8% or greater efficiency.

As explained in Section 3.2, SNO+ has a variety of interesting physics goals. Backgrounds for each of these physics signals will be different. But, one of the overriding background concerns is radon. Radon-222 ($^{222}$Rn) is an isotope which occurs in the $^{238}$U chain (Figure 3.3). Radon is naturally occurring in the air and typical ambient levels are equal to about 20 Bq/m$^3$. Unfortunately, mine air contains more radon than the air on the surface of the earth, between 40-100 Bq/m$^3$. Therefore, radon detection and control is very important to study.

Radon detection is carried out using a Lucas cell coated with zinc sulfide (ZnS). In this research, two new types of ZnS from two suppliers were examined to find the one that is more suitable for use. Furthermore, to keep the SNO+ detector away from radon contamination, a cover gas with low radon content is used to prevent the detector from being exposed to surrounding air to reduce the potential of radon contamination. Due to fluctuations in the mine air pressure, cover gas bags are used in the cover gas system. In this research, the fabrication of cover gas bags along with the emanation of the cover gas bag interior was studied.
Figure 3.3: The $^{238}$U decay chain.\[33\]
Figure 3.4: The $^{232}\text{Th}$ decay chain. \[33\]
Chapter 4

Selection of New ZnS and Data Analysis

Detecting and measuring $^{222}\text{Rn}$ is an important task in the SNO+ experiment since radon and radon daughters are important backgrounds. One of the troublesome daughters of radon decay is $^{214}\text{Bi}$, a major background for studies at lower energy, i.e. the range of interest in this thesis. Detection of $^{222}\text{Rn}$ directly determines the amount of $^{214}\text{Bi}$ because all nuclides after $^{222}\text{Rn}$ and before $^{214}\text{Bi}$ have short lifetimes (Figure 3.3). In other words, these nuclides are in equilibrium with each other and therefore the detection of $^{222}\text{Rn}$ provides a measure of the relevant backgrounds for the SNO+ experiment.

One technique for measuring radon, which has been used at Queens University since 1991 [1], is to extract radon from different materials by using a radon board and transferring it to a Lucas cell [34]. Counting the output of a Lucas cell by a counting system provides the rate of emanated radon from that material.

The hemispherical Lucas cells available at Queen’s University use silver-activated
zinc sulfide \((\text{ZnS(Ag)})\) as a radon detector. Using these Lucas cells for more than ten years has increased their background rate and thus they are no longer suitable for being used in measuring low-rate radon materials. The reason for increasing backgrounds as Lucas cells get old is the presence of \(^{210}\text{Pb}\), one of daughter isotopes of radon decay, and the decay of the daughters of \(^{210}\text{Pb}\). Based on Figure 3.3, as \(^{214}\text{Po}\) undergoes alpha decay, \(^{210}\text{Pb}\) with a half-life of 22.26 years is produced. \(^{210}\text{Pb}\) sticks to the surface layer of Lucas cells and its decay increases the Lucas cell background. One of the daughters of \(^{210}\text{Pb}\) is \(^{210}\text{Po}\) which undergoes alpha decay. This alpha emitter which is fed by \(^{210}\text{Pb}\) increases the Lucas cell background. The available Lucas cells at Queen’s originally had low number of background \((3\pm1 \text{ counts/day})\). However, after being used for several years, now they have background around 10 counts/day. As a conclusion, new Lucas cells were required for performing high-sensitivity radon detection for experiments being developed by the group at Queen’s, such as SNO+.

Besides the problem with old Lucas cells, the W.B. Johnson company which used to provide the ZnS(Ag) required for making Lucas cells is no longer supplying ZnS(Ag). Therefore new ZnS(Ag) supplier(s) must also be found.

In this section, the fabrication of new Lucas cells along with the associated counting system is explained. A new proposed data analysis algorithm used in the counting system is described. Two ZnS(Ag) suppliers, Rexon \[35\] and Eljen \[36\], were found. In order to select the product which is more sensitive to radon detection, both products were used in the new Lucas cells. The results obtained from the comparison of these two products are demonstrated and discussed. The selection is based on performance criteria like having low background and high light yield.


4.1 Lucas Cell

A Lucas cell is a scintillation particle detector used to count the radioactive decay of a gas sample. In this research work, it is used to measure the radon emanated from a material in vacuum. In this section, the structure of the Lucas cell used in our experiments is described.

A Lucas cell consists of a chamber made of materials with low radioactive background such as acrylic or stainless steel (a hemispherical acrylic chamber in our experiment). The inside surface of a Lucas cell is coated with ZnS(Ag), an inorganic scintillator. The passage of energetic particles through the ZnS produces scintillation light. The intensity of the emitted light can be greatly increased by the addition of some elements such as Ag. These elements are known as activators. ZnS(Ag) scintillator is usually used to count alpha particles. The top of a chamber, called a window, is transparent to allow the light produced in the ZnS(Ag) to be detected. Figure 4.1 shows the structure of the Lucas cell available at Queen’s. The principal advantage of this kind of Lucas cell as a detector is reasonably high efficiency with low background.

Lucas cells are evacuated and filled with a gas sample emanated from the material under test. Alpha particles emitted from radon and radon daughters in the gas sample interact with ZnS(Ag) and produce light flashes. A photomultiplier tube (PMT) is coupled to the top of the Lucas cell in order to detect these flashes.

4.1.1 Lucas Cell Fabrication

In order to fabricate a Lucas cell, the technique described in [37] was used. A hemispherical chamber, made out of UVT acrylic, was cleaned with Alconox soap and hot
water and dried. The volume of this chamber is $15 \text{ cm}^3$. Approximately 1.5 g of ZnS(Ag) and 4 mL of 1,3-dioxolane were mixed together to make a milky solution. An eyedropper was filled halfway, around 1 mL, with this solution and drops were put all along the side of the hemispherical chamber. Then the Lucas cell had to be rotated to make sure that the entire hemisphere was coated with an even layer of ZnS. After letting the Lucas cell dry for several hours, the window was attached to the coated hemispherical chamber by using dichloromethane which dissolved the acrylic and adhered these together. Connecting the Swagelok Quick Connect (see Figure 4.1) was the last stage of making a Lucas cell. Teflon tape was used to attach the Swagelok Quick Connect in order to prevent any leak. The entire process of fabricating a Lucas cell had to be done in a clean room.

The Lucas cell must be tested for leaks before use. This was accomplished by using a helium leak checker (a Leybold UL-200). First the Lucas cell was connected to the helium leak checker and pumped out. Then helium was sprayed around different parts
of the Lucas cell. If helium passes through a leak it will be detected by the helium leak checker. This device has a sensitivity of $10^{-8}$ mbar-L/s which is equivalent to almost 0.3 radon atoms per day. The Lucas cells that were fabricated were checked with this device and showed no leak at this level.

### 4.2 Alpha Counting System

An alpha counting system is used to count the scintillation events from alpha particle interactions with ZnS inside the Lucas cell. Later the results are used to determine the emanated radon from the material under test.

The alpha counting system consists of a high voltage (HV) power supply, a PMT, a spectroscopy amplifier, a 16-channel multichannel analyzer (MCA) and a computer. The HV source supplies 800 V to the PMT which is placed in a small black wooden box. The Lucas cell can be easily put in or taken out of this box. The output of the PMT goes to the amplifier (ORTEC 572). After amplification, signals are sent to a 16-channel MCA which is connected to a computer (Figure 4.2). The MCA model used is an ORTEC 920E, and the software used is Maestro-32, a MCA emulation software package. This software controls the MCA hardware and provides live spectral display.

The MCA is used to sort and count the events in real time. The sorting is based on a specific characteristic of the events. The characteristic of interest in our case is

![Diagram of counting system](image-url)
the height of the pulses which is proportional to the particle’s energy. An analog-to-
digital converter (ADC) which is part of the MCA is used to convert the height of
the pulses into a channel number. As pulses arrive over time, the MCA collects them
and draws a histogram which shows the distribution of number of pulses with respect
to the pulse height.

4.3 Analyzing Data

It is a well-known fact that noise can cause erroneous results in counting systems
especially when the number of counts is low. In this regard, many efforts are made to
reduce the noise level in the counting system as low as possible. Despite these efforts,
not all noise can be eliminated. Therefore, one can try to further reduce the effect
of noise by performing data processing techniques on the data set. In this section,
a method is explained by which the impact of random noise is reduced by collecting
the data in several intervals and then performing data analysis on them. All analysis
in this research work was carried out using the ROOT analysis package developed by
CERN.

4.3.1 Noise and Signal Regions

In order to distinguish between noise and the main signal, a preliminary process was
performed on the raw data. In this process, the data were separated into two regions:
the noise region and signal region (or the region of interest). In order to find the
boundary between these two regions, a Lucas cell with a built-in uranium source,
i.e. a spiked source, was used. An isotope like uranium emits a large number of
alpha particles and thus can be used for this purpose. Figure 4.3a shows a spectrum obtained with a uranium source. In this spectrum, a dip region can be observed around channel 40. Also shown in Figure 4.3b is a spectrum obtained from the counting system with no Lucas cell which represents the measurement system noise only. From the comparison of these two spectra, it can be concluded that the region of interest is after channel 40.

It is worth noting that there are 3 alphas before $^{210}$Pb in the decay chain of radon, as shown Figure 3.3. Therefore, one expects to see three peaks corresponding to each alpha in this spectrum. However, the energy of these alphas, especially those coming from $^{222}$Rn (5.5 MeV) and $^{218}$Po (6 MeV), are very close to each other. Therefore, it is hard to distinguish the peaks corresponding to the three alphas as a result of the counting system’s limited resolution; thus only one broad peak is visible in this spectrum.

### 4.3.2 Data Processing

The first step in the proposed method is to collect the output data of the counting system in sequential intervals with equal length of time instead of gathering them in just one data set. This enables us to analyze the data in each interval separately and then remove unacceptable intervals. The criterion for detecting unacceptable intervals is explained below.

Sometimes there is a relationship between the counts in the noise and signal regions. This happens, for example, when a burst of noise affects the number of counts in the signal region. This results in a correlation between the variation of
Figure 4.3: (a) The spectrum of a Lucas cell with a uranium source and (b) the spectrum obtained from the counting system without any Lucas cell.
the counts in the noise region and that of the signal region. In such circumstances, when
the number of counts is high in the noise region, it is usually high in the signal
region as well. Therefore, those intervals in which the number of noise counts has
significantly affected the number of counts in the signal region must be removed.

After collecting the data in equal-length intervals, it must be determined whether
or not there are any unacceptable intervals. In order to do that, the correlation
between the number of counts in the noise and signal regions in the complete data
set is calculated based on linear correlation coefficient \( r \) given by [38]:

\[
r = \frac{N \sum x_i y_i - \sum x_i \sum y_i}{[N \sum (x_i)^2 - (\sum x_i)^2]^{1/2}[N \sum (y_i)^2 - (\sum y_i)^2]^{1/2}}
\]  

where \( N \) is the number of intervals, \( x_i \) is the number of counts in the noise region in
each interval and \( y_i \) is the number of counts in the signal region in each interval. The
value of \( r \) ranges from -1 to 1, where zero corresponds to no correlation and 1 or -1 to
complete correlation. In this way, one can determine how much the noise and signal
counts are correlated in the complete data set. If the correlation is high, i.e. \( r > 0.5 \)
in our case, a flag is set in the analysis program showing that each data interval must
be checked separately in order to find those with unacceptable number of noise counts
as compared to the number of signal counts. The next question was how to find the
threshold for identifying unacceptable noise counts in any interval. This threshold
was simply set as two sigma greater than the average noise counts in the complete
data when the correlation is low, i.e. \( r < 0.1 \) in our case. When the unacceptable
intervals are removed, the correlation is calculated again to make sure that noise and
signal counts are well uncorrelated. It was observed that by this method typically
less than 5% of data intervals were eliminated. The final result is obtained by adding
up the integral of the signal region in each interval that was not removed.
4.4 Testing Different ZnS Products

W.B. Johnson company is no longer supplying ZnS which used to be employed in Lucas cells fabricated at Queen’s University. Therefore, two new suppliers, Rexon and Eljen were identified as potential sources of ZnS required for making the new Lucas cells. Since the quality and suitability of the ZnS supplied by these suppliers were not known, it was decided to run two tests using these two products in order to find the one which is better suited to our application.

In the process of making the cell, Rexon’s ZnS has an advantage over Eljen’s ZnS as it easily stuck to the acrylic while we had some difficulties in sticking Eljen’s ZnS to the acrylic. This is important especially when more than one cell is to be made.

After fabrication of the cells, they needed to be tested for background and light yield. For background measurement, each Lucas cell was evacuated for about 24 hours and then used for counting for about a week or more to obtain enough statistics. The results of background obtained from these two products is in Table 4.1. As can be seen, the background from Rexon’s ZnS is less than that of Eljen.

To confirm using the Rexon product in our Lucas cells, the light yields of Eljen and Rexon ZnS were measured. In doing so, Rexon and Eljen Lucas cells filled with radon extracted from a material with high radon emanation were used. The counting process was carried out for 3 days. Figure 4.4 shows the results of these experiments. As can be seen, the mean of the spectrum obtained by the Rexon Lucas cell is slightly higher than the mean of the spectrum for the Eljen Lucas cell. Rexon

<table>
<thead>
<tr>
<th>REXON Background (counts/day)</th>
<th>Eljen Background (counts/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 ± 1</td>
<td>7 ± 1</td>
</tr>
</tbody>
</table>

Table 4.1: Lucas cell backgrounds.
ZnS has a slightly higher light yield. In conclusion, with lower background, slightly higher light yield and easier application during fabrication, Rexon ZnS was chosen for making new Lucas cells.
Figure 4.4: Comparing two spectra based on their light yield. (a) The spectrum of a Rexon Lucas cell after counting for 3 days. (b) The spectrum of an Eljen Lucas cell after counting for 3 days.
Chapter 5

Cover Gas Bag

The SNO+ experiment will be measuring low energy solar neutrinos by using a liquid scintillator as an active detector. In order to be able to detect these neutrinos, the background should be reduced as much as possible. One of the main backgrounds in low energy experiments is $^{222}$Rn which is one of the daughters of $^{238}$U. Radon is a noble gas that can easily penetrate through different materials. The air in underground labs like SNOLAB contains an elevated amount of radon as compared to the air on the surface of the earth. Experiments like SNO+ can be significantly affected by radon in mine air, or in ordinary air for that matter. Therefore, one of the main concerns of these types of experiments is to reduce the amount of radon getting into the detector as much as possible.

Sealing the detector (or AV) from mine air and using ultra-pure nitrogen gas as a cover gas can significantly reduce the amount of radon getting into the detector. However, one problem that arises with sealing the system is that pressure fluctuations in the mine air (which could be as large as 10 kPa [39]) can develop pressure differentials which could cause an excess strain on the detector. To adapt to the pressure
fluctuations, it has been proposed to use flexible bags, known as cover gas bags, and attach them to the system via appropriate stainless steel pipes. The cover gas which fills the upper part of the AV can flow into these bags. Consequently, the inflation and deflation of these flexible bags will react to the variation of mine air pressure. On the other hand, these bags must act as radon barriers and therefore it is essential to make them from materials with low permeability to radon.

The inflation and deflation of the bags will cause electrostatic charges in the bags which is problematic for the experiment. In fact, the light produced by these electrostatic charges could travel through the stainless steel pipes and enter the AV and therefore interfere with the scintillation light produced by the signals of interest. In this regard, different configurations of stainless steel pipes can be used in the cover gas system in order to reduce the amount of electrostatic light that could get into the AV.

In this chapter, selection of material and the fabrication of cover gas bags will be explained. The number of radon atoms entering the bags as the result of diffusion was calculated and will be described. Also, the method used to find the rate of radon emanation from the bag interior will be described. Furthermore, the result of different configurations of the stainless steel pipes used to reduce the light produced by inflation and deflation of the bags will be discussed.

**5.1 Cover Gas Bag Material**

The first step for fabricating a cover gas bag is to choose a suitable material. The chosen material should have a low radon emanation rate and at the same time low permeability to radon diffusion. The bag material should also be strong and flexible
enough against various strains resulting from continuous inflation/deflation. This is very crucial for long-term use of these bags without developing considerable pinholes. DuPont and Tropack were two proposed manufacturers of multi-layer materials for fabrication of cover gas bags. In the middle of materials made by both manufacturers there is an aluminum foil layer which is impermeable to gases, especially radon. A preliminary result of radon emanation of both materials (both inside and outside surfaces) was in favour of DuPont. TROPAC, the name of the material manufactured by Tropack, has 330 atoms/day and DuPont has 210 atoms/day for a 200 L bag. The measurement of the radon emanation of the DuPont bag interior is presented in Section 5.4.2. TROPAC material was found to be more sensitive to developing pinholes than DuPont and thus needs to be handled with more care. Therefore, DuPont was chosen as the material for cover gas bag fabrication.

Based on the manufacturer data sheet, the composition of the DuPont multi-layer bags from outside to inside is: a nylon layer for strength, aluminum foil for impermeability to gases, and a clear low density polyethylene (LDPE) layer used for heat sealing the material to itself. The permeability of the DuPont roll material to radon was calculated and is presented in the next section.

The first DuPont material used for the test was in the form of pre-made bags (intended to carry milk). As these bags are folded for transportation, some pinholes are developed in the folded parts. Therefore, it was decided to use a new roll of DuPont material and fabricate the bags in-house.
5.2 Radon Diffusion Rate of DuPont Material

One of the important criteria for choosing material for making a cover gas bag is low permeability to radon. The diffusion permeability rate of DuPont roll material to O\textsubscript{2} gas, based on its data sheet, is less than 0.1 mL/m\textsuperscript{2}/day. Graham’s law \cite{40} was used to convert the diffusion rate of oxygen gas to radon. The law states that the diffusion rate of each gas is inversely proportional to the square root of the molar mass of the gas. Therefore

\[
D_{Rn} = \sqrt{\frac{M_{O_2}}{M_{Rn}}} D_{O_2}
\]  

(5.1)

where \(D_{Rn}\) is the diffusion rate of radon, \(M_{O_2}\) is the molar mass of oxygen gas which is equal to 32, \(M_{Rn}\) is the molar mass of radon which is equal to 222 and \(D_{O_2}\) is the diffusion permeability of DuPont material to oxygen gas which is less than 0.1 mL/m\textsuperscript{2}/day. Based on Equation 5.1, the diffusion rate of DuPont material for radon is calculated to be less than 0.038 mL/m\textsuperscript{2}/day. On the other hand, the activity of the radon in mine air, \(A\), is 3 pCi/L or 111 Bq/m\textsuperscript{3} \cite{41}. Therefore, the concentration of radon atoms, \(N\), can be obtained from:

\[
N = \frac{A}{\lambda}
\]

(5.2)

where \(\lambda\) is the radon decay constant which is equal to 0.18/day or 2.1\times10^{-6}/s. Equation 5.2 results in \(N = 5.3\times10^7\) atoms/m\textsuperscript{3}. Consequently, the production rate of radon, \(p\), is obtained by:

\[
p = D_{Rn}N
\]

(5.3)

which is equal to 2.3\times10^{-5} atoms/m\textsuperscript{2}/s. For one bag with surface area of 3.1 m\textsuperscript{2}, this amount is equal to 7.2\times10^{-5} atoms/s. After steady-state conditions are reached, the
number of atoms inside the bag, \(N_2\) is:

\[
N_2 = p\tau
\]  

(5.4)

where \(\tau\), the mean lifetime of radon, is \(4.77 \times 10^5\) s and therefore the number of atoms inside the bag would be less than 34 atoms. Therefore, the number of radon atoms penetrating the bag because of diffusion, in steady state, is less than 136 radon atoms for four cover gas bags.

5.3 Fabrication of a Cover Gas Bag

The cover gas bags must adapt to pressure fluctuations by supplying or removing a volume of gas above the detector equal to between 284–436 L (because the volume of the gas space in the detector is 880 L). Although this volume can be achieved by one bag, it was decided to use four bags in order to make the system redundant. The fabrication of a cover gas bag started by cutting two pieces of the material with the dimensions of 1.00 m by 1.56 m. This dimensions were taken from the pre-made 200 L DuPont bags. The most effective way to attach these two pieces and make a gas-tight bag is heat sealing. A DuPont bag is heat sealed to itself easily. The heat sealer system, which was developed before this study, was a hand roller ordered from McMaster-Carr. This hand roller was attached to a steel rail system to allow the heat sealer to roll and seal along a straight line (Figure 5.1). The DuPont material was sealed at a temperature around 130°C. After three sides of the bag were heat sealed, a fitting was attached to the middle of one side of the bag (Figure 5.2). The fitting was made of stainless steel and designed to attach the bag to 2" pipes in the cover gas system. Double O-rings were used in the fitting to ensure gas tightness. The last
step was to heat seal the fourth side of the bag. Each bag needed to be leak checked after fabrication. For leak checking, helium gas along with a Leybold UL-200 helium leak checker in sniffer mode with sensitivity of $10^{-8}$ mbar-L/s was used. Each bag is leak checked everywhere, especially seams and around the fitting. In the case of leaking around seams, the bag could be heat sealed again. In order to deal with the problem of developing pinholes in the bag, a black rubberized spray, Performix Brand Plasti Dip, similar to paint spray was used. This process was performed 5 times with one hour wait time between coat applications. This gave a thick enough coating to reduce the chance of pinholes. The rubberized bag is now ready for using in the cover gas system.

5.4 Radon Emanation of the DuPont Bag

The radon emanated from the bag interior directly affects the total amount of radon in the cover gas system. In preliminary results, the bag emanation (both inside and outside) was measured to give a rough idea about the material emanation. In this section, the procedure carried out for measuring the emanated radon from the bag interior is explained.

5.4.1 Radon Emanation System for a Material in Vacuum

The radon emanation system is used to extract the radon emanated from different materials in vacuum and transfer it to a Lucas cell. The radon emanation system consists of a chamber, a radon board and a vacuum pump. This system has been used at Queen’s for more than twenty years. In order to extract radon from a material,
Figure 5.1: Heat sealer used for sealing the cover gas bags.

Figure 5.2: Small cover gas bag with the fitting in the middle.
the material is placed inside the chamber. The sealed chamber is evacuated for about 24 hours. Then the material sits inside the chamber for at least 3 days to let the emanated radon be released and collected in the chamber. After 3 days, the chamber is connected to a radon board which has been pumped out several hours prior to the extraction. There are two traps in the radon board, known as the large and the small traps. The volume of the small trap is about 20 times less than that of the large one. The large (primary) trap is cooled with liquid nitrogen (LN$_2$). The radon from the test material is trapped inside the cooled large trap. It is then transferred to the small (secondary) trap by warming the large trap. The small trap is immersed in LN$_2$ prior to being used for trapping the radon. The radon in the small trap is transferred to a Lucas cell by warming the small trap. The reason for the smaller volume of the small trap compared to the large trap is to let most of radon expand into the Lucas cell. Finally, the Lucas cell will be counted by a counting system to get the rate of the emanated radon from the test material.

It is necessary to perform several emanations to reach to the steady-state emanation rate and eliminate the effects of adsorbed radon on the surface of the material and the chamber.

5.4.2 Emanation Procedure for the Bag Interior

A small bag was made with DuPont material for the purpose of radon emanation. The same procedure (including rubberizing) of making the normal cover gas bag described in Section 5.3 was used for making this bag. The surface area of the bag was 0.17 times the main 200 L bag. The bag was filled with 10 L of helium. Then the rate of radon from the bag interior was measured by emanating the bag using the radon
emanation system. The helium filled bag was connected directly to the radon board. The connection diagram of this experiment is shown in Figure 5.3. As can be seen, a flowmeter was used to measure the amount of helium transferred to the board.

The flowmeter measured the gas flow rate in units of SCFH (standard cubic feet per hour). There is a correction factor for different gases based on their density that should be taken into account. The correction factor for helium is 0.37 with respect to air. Therefore, if the flow meter is adjusted for 0.3 SCFH for helium, it means that after 20 minutes almost 1.05 liter of helium has passed through the flow meter.

The whole radon board and the pipe connected to the bag were evacuated for several hours prior to radon extraction. Then, both traps were cooled with liquid nitrogen. The extraction began by opening the valve at the helium bag while the V5 (see Figure 5.3) was closed. The needle valve was used to adjust the helium flow rate monitored by the flowmeter. Helium flowed through the radon board, transporting any emanated radon along with it, to be trapped. An ideal operation would have trapped most of the radon in the large trap by adjusting the flowmeter to a very low rate, say 0.2-0.3 SCFH. An extraction like this would take about 10-20 minutes. Longer extraction times would increase the amount of radon in the small trap.

First the amount of radon in the small trap was extracted by warming the trap and transferring the radon into a Lucas cell which was then removed. While the V11 was closed, all the valves from the small trap to the vacuum pump were opened in order to evacuate the pipes after the small trap. After evacuation, the small trap was cooled again with LN₂. The radon in the large trap was then transferred to the small trap by warming the large trap. Again the radon in the small trap was transferred to another Lucas cell by warming the small trap. Two Lucas cells were filled by the
Figure 5.3: Extracting radon from the helium-filled bag using the radon board.
trapped radon in the small and large traps and were counted in two counting system.

5.4.3 Converting Lucas Cell Counts to Radon Emanation Rate

A Lucas cell is used to measure the radon gas concentration. Alpha particles coming from the decay of radon produce scintillation when they strike the ZnS coating; these scintillations are subsequently counted by a PMT. As shown in Figure 3.3, there are three alphas associated with a radon decay. The multiplicity of alphas is accounted for to determine the number of radon atoms counted in the Lucas cell. The procedure for converting the number of Lucas cell counts to the number of radon atoms emanated from the source (such as the bag) is described below [1], [42]. Table 5.1 shows the parameters used in this calculation.

In the first step, the Lucas cell counts must be corrected by subtracting the Lucas cell background counts in order to obtain the counts corresponding to the main source. Therefore:

\[ H = C - b_{L}t_c \]  (5.5)

where \( H \) is the corrected number of Lucas cell counts. In order to obtain the number of radon atoms that decayed in the Lucas cell, \( R \), the corrected number of Lucas cell counts, \( H \), should be divided by \( 3 \times E_{\text{lucas}} \) to account for three alphas associated with each radon decay and the Lucas cell efficiency.

\[ R = \frac{H}{3E_{\text{lucas}}} \]  (5.6)

Radon decays exponentially with half-life of 3.82 day. Therefore, the number of radon
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Lucas cell counts</td>
<td>C</td>
</tr>
<tr>
<td>Uncertainty of Lucas cell counts</td>
<td>$\delta C$</td>
</tr>
<tr>
<td>Number of radon atoms</td>
<td>R</td>
</tr>
<tr>
<td>Uncertainty of number of radon atoms</td>
<td>$\delta R$</td>
</tr>
<tr>
<td>Efficiency of Lucas cell</td>
<td>$E_{lucas} = 0.74$</td>
</tr>
<tr>
<td>Uncertainty of the Lucas cell efficiency</td>
<td>$\delta E_{lucas} = 5% E_{lucas}$</td>
</tr>
<tr>
<td>Efficiency from the small trap to Lucas cell</td>
<td>$E_{small} = 0.64$</td>
</tr>
<tr>
<td>Efficiency from large trap to the small trap</td>
<td>$E_{large} = 0.75$</td>
</tr>
<tr>
<td>Efficiency from chamber to large trap</td>
<td>$E_{cham} = 1$</td>
</tr>
<tr>
<td>Emanation time</td>
<td>$t_e$ (d)</td>
</tr>
<tr>
<td>Counting time</td>
<td>$t_c$ (d)</td>
</tr>
<tr>
<td>Radon half-life</td>
<td>$t_{1/2} = 3.8235$ (d)</td>
</tr>
<tr>
<td>Radon decay constant</td>
<td>$\lambda = \frac{\ln 2}{t_{1/2}} = 0.18$ ($d^{-1}$)</td>
</tr>
<tr>
<td>Lucas cell background (counts/d)</td>
<td>$b_l \pm \delta b_l$</td>
</tr>
<tr>
<td>Chamber background emanation rate (atoms/d)</td>
<td>$b_c \pm \delta b_c$</td>
</tr>
</tbody>
</table>

Table 5.1: Parameters used for converting the Lucas cell counts to radon emanation rate of the source material [1, 42].
atoms when the counting started, $M$, can be calculated as:

$$M = \frac{R}{1 - e^{-M_c}}$$

(5.7)

To obtain the number of radon atoms in the chamber, the efficiency from the chamber to the large trap, from the large trap to the small trap and from the small trap to the Lucas cell should be multiplied by each other. Therefore, the number of radon atoms in the chamber, $F$, is:

$$F = \frac{M}{E_{small}E_{large}E_{cham}}$$

(5.8)

Since the source (the material in the chamber or helium in the bag) has been left for several days to emit the radon, the rate of the emitted radon inside the chamber, $V$, can be obtained as:

$$V = \frac{\lambda F}{1 - e^{-M_c}}$$

(5.9)

The chamber itself has a background and emits radon with a known emanation rate. Therefore, the source emanation rate, $S$, can be calculated as:

$$S = V - b_c$$

(5.10)

In the case of the bag only, the chamber emanation rate was set to zero.

In order to find the uncertainty of the source emitter rate, the uncertainty of each step of the calculation from Equation \[5.5\] to \[5.10\] should be calculated based on the general formula (in Equation \[5.11\]) for calculating uncertainty when the calculated quantity depends on more than one variable. This formula for a quantity like $h$ which depends on $x_1, x_2, ..., x_n$ is given by

$$\delta h = \sqrt{\left(\frac{\partial h}{\partial x_1}\delta x_1\right)^2 + \left(\frac{\partial h}{\partial x_2}\delta x_2\right)^2 + ... + \left(\frac{\partial h}{\partial x_n}\delta x_n\right)^2}$$

(5.11)

For calculating uncertainty, it should be noted that the number of radon atom decays
follows a Poisson distribution with $\delta R = \sqrt{R}$. Also the number of Lucas cell counts is related to the number of radon atoms with the same relative uncertainty. Therefore, the uncertainty of the number of Lucas cell counts can be obtained by (5.12):

$$R = \frac{C}{3E_{\text{lucas}}}$$

$$\frac{\delta R}{R} = \frac{\delta C}{C}$$

$$\delta C = C' \frac{\delta R}{R} = \frac{C}{\sqrt{R}} = \frac{C}{\sqrt{3E_{\text{lucas}}}}$$

$$\delta C = \sqrt{3CE_{\text{lucas}}}.$$ (5.12)

5.4.4 Results of Radon Emanation of the DuPont Bag

The emanation process was carried out for different time intervals for the small helium-filled DuPont bags as describe in Section 5.4.2. The results obtained from these tests are shown in Table 5.2 and used to calculate the amount of emanated radon from the 200 L. The first result after one week showed a high radon rate and it was hypothesized that the helium that was used to fill the bag carried in radon from the helium tank. After 3 weeks this radon is decayed and the emanation values in Table 5.2 are significantly reduced.

The target level for the $^{222}\text{Rn}$ in SNO+ experiment is 4890 atoms/year or 13.4 atoms/day, at levels comparable to Borexino. The radon coming from the cover gas system will decay in the neck of the SNO+ detector and it is expected that the radon activity transported into the spherical volume of the detector will be reduced by a

<table>
<thead>
<tr>
<th></th>
<th>time from filling the bag</th>
<th>atoms/day (10 L bag)</th>
<th>atoms/day (200 L bag)</th>
</tr>
</thead>
<tbody>
<tr>
<td>First attempt</td>
<td>one week</td>
<td>255±105</td>
<td>1500±617</td>
</tr>
<tr>
<td>Second attempt</td>
<td>four weeks</td>
<td>&lt; 67</td>
<td>&lt; 394</td>
</tr>
<tr>
<td>Third attempt</td>
<td>seven weeks</td>
<td>13±8</td>
<td>76.5±48</td>
</tr>
</tbody>
</table>

Table 5.2: Result of the emanation of the bag interior.
factor of 50 [43]. From the results shown in Table 5.2, the radon emanation of four 200 L bags would be $306 \pm 96$ atoms/day into the cover gas. Also, fewer than 136 radon atoms penetrate into the bag as a result of diffusion as explained in Section 5.2. Therefore, in total the radon atoms induced by the cover gas bags are fewer than $442 \pm 96$ atoms/day, as an upper limit. From these calculation less than 9 atoms/day get into the AV from the cover gas bags.

### 5.5 Reducing the Electrostatic Light Produced by Cover Gas Bags

It was explained in the introduction how the inflation and deflation of cover gas bags could result in electrostatic charges and produce light which can interfere with the light produced by the main signals in the detector. One method to reduce the effect of this unwanted light is to arrange the connecting pipes such that they attenuate this light. In this section, the configuration of these pipes and their attenuation are described.

Reference [44] states that it is required to attenuate the light intensity by five orders of magnitude. In order to measure the light attenuation in different pipes, the

<table>
<thead>
<tr>
<th>Pipe</th>
<th>Intensity Ratio (output/initial)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10&quot;</td>
<td>$0.90 \pm 0.02$</td>
</tr>
<tr>
<td>20&quot;</td>
<td>$0.89 \pm 0.02$</td>
</tr>
<tr>
<td>elbow</td>
<td>$0.26 \pm 0.02$</td>
</tr>
<tr>
<td>Tee</td>
<td>$0.0050 \pm 0.0007$</td>
</tr>
<tr>
<td>elbow and 10&quot;</td>
<td>$0.100 \pm 0.004$</td>
</tr>
<tr>
<td>Tee and 10&quot;</td>
<td>$(1.3 \pm 0.1) \times 10^{-3}$</td>
</tr>
</tbody>
</table>

Table 5.3: Light attenuation in highly polished stainless steel pipes.
intensity of light before and after each pipe was measured. High polished stainless steel pipes with 2 inches outer diameter, similar to what is going to be used in the SNO+ cover gas system, were used for this study. A light bulb was used as the light source and an optical power meter (OPM) used for measuring the intensity of light, as illustrated in Figure 5.4. An OPM is a device used to measure the power in an optical signal. The Newport 1815-C Power Meter which was used in this study is capable of measuring from nanowatts to kilowatts. As a beam of light passes through these pipes, it can lose its intensity by two processes. The light can be absorbed and/or can be scattered by these pipes. The results of these measurements are shown in Table 5.3. It can be seen that the light is reduced by $10^3$ by using a Tee and a 10" pipe. Using two Tees and two 10" pipes gives a reduction of $10^6$, which meets the requirements.
Figure 5.4: Set up for measuring light attenuation in stainless steel pipe; in this figure a Tee and a 10 inch pipe has been used.
Chapter 6

$^8\text{B}$ Solar Neutrinos at Lower Energies

The SNO+ experiment is going to use linear alkylbenzene (LAB) as an active detector. LAB is an organic scintillator which produces significantly more light than water and the Čerenkov process (the process used in the SNO experiment). That makes SNO+ more sensitive to the lower energy spectrum of solar neutrinos.

In this chapter, the sensitivity of SNO+ to $^8\text{B}$ solar neutrinos in the energy range of 2.5 to 5 MeV is described. SNO+ will be able to confirm some of the SNO results for energies beyond 3.5 MeV. SNO+ will have increased sensitivity to observe the MSW-predicted upturn in the survival probability where larger distortions in the energy spectrum appear for energies between 2.5 to 3.5 MeV.
CHAPTER 6. $^8B$ SOLAR NEUTRINOS AT LOWER ENERGIES

6.1 $^8B$ Signal and Backgrounds

The $^8B$ neutrino signal in SNO+ will be detected through the neutrino elastic scattering interaction with the target electrons in the LAB molecules. These recoil electrons, as charged particles, deposit energy as they pass through the LAB and produce scintillation light which will be detected by the PMTs. From the recoil electron energy spectrum, the neutrino energy spectrum will be extracted based on the differential scattering cross section.

There are two radioactive background sources in the SNO+ experiment, namely internal and external. In this study, only the internal backgrounds, i.e. those originating from within the LAB volume, were used. The external backgrounds, i.e. those which are produced in regions outside the scintillator volume (e.g. light water and acrylic vessel) and leak into the scintillator volume, are also present. The number of these backgrounds decreases exponentially with the distance from the edge of the AV. By defining a fiducial volume inside the AV, these backgrounds can be neglected. In this study, a 50% fiducial volume cut was assumed to reject the external backgrounds.

There are three main backgrounds to consider in the energy range of 2.5 to 5 MeV, namely $^{214}\text{Bi}$, $^{208}\text{Tl}$ and $^{10}\text{C}$. The $^{214}\text{Bi}$ and $^{208}\text{Tl}$ originate from the naturally occurring radioisotopes $^{238}\text{U}$ and $^{232}\text{Th}$ respectively. $^{10}\text{C}$, on the other hand, is a cosmogenic background which is produced by cosmic ray interactions with $^{12}\text{C}$ in LAB. In the next sections, these backgrounds will be discussed in more detail. A technique for tagging and removing $^{214}\text{Bi}$ events will be described.
Figure 6.1: The main backgrounds in the energy range of 2.5 to 5 MeV, for two-year livetime inside the 50% fiducial volume. Borexino background levels were used for these estimates. This plot shows the backgrounds without additional reduction.

6.1.1 $^{214}$Bi Tagging by Beta and Alpha Particles

Radiation from naturally occurring radionuclides such as $^{238}$U and its daughters is a potential source of background in the SNO+ detector. The short-lived isotope $^{214}$Bi which occurs after $^{222}$Rn in the $^{238}$U chain is one of the most important backgrounds to study for SNO+. As shown in Figure 3.3, it has a beta decay to $^{214}$Po > 99% of the time with a Q-value of 3.27 MeV. The energy deposited by the $^{214}$Bi beta decay is in the energy range of interest for $^{8}$B solar neutrinos, as shown in Figure 6.1. In this section, the procedure proposed to tag and remove this background is described.

Following the $^{214}$Bi beta decay, $^{214}$Po will alpha decay to $^{210}$Pb with a half-life of 164 $\mu$s. These beta and alpha events are in coincidence with each other. This coincidence can be detected by using a sequence of cuts to select the events that occur within several half-lives of $^{214}$Po. By this procedure, which is called beta-alpha
tagging, the $^{214}\text{Bi}$ can be tagged and rejected from the data sets. It should be noted that due to the quenching of the scintillation light produced by alpha particles, the 7.7 MeV alpha from $^{214}\text{Po}$ is observed in LAB-PPO at a much lower energy of around 0.8 MeV.

To tag the $\beta$ and $\alpha$ which are in coincidence with each other and reject the $^{214}\text{Bi}$, one wants to identify any event that could have been from $^{214}\text{Bi}$ decay by searching for the $\alpha$ from $^{214}\text{Po}$ in a coincidence window given by the time between the emission of the $\beta$ and $\alpha$. The length of the coincidence window, which is taken as several half-lives of $^{214}\text{Po}$ (164 $\mu$s) can change the efficiency of tagging a $^{214}\text{Bi}$ background event and the accidental probability of losing a true signal event. If this coincidence window is very short, then while the probability of losing signal will be very low, the probability of identifying a coincident event will also be low. On the other hand, if the time window is very long, while there will be a greater chance to identify a coincidence event, there will also be a higher probability of accidentally rejecting the signal. Having low signal loss and high background rejection are the main parameters for choosing the best window length.

To determine the optimum coincidence window length, the theoretical time efficiency is defined by:

$$\epsilon = e^{-\lambda t_1} - e^{-\lambda t_2}$$

(6.1)

where $t_1$ is the event trigger time window of the electronics to be used in SNO+ and equal to 400 ns, $t_2$ is the time window and $\lambda$ is the decay constant of $^{214}\text{Po}$ and equal to $4.2 \times 10^3$ s$^{-1}$. It was found that by choosing the length of coincidence window equal to 3 ms, i.e. more than 18 times the half-life of $^{214}\text{Po}$, and assuming the events that occur within a single trigger window are not separately identifiable, that 99.8%
efficiency is achieved to reject any $^{214}$Bi decay that would be background.

In the process of tagging $^{214}$Bi, there is a possibility that a $^8$B solar neutrino event can be randomly followed by a particle in the energy range of the $^{214}$Po alpha and mistakenly be removed as a Bi-Po coincidence event, which results in losing signal. In order to find the probability of losing signal, the rate of events in the $^{214}$Po energy range must be found.

Based on Figure 6.2 that shows all the backgrounds originating from $^{238}$U and $^{232}$Th chains, and by integrating the backgrounds in the Po energy range (0.65 to 1 MeV), it can be found that there are 15,000 background events (both alpha and beta) per year which means the rate of backgrounds is $4.8 \times 10^{-4}$ Hz. Consequently, the probability of observing one or more events in this region in the coincidence time window (3 ms in this case) is $1 - P(0)$, where $P(0)$ is the probability of seeing zero event. From Poisson statistics, the probability of observing zero events in time $\Delta t$ is:

$$P(0) = e^{-r\Delta t} \quad (6.2)$$

for rate $r$. Therefore the probability of observing zero events in the energy range of the $^{214}$Po alpha within a time window of 3 ms is 0.999998 and consequently the probability of mistagging and signal loss is $1 - 0.999998$, which is negligible.

In order to find the total tagging efficiency, it is also required to find the efficiency of the energy cut for the $^{214}$Po alpha event. By considering a $\pm 4\sigma$ energy range, being 0.65 to 1 MeV, the efficiency of the energy cut is 99.994%. Thus, this energy cut range is effective because multiplying it with the efficiency of the time window leaves the total tagging efficiency at 99.8%. Meanwhile, the energy range of 0.65 to 1 MeV does not have a large background rate and random rejection of good signal events is negligible.
CHAPTER 6. $^8B$ SOLAR NEUTRINOS AT LOWER ENERGIES

Figure 6.2: Energy spectra of some of the internal backgrounds expected to be found in $^{214}$Po region. These are the number of events expected per year over the full 6-m radius of the AV volume. The $^{214}$Po alpha energy distribution is shown in orange centered at 0.85 Mev. Expected background rates and number of events are taken from [45].

Figure 6.3: Expanded view of the energy spectrum from $^{214}$Po alpha decays. 99.994% of the decays lie in the energy range of 0.65 to 1 MeV, assuming a pure Gaussian resolution function.
6.1.2 $^{208}\text{Tl}$

Thorium is a naturally occurring radioisotope and another potential source of background in the LAB in SNO+. The decay chain of $^{232}\text{Th}$ is shown in Figure 3.4. $^{208}\text{Tl}$ is an isotope at the end of the Th decay chain. $^{208}\text{Tl}$ has a beta decay to $^{208}\text{Pb}$ with a Q-value of 4.99 MeV which makes it one of the main backgrounds in the energy range of 2.5 to 5 MeV.

$^{208}\text{Tl}$ can be measured in-situ by alpha-beta tagging. This can be done by first identifying a possible beta from $^{208}\text{Tl}$ decay, and then looking for the preceding alpha emerging from the decay of $^{212}\text{Bi}$ into $^{208}\text{Tl}$. Equation 6.1 shows how the time efficiency of tagging is calculated. The time window for tagging $^{208}\text{Tl}$ should be in the order of a few minutes since the half-life of $^{208}\text{Tl}$ is 3.05 minutes. The larger time window makes the tagging with high efficiency and low signal loss more challenging; however, preliminary results from [46] suggest that $^{208}\text{Tl}$ might be tagged with nearly 90% efficiency. The amount of $^{212}\text{Bi}$, the parent of $^{208}\text{Tl}$, can also be measured in another decay channel by beta-alpha tagging with a high efficiency. As shown in Figure 3.4, $^{212}\text{Bi}$ also has a beta decay to $^{212}\text{Po}$ (64% of the time) and following that, $^{212}\text{Po}$ has an alpha decay to $^{208}\text{Pb}$ with the half-life of 300 ns. Therefore, identifying a possible beta from $^{212}\text{Bi}$ and then searching for the alpha coming from the decay of $^{212}\text{Po}$ to $^{208}\text{Pb}$ in a time window of the order of microseconds (beta-alpha tagging) can be used to measure the amount of $^{212}\text{Bi}$ with high efficiency. This measured amount of $^{212}\text{Bi}$ can be used to measure and constraint the number of $^{208}\text{Tl}$ decays in the previously mentioned decay channel.
6.1.3 $^{10}$C

Cosmic rays such as muons and their secondaries can produce radionuclides and neutrons in an organic liquid scintillator by interacting with $^{12}$C, the most abundant nucleus heavier than $^{1}$H in the liquid scintillator. The decays of these radionuclides and the $\gamma$ rays from the capture of neutrons are called cosmogenic backgrounds. One of the long-lived cosmogenic isotopes which is in the energy range of interest, 2 to 5 MeV, is $^{10}$C with a lifetime of 27.8 s. The energy deposited by $^{10}$C in a liquid scintillator is at least 1.7 MeV and stretches as far as 3.6 MeV. The energy deposited by $^{10}$C consists of one de-excitation $\gamma$ and two annihilation $\gamma$’s from the positron emitted in the decay of $^{10}$C. Although $^{10}$C is within the energy region of interest, the production rate of the $^{10}$C is low and can be ignored as demonstrated below.

SNO+ has an advantage over other liquid scintillator experiments by having a depth of 6,000 meters water equivalent. SNO+ is located in SNOLAB with 2 km rock overburden that reduces the cosmic ray muon flux and backgrounds enormously. The expected rate for $^{10}$C in SNOLAB is determined by [47]:

$$ R = R_0 (\frac{E_\mu}{E_\mu^0})^\alpha (\frac{\phi_\mu}{\phi_\mu^0}) $$

(6.3)

where $E_\mu$ and $\phi_\mu$ are the SNOLAB mean muon energy and flux (350 GeV and 0.012 $\mu$/m$^2$/h respectively [48]), and $E_\mu^0$ and $\phi_\mu^0$ are the Borexino mean muon energy and flux (320 GeV and 1.16 $\mu$/m$^2$/h respectively [49]) and $\alpha$ is a scaling parameter. The scaling parameter $\alpha$ was obtained in [50] by fitting the production yield of each cosmogenic isotope as a function of muon beam energy and the $\alpha$ for $^{10}$C based on Table IV in [50] is 0.81. Therefore, the expected rate for $^{10}$C from Equation 6.3 in SNOLAB is 0.06 cpd/kilotonne which is equal to 0.047 cpd/(780 tonnes). This rate is much smaller than the rate of the $^8$B signal, 1.3 cpd/(780 tonnes) in the same region,
and can be ignored.

6.2 Simulation

In order to study the sensitivity and physics potential of SNO+ to $^8$B solar neutrinos simulations were used. In this section, the details of this simulation are described.

In order to perform this study, the signal and background energy spectra need to be known. For the background energy spectrum, the SNOMAN-based Monte Carlo simulations [51] were used. For the $^8$B signal energy spectrum, the simulated neutrino elastic scattering spectrum in D$_2$O used in SNO collaboration was employed [52]. QPhysics (a package of analysis routines developed at Queen’s, that handles solar neutrino physics calculations for SNO) was used to simulate the $^8$B spectrum based on the LMA-MSW model. An important correction needed to be made. Since these calculations were scaled from SNO and occurred in D$_2$O, it was necessary to correct for the 12% higher electron density in LAB compared to D$_2$O.

A Gaussian smearing as the standard energy resolution was applied to these simulated spectra to account for the detector energy resolution. The sigma of this Gaussian was determined by considering the number of PMTs expected to detect the photons associated with an event of a given energy. In the Solar Phase of SNO+, the expected light yield in the detector is 480 PMT hits/per MeV which results in an energy resolution of 2.6% ($\sqrt{1440/1440}$) at 3 MeV.

The signal and backgrounds were normalised to the expected number of events per year. The expected number of $^8$B neutrinos in the LAB volume is 1,636 per year (from 0 to 15 MeV). Based on Borexino internal background levels, the expected number for $^{214}$Bi is 4,890 and for $^{208}$Tl is 244 per year in 780 tonnes LAB without
any reduction. The 99.8% and 90% tagging efficiency would change these numbers to 10 and 24 events/year for $^{214}$Bi and $^{208}$Tl respectively.

When performing a simulation, the simulated backgrounds and signal were used to create two distributions: the fake data distribution and the probability density function, PDF, distributions for fitting to fake data sets.

To generate fake data sets, the simulated backgrounds and signal were added together. For each bin in the fake data sets there is a contribution from both signal and backgrounds. After adding the number of events for both signal and backgrounds in each bin, which is the mean of that bin, a random Poisson fluctuation is applied to each bin. For this study 1,000 fake data sets were generated.

The background and signal PDFs were fitted to fake data sets using the maximum-likelihood method.

### 6.3 Analysis and Signal Extraction

In this section, the analysis used to extract the signal from the artificial data set is described. This analysis consists of fitting artificial data with known Monte Carlo (MC) PDFs using a likelihood fitter available in Roofit [53], applying constraints and extracting signal. A detailed description of the likelihood method can be found in [38]. Here a brief description, extracted and summarized from [38] and [33], of this method is given.
6.3.1 The Maximum Likelihood Fit

The maximum likelihood fit technique is one of the most powerful methods in statistics for parameter estimation. The likelihood of an event is defined as the probability of observing that event when the measured value and a model for that event are available. Let us assume there are N data points corresponding to N independent variables, \( x_i \), and N dependent variables, \( y_i \), where \( y_i = y(x_i, a) \). The goal is to find parameter \( a \) (that can be more than one) by fitting the \( y_i \) with the data points which is called parameter estimation. In order to do this, first each \( y_i \) is converted to a normalized probability density function (PDF). Then, these PDFs are multiplied by each other to obtain the joint probability density function. The likelihood function is obtained by the product of the probability of each event in the corresponding data set, i.e.:

\[
L(a) = \prod_{i=1}^{N} P(x_i) \tag{6.4}
\]

where \( P(x_i) \) is the PDF of the event \( i \). In order to find the parameters, the likelihood function should be maximized. This is computationally more straightforward and precise by calculating the logarithm of the likelihood function, i.e.:

\[
L(a) = \sum_{i=1}^{N} \log P(x_i) \tag{6.5}
\]

Therefore different parameters can be obtained by maximizing the log of the likelihood function.

When the total number of events (or data points, N) is regarded as a free parameter, it is better to use the extended maximum likelihood fit technique for parameter estimation. For example, in this study the expected value of the signal and backgrounds, \( N_j \) are suppose to be estimated and these value are regarded as free parameters in the likelihood function. Therefore the expected total number of events
N, which is equal to the sum of these expected values, is also a free parameter. Since a data set now consists of different event types such as different backgrounds and signals (for simplicity both types are called signal type) then the event probability can be separated into the probability for each event type. Consequently, the probability of measuring a set of observable values, $x_i$, becomes the sum of the probability of measuring those values for an event of different signal types:

$$P(x_i) = \sum_{m=1}^{m} F_j P(x_i|j) = \sum_{j=1}^{m} \frac{N_j}{N} P_j(x_i)$$

(6.6)

where $m$ is the total number of signal types, the $F_j$ is the probability of observing an event of signal type $j$, and represents a fraction of events of that type in the whole data set. $P_j(x_i)$ is the PDF for the signal of type $j$. $N_j$ is the number of events of signal type $j$ and is varied in the fit to maximize the likelihood function.

The observed number of events, $N$ is a random number obtained from a Poisson distribution with the mean value of $\nu$. The observed number of events for the signal type $j$, $N_j$ also represents a Poisson distribution around the true value, $\nu_j$ ($\nu_j = \nu \frac{N_j}{N}$). Therefore the extended likelihood function is formed by multiplying the likelihood function by a Poisson PDF:

$$L = \frac{e^{-\nu} \times \nu^N}{N!} \times \prod_{i=1}^{N} P(x_i) = \frac{e^{-\nu} \times \nu^N}{N!} \prod_{i=1}^{N} \nu P(x_i)$$

(6.7)

As already mentioned computationally it is more straightforward to change this form of the likelihood function to the logarithm of the function. In the software used in this work, the formulation is based on the minimization of the negative of the log likelihood. We can replace the $\nu$ by $\nu = \sum_{j=1}^{m} \nu_j$ and eliminate the constant terms such as $\nu$ and $N!$ (which does not change the location of the minimum of the log
likelihood). Thus the negative log-likelihood function can be expressed as:

\[ L = -\log(L) = -\sum_{i=1}^{N} \log(\sum_{j=1}^{m} \nu_j P_j(x_i)) + \sum_{j=1}^{m} \nu_j. \]  

(6.8)

In this equation, \( \nu_j \), are the fit parameters and can be estimated by minimizing the logarithm of the extended likelihood function.

### 6.3.2 Gaussian Constraints

A constraint on the fit parameters can be applied when there is an available knowledge on the true value of the fit parameters. Some of the fit parameters like those corresponding to the number of events of a radioactive background can be measured by external measurements (ex-situ). For example, it may be possible to measure some of the backgrounds in the detector using radio-assay techniques. The information on the number of backgrounds can also be extracted directly from the data taken by the detector (in-situ), in a complementary way to fitting signals and backgrounds. As an example, in SNO+ \(^{214}\)Bi can be measured in-situ by beta-alpha tagging. This can be used as a direct measurement of the amount of this isotope and the backgrounds produced by this isotope can be known. This information can be used to constrain this background in the fit.

As described in Section 6.1.1 and 6.1.2, \(^{214}\)Bi and \(^{208}\)Tl can be identified and tagged by the beta-alpha and alpha-beta coincidences. The process of tagging these isotopes provides a complementary measurement of the decay rates that we would like to include in the extended likelihood function. In order to apply this constraint, the extended maximum likelihood function is multiplied by the constrained PDF, \( C(\nu) \)

\[ L_c = C(\nu) \times \mathcal{L}. \]  

(6.9)
Often a Gaussian distribution is used for $C(\nu)$. In the case of one constraint parameter and considering the true value of parameter $\nu$ as $\nu_e \pm \sigma_{\nu_e}$, then the Gaussian distribution can be written as:

$$C(\nu) = \frac{1}{\sqrt{2\pi} \sigma_{\nu_e}} \exp\left(-\frac{(\nu_e - \nu)^2}{2\sigma_{\nu_e}^2}\right)$$  \hspace{1cm} (6.10)

In the case of the log likelihood or negative log likelihood function, the constraint term needs to be added to this function. The unconstrained parameters have $\sigma_{\nu_e} \rightarrow \infty$, which makes the contribution from that term zero.

Since the constraints are based on measurements with some uncertainty, they cannot be assumed fixed and should be varied among the test data sets [54]. By repeating an experiment several times, the results are usually different but distributed around the true value. This applies to both data sets and the constraints during measurements. In other words, keeping the constraints fixed would result in bias in the analysis.

In this work, the $^{214}$Bi and $^{208}$Tl in the likelihood function are constrained based on the assumption that an in-situ measurement can be made using the delayed beta-alpha and alpha-beta coincidences. Adding these constraints to the likelihood fit should improve the extraction of the signal.

Constraint values come from uncertainties on beta-alpha and alpha-beta tagging efficiency, such as statistical uncertainty on the amount of $^{214}$Bi and $^{208}$Tl, uncertainty on trigger efficiency and uncertainty due to the energy cut. The statistical error follows Poisson statistics which is the square root of the number of $^{214}$Bi and $^{208}$Tl events, scaled to the number of residual events after tagging. Uncertainties in the constraint from other sources are yet to be determined. Therefore, in this research
work, different constraint values in the fit were used to show their impact on signal extraction.

### 6.3.3 Extracting Signal

The purpose of studying low energy $^8$B solar neutrinos in SNO+ is to test the LMA-MSW effect in different energy bins (2.5 to 5 MeV). In order to simulate $^8$B signal extraction from the data set, the $^8$B PDF was divided into different energy bins. Each bin then was treated as a separate fit parameter in the analysis. The bin width influences the accuracy of the signal extraction. If the bins are too narrow the statistical fluctuations become large. On the other hand, if the bins are too wide the $^8$B spectrum shape can not be fully explored. In this study, the $^8$B energy spectrum was divided into 5 energy bins each with 0.5 MeV width.

The $^{214}$Bi, $^{208}$Tl and signal PDFs were fit to the fake data, while the two backgrounds were constrained in the fit as described in Section 6.3.2, with varying assumptions about the precision of the additional constraint. The 7 fit parameters and their errors (two backgrounds and five signals parameters) were found by the fit. The fits were performed for 1,000 fake data sets and bias and pulls were used to evaluate the behaviour of the signal extraction likelihood fit.

### 6.3.4 Verification Using Bias and Pull Histograms

A bias and pull term for each data set can be defined based on true and fitted values as:

\[
Bias = \frac{\text{fitted value} - \text{true value}}{\text{true value}}
\]  
(6.11)
A bias (pull) histogram is defined and filled with the bias (pull) term associated with each data set. This is done for all seven parameters being extracted in this study. These histograms should be distributed around zero and the pull histogram should have a width approximately equal to one. The fit is biased and indicates a problem with signal extraction if the fit bias for any parameter significantly deviates from zero.

6.3.5 Results

The fitting technique explained in Section 6.3.1 along with constraints described in Section 6.3.2 were applied to the fake data obtained from simulations. In this section, the results are presented and discussed. In this regard, first the goodness of the fit is verified by the bias and pull method in order to ensure the validity of subsequent analyses. Different background levels and constraint values were applied and compared. Two and five years livetime of simulated data were used.

The bias and pull method was applied to all of the analysis variations and the results for only one configuration are shown here as an example. In this configuration, the $^{214}\text{Bi}$ was reduced by 99.8% but $^{208}\text{Tl}$ events were assumed to be untagged and the number of those events not reduced. The results for the two-year livetime data set with a 50% fiducial volume cut with 25% constraint of $^{208}\text{Tl}$ and 30% constraint of the residual $^{214}\text{Bi}$ are shown. Figure 6.4 shows the bias of the fit for different parameters. These values were obtained from 1,000 fake data sets. For each data set, we did the fit and extracted parameters. Then, over the ensemble of 1,000 extracted values, we were plotting the mean value of the histogram of the bias values and the
Figure 6.4: Bias histogram for $^{214}$Bi and $^{208}$Tl backgrounds and 5 $^8$B signals. This plot shows the fit is unbiased since all of the parameters have bias values which are distributed around zero.

RMS error of the histogram as the error bar. As can be seen from Figure 6.4, the mean values of the bias for all the parameters are distributed around zero.

The pull plot is shown in Figure 6.5. For this histogram, we extracted the values for backgrounds and signal and then calculated the pull value (see Equation 6.12) from each of the 1,000 fake data sets. Then, the error bars were plotted by using the RMS error of the histogram. The results are pull-value histograms centered at zero with width one, as can be seen in Figure 6.5 which indicate that the fit is working correctly.
In order to see if the signal extraction and its error are affected by different background levels and constraint values, $^{214}$Bi and $^{208}$Tl background levels were changed and different constraint values applied to these backgrounds. The regions we expect to see the effect of $^{214}$Bi and $^{208}$Tl constraints on $^8$B can be deduced by examining Figure 6.1. The $^8$B$_1$ (2.5-3.0 MeV) and $^8$B$_2$ (3.0-3.5 MeV) parameters can be affected by $^{214}$Bi constraints since they are in the energy range of 2.5 to 3.5 where the number of $^{214}$Bi is considerable. $^{208}$Tl constraints can be checked by looking at $^8$B$_2$ to $^8$B$_5$ (3.0-5.0 MeV). This figure is for two-years livetime inside the 50% fiducial volume without any $^{214}$Bi or $^{208}$Tl reduction.
Figure 6.6 is used to show that different background levels have different impacts on the error bars (error of the fit) of the extracted $^8$B signal parameters. In doing so, three plots corresponding to three different background levels are shown. In plot 6.6a and 6.6b only $^{214}$Bi was reduced by different values while $^{208}$Tl remained intact. In plot 6.6a, $^{214}$Bi was reduced by 90% and in plot 6.6b, $^{214}$Bi was reduced by 99.8%. Plot 6.6c shows the case where $^{214}$Bi was rejected by 99.8% and $^{208}$Tl by 90%. For all these plots we used 30% and 25% constraint values on the residual amounts of $^{214}$Bi and $^{208}$Tl, respectively, after the tag removed some large fraction of the events. As can be seen, the error bars in plot 6.6b are smaller than that of plot 6.6a in the energy range of 2.5 to 3.5 MeV where the $^{214}$Bi is a dominant background. The comparison of plot 6.6c and 6.6b also shows the effect of reducing $^{208}$Tl on the error bars in the energy range of 3.0 to 5.0 MeV. As a conclusion, it is imperative to reduce the background levels in our study to obtain small error bars. This can be achieved by in-situ measurements as described in Section 6.1.1.

The results of constraining $^{214}$Bi and $^{208}$Tl with different values are shown in Tables 6.1 and 6.2. Five-years livetime inside a 50% fiducial volume cut with 99.8% reduction of $^{214}$Bi and no reduction of $^{208}$Tl was considered for this study.

<table>
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<th>Constraint values</th>
<th>5%</th>
<th>10%</th>
<th>20%</th>
<th>30%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{214}$Bi(events/5 years)</td>
<td>6.8 ± 0.34</td>
<td>6.8 ± 0.68</td>
<td>6.85 ± 1.37</td>
<td>6.86 ± 2.05</td>
</tr>
<tr>
<td>$^8$B₁(events/5 years)</td>
<td>292.9 ± 17.6</td>
<td>292.5 ± 17.6</td>
<td>292.9 ± 17.6</td>
<td>292.9 ± 17.6</td>
</tr>
<tr>
<td>$^8$B₂(events/5 years)</td>
<td>275.7 ± 27.4</td>
<td>275.7 ± 27.4</td>
<td>275.7 ± 27.4</td>
<td>276 ± 27.4</td>
</tr>
<tr>
<td>$^8$B₃(events/5 years)</td>
<td>254.4 ± 62.1</td>
<td>254.4 ± 62.2</td>
<td>254.4 ± 62.1</td>
<td>254.4 ± 62.1</td>
</tr>
<tr>
<td>$^8$B₄(events/5 years)</td>
<td>232.1 ± 56.7</td>
<td>232.1 ± 56.7</td>
<td>232.1 ± 56.7</td>
<td>232.1 ± 56.7</td>
</tr>
<tr>
<td>$^8$B₅(events/5 years)</td>
<td>213.5 ± 21.0</td>
<td>213.5 ± 21.0</td>
<td>213.5 ± 21.0</td>
<td>213.5 ± 21.0</td>
</tr>
</tbody>
</table>

Table 6.1: Results for constraining $^{214}$Bi with different values for five-years livetime inside the 50% fiducial volume. $^{214}$Bi is reduced by 99.8%. $^{208}$Tl is not reduced and has a constraint of 25%.
Figure 6.6: These three plots are used to demonstrate the effect of different background levels on the extracted $^8B$. Plots (a) and (b) are used to compare different $^{214}$Bi background levels. In plots (a) and (b) $^{214}$Bi is reduced by 90% and 99.8% respectively, but $^{208}$Tl remains intact. Plots (b) and (c) show the effect of different $^{208}$Tl background levels, since in (c) $^{208}$Tl is reduced by 90%.
Table 6.1 shows the results of constraining $^{214}$Bi with different values. As can be seen, different constraint values on $^{214}$Bi have no impact on the signal extraction and its error. This is because the number of $^{214}$Bi events after the beta-alpha tag rejects 99.8%, is around 7 events in 5 years and is small compared to the amount of $^8$B solar neutrino events. The precision of the constraint that one can apply to the residual amount of $^{214}$Bi after the tag is thus not important.

Table 6.2 shows the results of constraining $^{208}$Tl with different values. Since no reduction is used for $^{208}$Tl, the number of $^{208}$Tl is high enough (585 events/5 years) to affect the error bars of the $^8$B signal. The better the $^{208}$Tl can be constrained, the smaller the error bars on the $^8$B signal extracted. It is worth pointing out that the constraint value for $^{214}$Bi and $^{208}$Tl are coming from the beta-alpha and alpha-beta tagging efficiency. The results of reducing $^{208}$Tl with 90% is not shown since the number of $^{208}$Tl background reduces significantly (59 events/5 years) that it does not change the error bars.

Finally, $^8$B extraction for two-years and five-years livetime inside a 50% fiducial volume cut are compared. For this comparison, $^{214}$Bi is rejected by 99.8% with 30% constraint and $^{208}$Tl is reduced by 90% with 25% constraint. The results for two years

<table>
<thead>
<tr>
<th>Constraint values</th>
<th>10%</th>
<th>15%</th>
<th>25%</th>
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<tbody>
<tr>
<td>$^{208}$Tl</td>
<td>583.3 ± 58.2</td>
<td>584.8 ± 87.3</td>
<td>586.5 ± 144.8</td>
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<tr>
<td>$^8$B$_1$</td>
<td>293 ± 17.6</td>
<td>293 ± 17.6</td>
<td>292.9 ± 17.6</td>
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<tr>
<td>$^8$B$_2$</td>
<td>276.4 ± 20.5</td>
<td>276.2 ± 22.3</td>
<td>275.7 ± 27.4</td>
</tr>
<tr>
<td>$^8$B$_3$</td>
<td>256.4 ± 32.2</td>
<td>255.8 ± 41.5</td>
<td>254.4 ± 62.1</td>
</tr>
<tr>
<td>$^8$B$_4$</td>
<td>233.9 ± 29.9</td>
<td>233.4 ± 38.1</td>
<td>232.1 ± 56.7</td>
</tr>
<tr>
<td>$^8$B$_5$</td>
<td>214 ± 17.1</td>
<td>214 ± 18</td>
<td>213.5 ± 21.0</td>
</tr>
</tbody>
</table>

Table 6.2: Results for constraining $^{208}$Tl with different values for five-years livetime inside the 50% fiducial volume. $^{208}$Tl is not reduced. $^{214}$Bi is reduced by 99.8% and has a constraint of 30%.
Figure 6.7: $^8$B extraction for two-years livetime inside a 50% fiducial volume. In this plot $^{214}$Bi is rejected by 99.8% and has a constraint of 30%. $^{208}$Tl has a constraint of 25%. The green spectrum is the undistorted $^8$B spectrum shape with the same number of events as the LMA-MSW spectrum. The blue is the extrapolation of the SK results to the low energy region.
Figure 6.8: $^8$B extraction for five-years livetime inside the 50% fiducial volume. The configuration is the same as in Figure 6.7.
and five years are presented in Figures 6.7 and 6.8, respectively. In these figures, the extracted $^8$B (the extracted $^8$B spectrum is the mean value from the 1,000 fake data set ensemble) is compared with two spectra shown in green and blue. The green one is the undistorted $^8$B spectrum which is normalized to the number of events expected in the LMA-MSW spectrum. This enables us to compare these two spectra based on their shape.

The electron neutrino survival probability $P_{ee}$ describes the suppression of the flux of electron neutrinos from the sun; the value measured by SNO at higher energies is roughly $P_{ee} = 0.34$. After solar neutrinos oscillate, the $\nu_\mu$ and $\nu_\tau$ flux components can also interact via elastic scattering with electrons, with a smaller cross section than for $\nu_e$. This was included in the above simulations and comparisons with the LMA spectrum in red.

The Super-Kamiokande (SK) experiment observed neutrino scattering off electrons at higher energies. The effective flux they observed (because of the $\nu_\mu$ and $\nu_\tau$ contributions) was 0.45 SSM, for energies greater than 4.5 MeV. The blue spectrum in Figure 6.7 and 6.8 is the extrapolation of the SK results to the low energy region using a flat (constant with energy) suppression factor of 0.45.

These two plots are used to give us an overview of the expected $^8$B solar neutrino signal and its error in different energy bins for two and five years data inside the fiducial volume. Although the uncertainties are small especially in the region of 2.5 to 3.5 MeV, the ability to distinguish between the expected (but not yet observed) LMA spectrum versus the undistorted $^8$B spectrum with flat suppression factor of 0.45 will not have high statistical significance.

In order to estimate the difference between these two plots, we look at the range
2.5 to 4 MeV where the difference is more significant (see Figure 6.8). The expected number of $^8$B with LMA spectrum in the energy range of 2.5 to 4 MeV is 823.2 counts/year and for the undistorted $^8$B spectrum multiplied by a flat factor of 0.45 is 765.2 counts/year. The uncertainty in the extracted signal, integrated from 2.5 to 4 MeV is $\pm 30$. The difference between the LMA spectrum and the undistorted flat 0.45 spectrum is only about $2\sigma$, for this extracted statistical error.
Chapter 7

Summary and Conclusion

LMA-MSW oscillations for $^8$B solar neutrinos have been tested by experiments such as SNO for energies higher than 3.5 MeV. As SNO+ is designed to measure the solar neutrino flux at a lower energy range, it is able to study LMA-MSW oscillations at energies less than 3.5 MeV, where the size of deviations between the expected behaviour and discrepancies due to new physics is thought to be larger. This research is concerned with extracting $^8$B solar neutrinos in different energy bins by fitting the Monte Carlo PDFs with fake data sets. In doing so, $^{214}$Bi, one of the main backgrounds in the energy range of interest, was tagged and removed by 99.8%.

One of the main sources of $^{214}$Bi background is $^{222}$Rn entering the SNO+ detector. This can happen from emanation of $^{222}$Rn from materials within the SNO+ detector, the cover gas system or contamination in the acrylic vessel and the liquid scintillator. Therefore, radon measurement and control are important tasks in the success of the SNO+ experiment. In this regard, Lucas cells are used to detect radon emanated from different materials. In this research, experiments were carried out to find a suitable supplier for zinc sulfide (ZnS), a scintillation material for use in Lucas cell
fabrication. The criteria for selection were low background, high light yield and ease of fabrication. The result of these experiments showed that the ZnS supplied by the company Rexon is superior to another alternative.

As another means to control radon, cover gas is used in the SNO+ experiment to act as a barrier to prevent radon penetration. In doing so, cover gas bags are employed to react to the variation of mine air pressure. The material used to make cover gas bags must show small radon emanation and at the same time have low permeability to radon. The selected material was from DuPont. In this research, fabrication of these cover gas bags along with the measurement of radon emanation from the interior of these bags were performed. The results showed that less than 9 radon atoms per day would be induced in the detector as a result of using these cover gas bags.

Finally, in the analysis section of this research work, it was shown that by beta-alpha tagging, $^{214}\text{Bi}$ can be tagged and removed by 99.8%. Further, $^8\text{B}$ signal extraction and its error were compared for different background levels, constraint values and also for two and five years livetime inside a 50% fiducial volume cut. As a result, the MSW-LMA and the undistorted $^8\text{B}$ spectrum with flat suppression factor of 0.45 were compared. The results showed that the ability to distinguish between the expected (but not yet observed) LMA spectrum versus the undistorted $^8\text{B}$ spectrum at 0.45 times the SSM flux will not have high statistical significance.
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